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STATIC VAR COMPENSATORS

Prepared by

Working Group 38-01
Task Force No. 2 on SVC

Edited by

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CIGRE WG38-01 TASK FORCE No.2
ON STATIC VAR COMPENSATORS

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Prepared by
Working Group 38-01; Task Force No. 2 on Static Var Compensators

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INTRODUCTION

The rapid developments of semiconductor devices and control techniques within the last two decades have enabled the development of controllable shunt reactive compensation devices with rapid response for electric power system applications. In recognition of the potential applications and the impact of such a flexible system design tool on future electric power systems CIGRE Study Committe 31, in September 1980, decided to form and "Ad Hoc Task Force on Static Var Compensators" as part of Working Group 31-01 activities. This task force was to review the progress on the subject since the last published CIGRE work on modelling such devices in 1977 and carry out an International Survey of operational experience with such devices so that necessary guidelines for future applications could be prepared.

Following nominations of experts from utilities, manufacturers, research organisations and universities, the terms of reference of the Task Force were established, and work commenced in December 1981. The Task Force members agreed that the relevant information existed in part in a wide variety of published papers and in part in the experience gained through practical schemes. The terms of reference were established as the provision of practical guidance in the form of a single report covering applications, functional specification, modelling, operational experience as well as the terms and definitions associated with static var compensators in electric power systems. The terms of reference excluded applications associated with HVDC transmission and industrial load compensation as these were covered by other CIGRE Study Committees.

Following the September 1982 CIGRE re-organisation, the task force was requested to continue its work as "Task Force No.2. on Static Var Compensators" attached to CIGRE Working Group 38-01. This book is the result of the Task Force work on the subject.

During the course of its work, the task force held some eight full and four sub-group meetings. Rapid progress was ensured by assigning tasks to sub-groups of specialists. Early discussions indicated the need for provision of guidance on testing of static var compensators as there was no single international standard covering such tests. This guidance, based upon experience obtained with installations to the present date, has been added.

In order to survey the international experience gained from operating such devices, a questionnaire was circulated in August 1983. Information on each particular application and operational experience was requested for both currently operational installations and those being planned or on order. The detailed replies received from some 25 utilities on 73 individual installations up to 1985 are gratefully acknowledged and summarised in this book.

The subject matter of the report is covered in nine chapters including a glossary of terms and definitions The bibliography is the result of team work as each expert has contributed as required and agreed. A list of the contributing task force members is included in these pages.

As Chairman it fell to me to bring together the prodigious efforts of the contributing experts and edit the report. I would like to take this opportunity to thank the contributing Task Force members, whose time is in much demand by their own as well as international organisations, for their continued strong support during the course of this work. The continued support of their organisations and my own organisation is also gratefully acknowledged. Special thanks are due to Professor Dr. K. Reichert in bringing together the material on power system studies, SVC modelling and specification. My thanks are also due to the task force Secretary, Mr. W.B. Jervis, for his patient help and sense of humour which helped to resolve many problems. The efforts of Mrs J. Snell, Mrs L. Baker, Mrs T. Brooke and Mrs A. Dudley in typing the manuscript are also gratefully acknowledged, together with the efforts of Mr. G. Dallimore in organising the diagrams and general preparation.

It is the hope of all contributors that the report will be of practical value to practising utility engineers.

I.A. ERINMEZ
Chairman
September 1985

CONTENTS

CHAPTER 1

APPLICATION OF STATIC VAR COMPENSATORS TO ELECTRIC POWER SYSTEMS

1.1 INTRODUCTION

This Chapter briefly describes the application of static var compensators (SVCs) as the solution to a number of problems encountered in power systems. The chapter is not intended as a full treatise of the subject which is further discussed in detail in the references provided. Industrial applications such as power factor correction and flicker reduction have not been included as they are beyond the terms of reference of this book.

Static var compensators (SVCs) are shunt connected static generators and/or absorbers of reactive power (volt ampere reactive or var) whose outputs are varied so as to maintain or control specific parameters of the electrical power system. The term 'static" is used to indicate that SVCs unlike synchronous compensators have no moving or rotating main components. Thus, the SVCs consist of static var generator and/or absorber device(s) (SVG), capable of drawing capacitive and/or inductive current from an electrical power system, and a suitable control device, as illustrated in fig. 1.1. A static var system (SVS) is then defined as a combination of different static and mechanically switched var compensators whose outputs are co-ordinated. Finally, a var compensating system (VCS) is defined as a combination of both static var systems and rotating var compensators whose outputs are co-ordinated. These definitions will be utilised throughout this report.

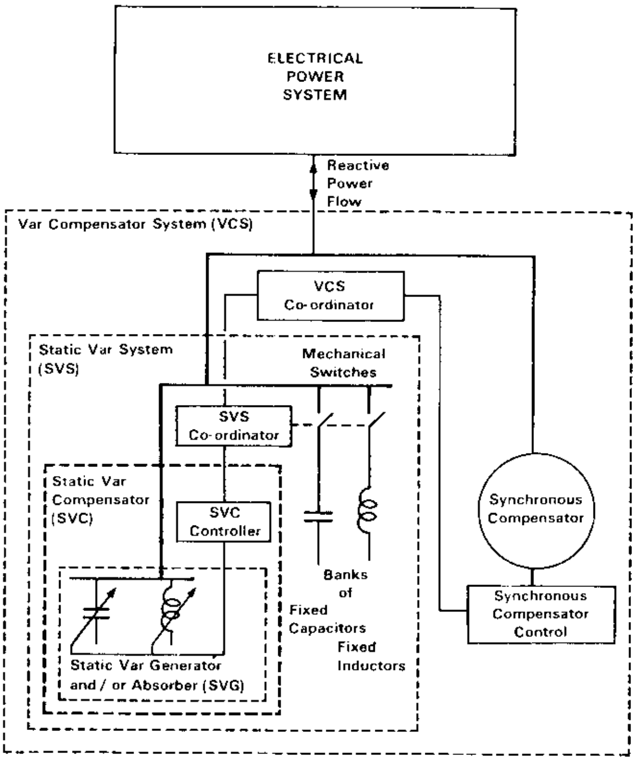


Fig. 1.1 Diagram illustrating the definition of static var compensator and its relationship with other reactive compensation devices

A typical voltage-current characteristic of an SVC is shown in fig. 1.2a. The SVC by absorbing or generating reactive power within its working range is able to maintain virtually constant voltage. This characteristic behaviour is equivalent to an ideal system voltage source (U_{ref}) being in phase with the system voltage (U) at the point of connection, or a voltage controlled shunt susceptance (B) at the same point as shown in figs. 1.2b and 1.2c. The SVC is thus similar to a synchronous compensator except that it has no mechanical inertia and its speed of response is much faster.

Throughout this report the SVC is treated like a load; with positive reactive power ($Q>0$) indicating that the SVC is behaving like an inductor and negative reactive power ($Q<0$) indicating that SVC is behaving like a capacitor. This means that SVC is modelled as a load susceptance, i.e. $B = -Q/U^2$ is negative for an inductor and positive for a capacitor.

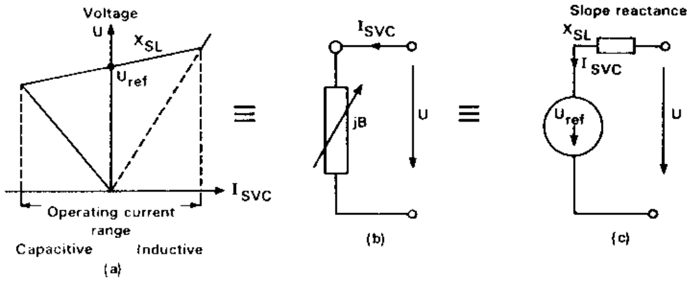


Fig. 1.2 Typical steady-state voltage current characteristic of SVC and its equivalent representation

Static var compensators (SVCs) with particular characteristics and control are applied to power systems to solve a variety of problems, namely :

a) to achieve effective voltage control
b) to balance loading of individual phases (i.e., asymmetrical loads)
c) to increase active power transfer capacity of both existing and new transmission systems
d) to increase transient stability margin
e) to increase damping of power oscillations
f) to reduce temporary overvoltages
g) to damp subsynchronous oscillations
h) to provide reactive power to AC-DC converters.

In some of these applications, in order to achieve the desired control, the reactive power can be varied slowly so that mechanical switching of shunt reactors and capacitors is satisfactory, while in others fast variation is required which can be achieved by static var compensators.

1.2 VOLTAGE CONTROL

In power systems with a low short-circuit fault MVA level or with long transmission lines (i.e. weak systems), the voltage is significantly affected by load variations as well as by switching of system elements such as transmission lines, reactors, capacitor banks and transformers. Under heavy loads, the voltage will drop considerably or even collapse (refs 289, 333). This may cause operation of undervoltage relays and/or voltage sensitive controls leading to extensive disconnection of loads and thus adversely affecting the consumers. However, when the load is light, overvoltages can arise owing to the Ferranti effect on unloaded lines, capacitive overcompensation of the system, and temporary overexcitation of synchronous machines. Overvoltages cause transformer saturation, which results in excessive harmonic generation, harmonic resonances and, possibly, ferroresonance with capacitor banks, transmission lines or cables. This could cause multiple operations of surge arresters and, possibly, their destruction, harmonic heating of capacitors and motors, as well as damage to consumers equipment.

Voltage variation at the receiving end of a weak power system as a function of the system loading can be modelled by a simple system shown in fig. 1.3, where E is the system equivalent EMF and X_e is the equivalent system reactance inversely proportional to short-circuit fault MVA infeed (i.e. system strength) at the busbar.

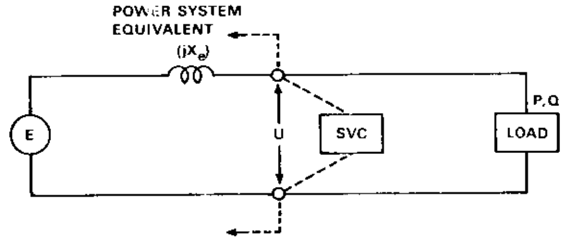


Fig. 1.3 System and SVC equivalent for load voltage control

From classical theory, the voltage at the load busbar of such a system will tend to collapse for increasing amounts of power demanded by the load if no reactive compensation is applied as shown in curve (a) of fig. 1.4. Provision of an SVC at the load point will, within its rated range, maintain the load voltage within design rating limits as shown in curve (b) of fig. 1.4. If, however, the SVC has unlimited rating as shown in curve (c) of fig. 1.4 then it is of course possible to hold constant voltage at the load busbar for any load condition.

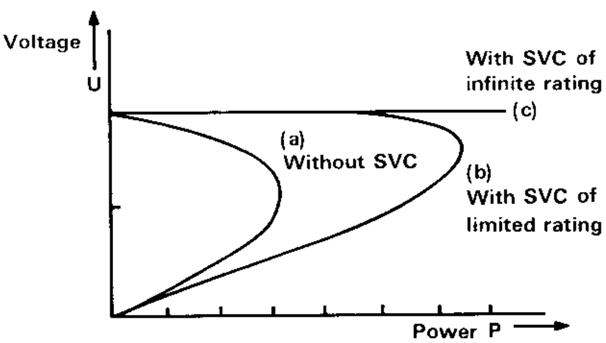


Fig. 1.4 Voltage variation at a load busbar as a function of loading at constant lagging power factor, with and without SVC

1.3 LOAD BALANCING

Asymmetrical or single phase loads may affect voltages especially in weak systems, causing voltage asymmetry and overloading of system components as well as generation of additional losses in rotating machinery. By adding appropriate reactive shunt components, the following objectives could be achieved (ref. 130, 289, 333) :

- balancing of load and voltages
- power factor correction

For balancing asymmetrical, continually varying loads such as arc furnaces, railways, etc., a static Var compensator with individual control of its phase-to-phase reactive components is the only practical solution.

If the phase-to-phase load admittances at a particular instant are $(G_{ab} + j\,B_{ab})$, $(G_{bc} + j\,B_{bc})$, and $(G_{ca} + j\,B_{ca})$, according to the complex power relationship $P - j\,Q = U^2\,(G + j\,B)$, then the phase-to-phase reactive shunt compensation susceptances B_{ab}, B_{bc} and B_{ca} required for load balancing are given by the following expressions (see fig. 1.5a) :

$$B^C_{ab} = -B_{ab} + (G_{ca} - G_{bc})/\sqrt{3}$$

$$B^C_{bc} = -B_{bc} + (G_{ab} - G_{ca})/\sqrt{3}$$

$$B^C_{ca} = -B_{ca} + (G_{bc} - G_{ab})/\sqrt{3}$$

where the terms $-B_{ab}$, $-B_{bc}$ and $-B_{ca}$ in the above equations provide the load reactive compensation and the terms $(G_{ca} - G_{bc})/\sqrt{3}$, $(G_{ab} - G_{ca})/\sqrt{3}$ and $(G_{bc} - G_{ab})/\sqrt{3}$ provide the balancing of the active power loads among the phases. The resultant phase-to-phase loading (fig. 1.5) is equal to :

$$G = (G_{ab} + G_{bc} + G_{ca})/\sqrt{3}$$

as shown in fig. 1.5b. If, for example, the load is single phase active power load across phases a and b (i.e. $G_{bc} = G_{ca} = 0$, $B_{ab} = B_{bc} = B_{ca} = 0$) then we have :

$$B^C_{ab} = 0 \text{ and } B^C_{bc} = -B^C_{ca} = G_{ab}/\sqrt{3}$$

which means that the application of an equally sized capacitor between phases b and c and reactor between phases a and c will be necessary for balancing this single phase load.

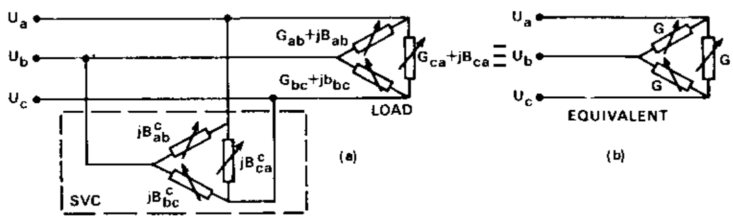


Fig. 1.5 Load balancing and power factor correction to unity

After the balancing is achieved in the above manner additional symmetrical susceptance can be applied across each phase pair of the SVC to provide power factor correction different from unity or to control the load voltage within closer limits.

1.4 POWER TRANSFER CAPACITY INCREASE

The transmission capacity of a power system is generally limited by the operating voltages and the transfer reactance across the system. For an interconnected transmission system modelled by a single machine against infinite bus equivalent, the power is given by the expression :

$$\frac{P}{P_m} = \sin\delta \quad , \quad P_m = \frac{E^2}{X}$$

where

- E the magnitude of the sending-end machine internal voltage and infinite bus voltage
- X the equivalent interconnecting reactance including the machine, transformer leakage, transmission line and equivalent system reactances
- P the active power transfer
- P_m is the maximum active power transfer
- δ the power angle between the sending and receiving end machine internal voltages.

Maximum steady-state active power transmission, $P_m = E^2/X$, is achieved at $\delta = 90°$, which represents the theoretical steacy-state stability limit.

SVCs applied at locations along a transmission system will tend to increase the power transfer capacity by virtue of the voltage support provided by the SVC at the point of connection. When an SVC of infinite rating is applied at the middle of the interconnecting reactance, then the power transfer capacity is modified as follows (see fig. 1.6) assuming U = E :

$$\frac{P}{P_m} = 2 \sin \frac{\delta}{2}$$

which means that the theoretical steady-state stability limit is now achieved at $\delta = 180°$, and the maximum active power transfer is doubled.

Under maximum active power transfer operation, the SVC rating $Q_{C\,max}$ required for steady-state stability is equivalent to four times the maximum active power transfer, that is ($4P_m$). In practice a lower level of compensation is usually adopted for economic reasons. If a compensator with limited capacity is operated above its rating it acts as a constant shunt susceptance, which means that the midpoint voltage can no longer be kept constant at the value E. In this case the active power transfer reduces to a level given by the expression :

$$\frac{P}{P_m} = \frac{1}{1 - \frac{Q_C}{4P_m}} \sin\delta$$

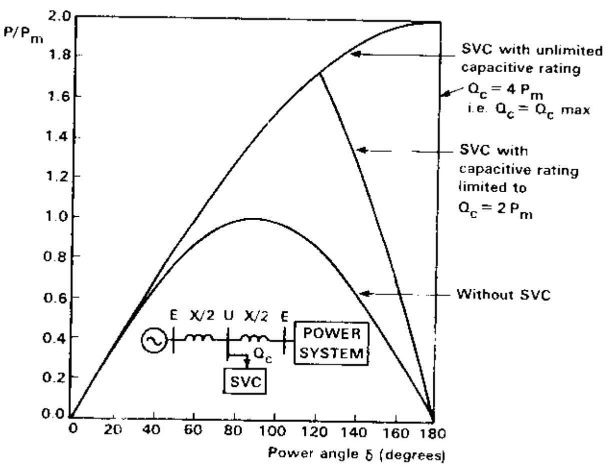


Fig. 1.6 Power transfer characteristics of a transmission system, with and without SVC

The power transfer characteristics of the transmission system as a function of the power angle with and without an SVC at the middle of the interconnecting reactance are given in fig. 1.6.

The power transfer capacity increase obtainable for a particular system with SVCs connected at strategic locations can be determined by load flow studies.

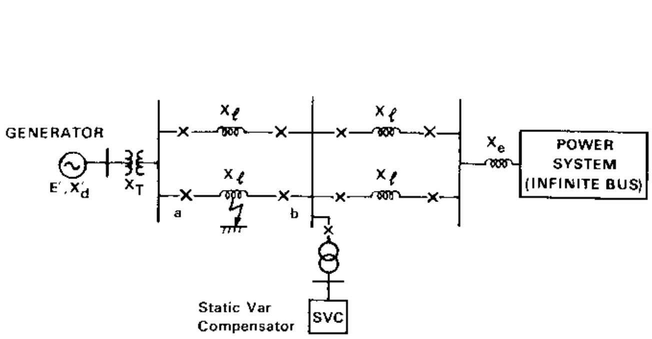
1.5 TRANSIENT STABILITY IMPROVEMENT

In order for the power system to remain stable, even after large disturbances due to faults cleared by protective switching, power transfer over the system must remain sufficiently below the steady-state stability limit. The maximum power level for which transient stability is maintained under a particular system operating condition is known as the transient stability limit. For a simple power system shown in fig. 1.7, a prefault power transfer of P_1 is assumed. During the fault, the system power transfer capability drops from a prefault level represented by curve 1 to that of curve 2. Since the mechanical input remains constant, the generator will accelerate until the fault is cleared at rotor angle δ_c by switching the faulty line out of service enabling the power transfer to recover, albeit to a reduced level represented by curve 3 (refs 261, 289). This accelerating energy is represented by area A_1. The rotor continues its swing due to the accumulated kinetic energy but now decelerates, since the transmitted power is forced to exceed the prime mover input. The maximum value of rotor angle is reached when the decelerating energy, as defined by area A_2, is equal to the accelerating energy defined by area A_1.

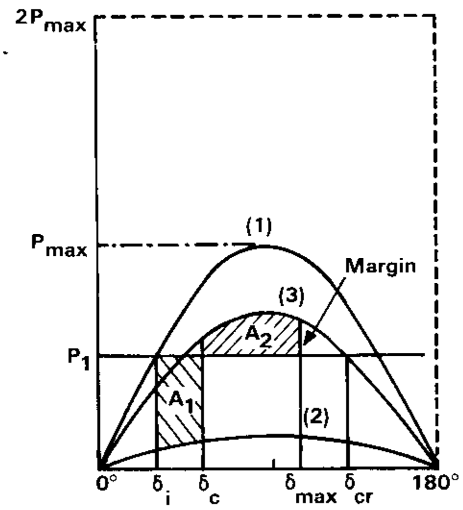
If for the given post-fault system the maximum rotor angle (δ_{max}) reached is below the critical rotor angle (δ_{cr}) the system will remain transiently stable. The critical rotor angle represents the rotor angular swing beyond which rotor deceleration cannot be maintained. As long as δ_{max} is smaller than δ_{cr}, decelerating energy is available to restore the rotor to a steady-state condition. This allows some margin for the system to cope with further variations of system operating conditions or more severe disturbances.

When the SVC is applied at a central location, the power transmission capability increases as shown in fig. 1.7c. For the same power transfer level, a larger decelerating energy is available thus increasing the transient stability margin.

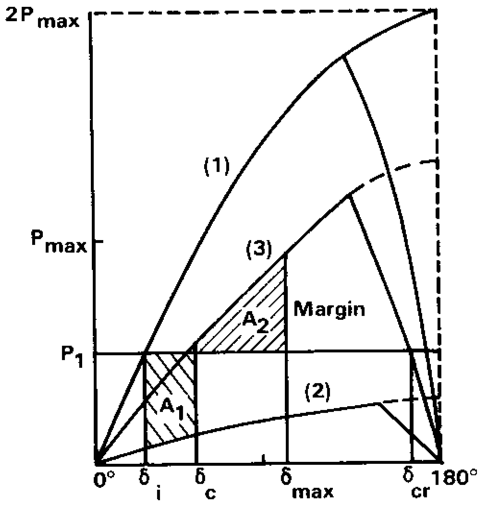
In some applications the voltage reference is automatically adjusted such that under steady-state conditions the compensator output will be zero or at a preset operating value. This enables sufficient compensation within the full rated range of the compensator to be available for voltage support in the post-fault period to increase the transient stability margin.



(a) Equivalent power system



(b) Without SVC



(c) With SVC

(1) Prefault (2) During fault (3) Postfault

Fig. 1.7 Improvement in system transient stability margin with an SVC

1.6 IMPROVEMENT OF SYSTEM DAMPING

In electric power systems large disturbances caused by system faults, load rejection or critical accidental switching are relatively infrequent while small disturbances arise frequently as a result of normal load variations and switching operations. Such disturbances cause electro-mechanical oscillations which are generally damped by generator rotor damper circuits and power system stabilisers associated with generator excitation controls. However, undamped power oscillations which could result in sustained voltage and power swings and even in loss of synchronism between generators, can arise following a small disturbance, when either :

(i) power transfer capability defined by the transfer impedance(s) of the systems;
or
(ii) generator excitation control, governor control and system load characteristics, either individually or in combination, are such that negative damping and/or reduction of synchronising torque occurs.

The damping of such oscillations is a function of transmission system design, generator excitation control, generator design and system load characteristics. However, by providing continuously controlled fast response reactive compensation in the form of an SVC, it is possible to improve system damping performance by including relevant signals in the SVC control system (refs. 173, 332). Fig. 1.8 illustrates the damping improvement obtained by an SVC applied to a large power system (ref. 332).

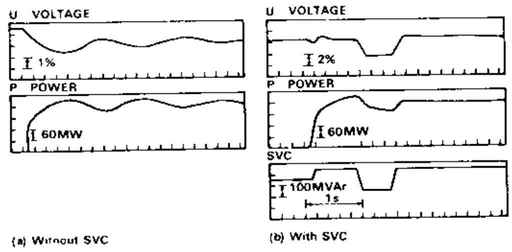


Fig. 1.8 Illustration of system damping improvement by an SVC in a large power system, the system voltage and power response to a line switching disturbance

1.7 SUBSYNCHRONOUS RESONANCE DAMPING

When series capacitors are used to compensate the series inductance of long transmission lines, a phenomenon known as subsynchronous resonance (SSR) can occur (ref. 185). The phenomenon occurs when the series capacitors resonate with the equivalent inductance of the generator and transmission line at a frequency lower than the system nominal frequency. Under such resonance conditions, the mechanical impedance of the generator shaft system may exhibit negative damping for a particular torsional mode. As a result, torsional oscillations will spontaneously arise and continue to increase in amplitude until the generator shaft system is destroyed. The application of an SVC for damping subsynchronous resonance by incorporating suitable controls is illustrated in fig. 1.9 (ref. 264, 265).

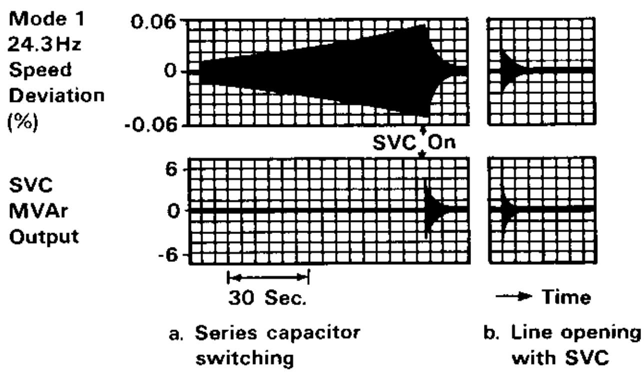


Fig. 1.9 Illustration of system switching leading to self-excited subsynchronous oscillations and damping performance improvement obtained by SVC

1.8 REACTIVE COMPENSATION OF AC-DC CONVERTERS AND HVDC LINKS

Due to their inherent characteristics, AC-DC converters consume reactive power which is typically 60% of their active power independent of their mode of operation. During AC and/or DC system disturbances, large transient variations in this reactive power demand can be experienced depending upon the system equivalent reactance and converter controls. Such large reactive power variations can cause substantial dynamic or temporary changes in the AC system voltage, especially when the equivalent AC system impedance at the converter busbar is high (refs 196, 324).

Due to their inherent high speed of response, SVCs with adequate reactive power generation and absorption capability, represent an effective method in controlling such disturbances. The installation of an SVC as part of the converter complex would enable:

- better control of AC voltage by reducing the effect of reactive power variations due to changes in converter demand and/or switching of filter banks
- reduce the dynamic and temporary overvoltages due to converter blocking
- assist in the recovery of the AC system from faults

References (278, 309, 343, 368, 379 and 380) contain relevant information on applications of SVCs for HVDC link compensation purposes.

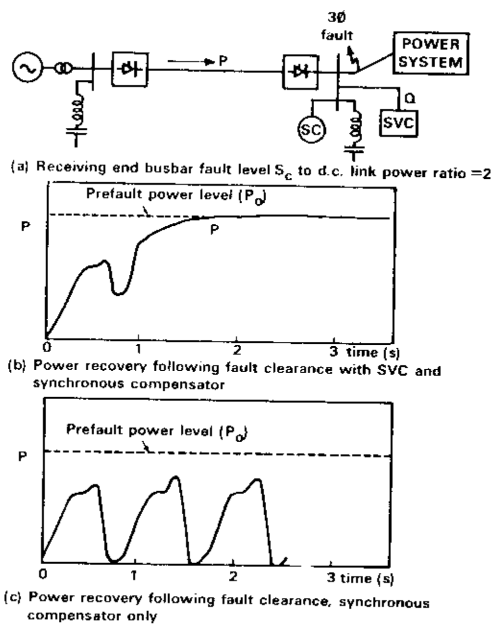


Fig. 1.10 Comparison of SVC and synchronous compensator performance on HVDC transmission system

Fig. 1.10 illustrates the application of an SVC to an HVDC transmission shceme feeding power to a weak power system (characterised by a large impedance or low short-circuit fault MVA level) at the inverter busbar. Power transmitted across the HVDC link can be more quickly restored following an AC system fault if the speed of response of the SVC is combined with the ability of the synchronous compensator to increase the short-circuit fault level.

1.9 REDUCTION OF TEMPORARY AND LINE ENERGISATION OVERVOLTAGES

Temporary overvoltages at load rejection arise as a result of the interaction between line inductance and capacitance (Ferranti effect), capacitive overcompensation, temporary overexcitation and overspeed of synchronous machines. In addition to imposing voltage stresses in general, these overvoltages can cause undesired operation of surge arresters. SVCs with appropriate overload capability in the reactive power absorption range, can contribute to fast voltage reduction as illustrated in fig. 1.11 (ref. 290). The surge arrester operation obtainable with and without an SVC is illustrated in fig. 1.12 (refs 224, 290, 299).

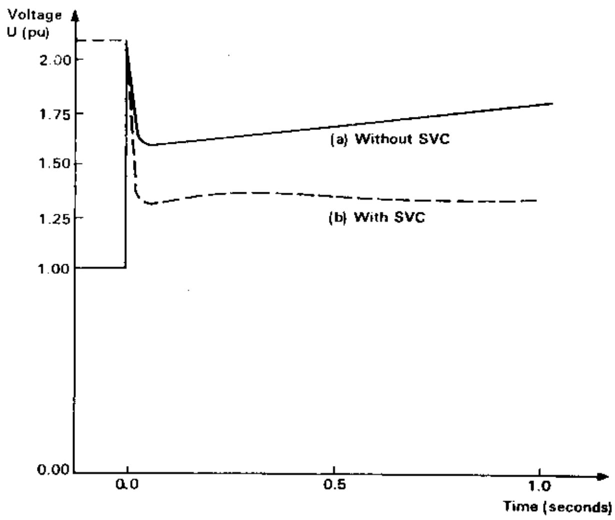


Fig. 1.11 An illustration of load rejection overvoltage reduction by an SVC

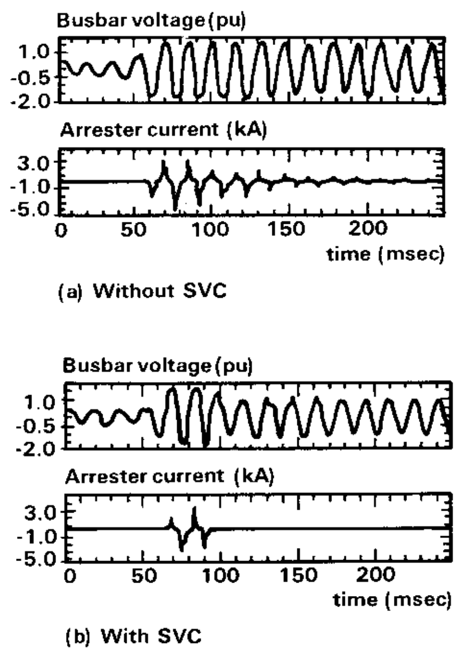
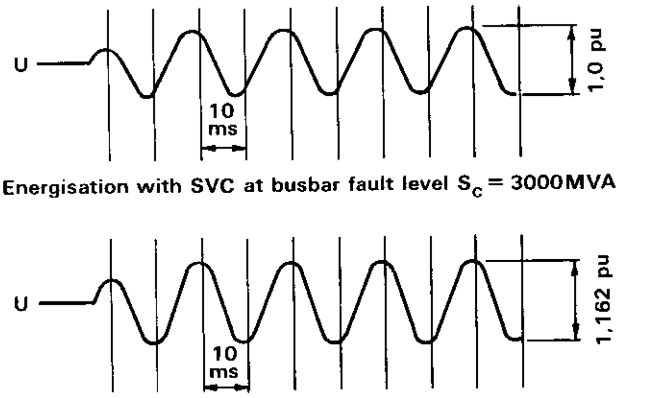


Fig. 1.12 Illustration of the effect of SVC in reducing load rejection overvoltages and undesirable multiple surge arrester operation

In power systems the reactive power generated by transmission lines and cables is utilised for effective voltage regulation during heavy power flows. However, under light load or line charging conditions excessive voltage rises can occur if the reactive power generated by the lines and cables is not effectively absorbed. In some applications, especially in systems with long transmission lines and/or cables, the utilisation of a circuit breaker switched shunt reactor is not found satisfactory (ref. 284). In these cases an SVC in the form of a controlled shunt reactor is utilised to limit the transient voltage rises within acceptable limits. The line energisation voltages measured at the receiving end of the transmission line/cable, with an SVC at the receiving end in service, are shown in fig. 1.13



Energisation without SVC at busbar fault level S_c = 3000MVA

Fig. 1.13 Illustration of transmission line/cable energising voltages measured at the receiving end with and without an SVC in service

1.10 SUMMARY

Static var compensators are applied to power systems to perform a variety of functions. Through their ability to offer continuous and fast reactive power control economically, they are being increasingly utilised in applications other than the traditional system voltage control such as increasing the power transfer capability of existing transmission systems, increasing the system transient stability margin, providing additional damping for small disturbances, and for providing dynamic reactive power compensation to AC-DC converters in DC transmission and interconnection systems. In addition, SVCs are applied to balance phase loading, to damp subsynchronous resonance and to reduce temporary overvoltages.

The applications of SVCs to power system problems are summarised in Table 1.1. SVCs have proved an economical and efficient means of providing dynamic reactive power compensation of power systems establishing them as a powerful system design tool in alleviating problems and enhancing system steady-state and dynamic performance.

Table 1.1 : SVC Functions - VS - Problems in power systems

SYSTEM PROBLEM / SVC FUNCTION	VOLTAGE INSTABILITY	LOAD UNBALANCE	TEMPORARY OVER-VOLTAGES	INSUFFICIENT POWER TRANSFER CAPACITY	INSUFFICIENT TRANSIENT STABILITY MARGIN	INSUFFICIENT SYSTEM DAMPING	SUB-SYNCHRONOUS RESONANCE	REACTIVE COMPENSATION OF AC-DC CONVERTER STATION
VOLTAGE CONTROL	X	X	X	X	X	X	X	X
LOAD BALANCING		X						
REACTIVE COMPENSATION		X		X	X			X
POWER OSCILLATION DAMPING					X	X		
SUB-SYNCHRONOUS RESONANCE DAMPING							X	

CHAPTER 2

STATIC VAR COMPENSATOR TYPES AND BASIC CHARACTERISTICS

2.1 INTRODUCTION

Controlled reactive compensation in electric power systems is presently achieved with a variety of shunt devices which can be categorised as follows (fig. 2.1) :

- Synchronous Condensers (rotating machines)
- Static Var Compensators (SVC) with
  1. stepwise, active control : mechanically switched capacitors and reactors (MSC and MSR)
  2. continuous, inherent control : saturated reactors (SR)
  3. continuous active control : thyristor controlled reactors (TCR), self or line-commutated convertors (SCC or LCC)
  4. discontinuous active control : thyristor switched capacitors (TSC) or thyristor switched reactors (TSR).

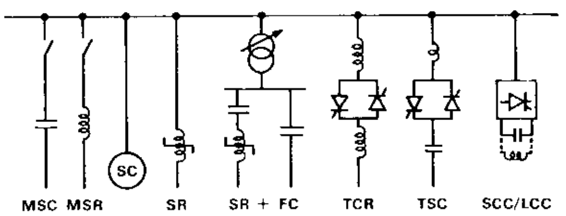


Fig.2.1 Shunt devices for controlled reactive compensation

The abovementioned devices can be used alone or in any combination. Some of these devices are suitable for constant or slow-varying compensation only, while others allow fast variation of the reactive power or shunt susceptance as required by the particular power system application.

The following survey deals with static var compensation devices (SVCs) with inherent or active control. Information is given on the basic structure of the SVCs, detailing their output and control characteristics, harmonic performance, loss characteristics, overvoltage performance and special features. A comparison of the devices is given in a tabular form together with information on typical applications.

2.2 MECHANICALLY SWITCHED CAPACITORS (MSC)

The basic scheme typically consists of a single capacitor unit or a bank or capacitor units connected to the power system by a circuit breaker either directly or via a transformer. A small reactor might be connected in series with the capacitors to damp energising transients and to reduce harmonics. Prestrike and restrike-free circuit breakers have to be used to avoid system overvoltages due to capacitor switching transients.

The output characteristic (U-I) is linear, defined by the rated values of the voltage and current (U_{rated}, I_{rated}) as shown in fig. 2.2.

The response time is equal to the switching time given by the circuit breaker arrangement which is in the order of 100 ms following the initiation of an operating instruction. Frequent switching is not possible unless discharge devices are provided. Normal switching frequency is 2 to 4 times/day with the capacitors connected under heavy system load and disconnected under light system load conditions.

Harmonics from the power system may provide additional load (current and voltage stress) to the capacitor depending on the system.

Losses are quite low and are typically 0.02 - 0.05% of the nominal MVA rating.

Shunt capacitors are sensitive to overvoltages and overcurrents. Appropriate protection in the form of unbalance, overvoltage and overcurrent protection is typically required. Typical applications of mechanically switched shunt capacitors are :

- voltage support in weak systems
- power factor correction
- HVDC link compensation

Because of the linear voltage versus current characteristic, the output of shunt capacitors during system disturbances is most unfavourable, as their reactive output is proportional to the square of the voltage giving much reduced reactive power output at a reduced voltage. If used in an appropriate combination with other devices, such as TCRs, this obstacle can be largely overcome by installing more shunt capacitors.

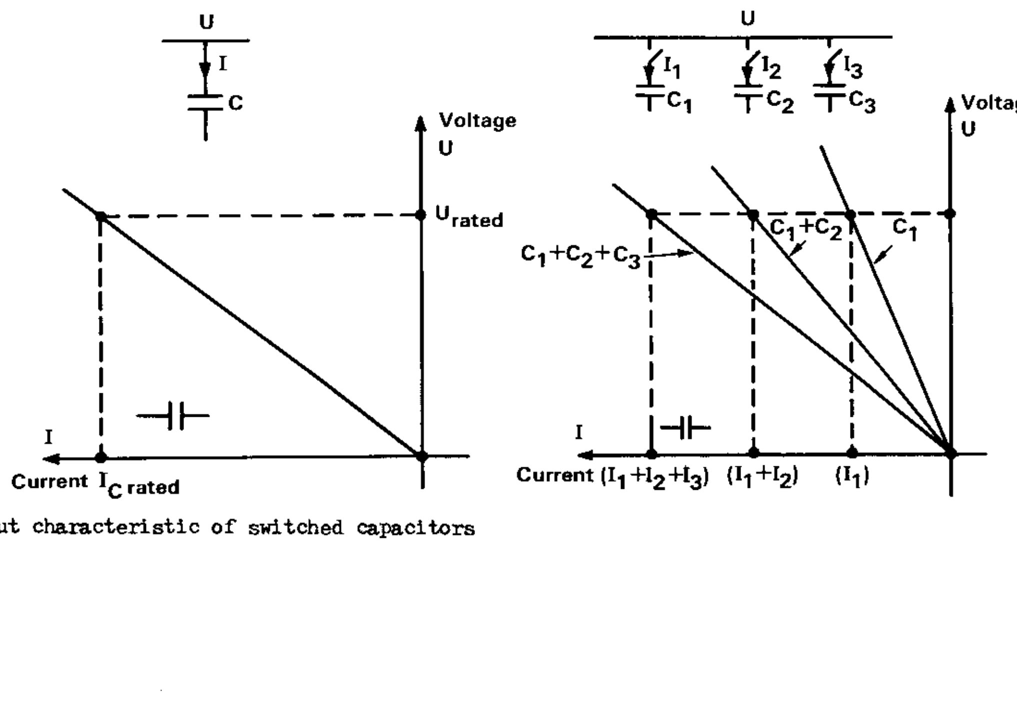


Fig. 2.2 Output characteristic of switched capacitors

Shunt capacitors in use, range in size from a few KVar at low voltage in one unit to a bank of units rated hundreds of MVar at EHV applications.

2.3 MECHANICALLY SWITCHED REACTORS (MSR)

The basic scheme typically consists of a shunt reactor connected by a circuit breaker or a disconnect switch to a transmission line, a busbar or a transformer tertiary winding. Reactors for high voltage applications are built like transformers in single or three-phase units, either with air-gaps in the iron cores or with shrouded iron coil designs to achieve a linear voltage versus current characteristic (i.e., constant reactance). For low voltage applications air-cored reactors (coils) are preferred. Circuit breakers used for switching the reactors may need to be equipped with opening resistors and should not chop the current. The reactor may have to be protected by surge arresters against overvoltages due to possible current chopping.

The output characteristic (U-I) is linear in the operating range and will deviate from linearity for iron-core or shrouded iron reactors due to saturation as shown in fig. 2.3.

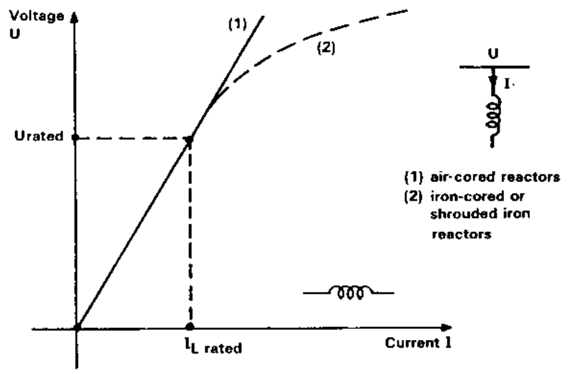


Fig. 2.3 Output characteristic of shunt reactors

The response time is equal to the switching time given by circuit breaker arrangement and will be in the order of 100 ms following the initiation of an operating instruction.

Harmonics are not produced in the normal operating range. However, the reactor current will be distorted in the saturation range at higher than nominal voltages.

Losses are low and are typically 0.2 - 0.4% of nominal MVA rating.

Shunt reactors are not sensitive to overvoltages and currents. They are usually able to operate under such conditions for a limited period of time.

Typical applications of mechanically switched shunt reactors are :

- compensation of long transmission lines and/or cables for voltage control (e.g. switching and load rejection overvoltages)
- compensation of capacitive shunt susceptance of transmission lines and/or cables
- voltage and reactive power control in urban power systems with underground cables.

Shunt reactors in use range from a few MVar in HV to hundreds of MVar at EHV applications.

2.4 SATURATED REACTOR COMPENSATOR (SR)

The basic element of a SR is a magnetic core with a strongly non-linear magnetic characteristic U-I as shown in fig. 2.4c.

Assuming a sinusoidal current (i) flows in the winding large enough to saturate the core (see fig. 2.4b), the resulting flux ($\emptyset$) has a trapezoidal waveform. The induced voltage $u = N\ d\ \emptyset/dt$ consists of impulses whose magnitude $\hat{u}$, width τ and the peak magnitude $\hat{u}_1$ of their fundamental frequency component u_1 are given by the following expressions for $\tau \ll T$:

$$\hat{u} = 2.N.\emptyset_S \ / \ \tau$$

$$\tau = (T.i_S) \ / \ (\pi.\hat{i}) = (T.N.\emptyset_S) \ / \ (\pi.L_m.\hat{i})$$

$$\hat{u}_1 = \frac{8}{T} \cdot \emptyset_S \cdot N$$

with $T = 1/f$ the time period at the particular frequency, L_m the magnetizing inductance ($L_m = N\emptyset_S/i_S$), and $\hat{i}$ is the peak magnitude of the current.

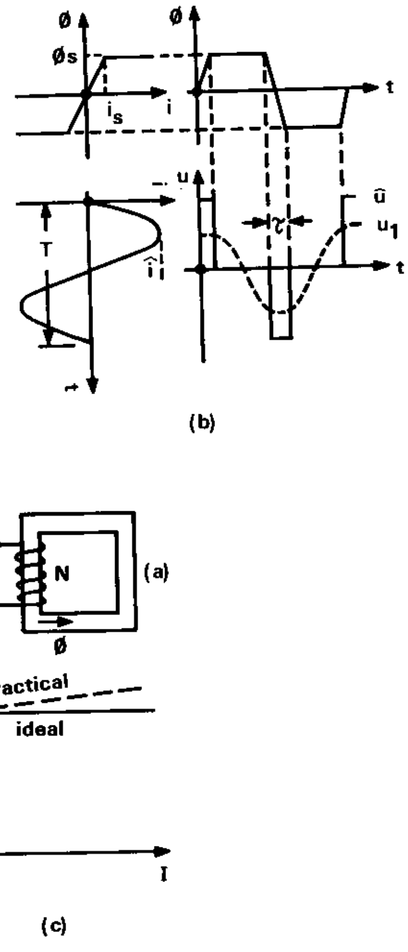
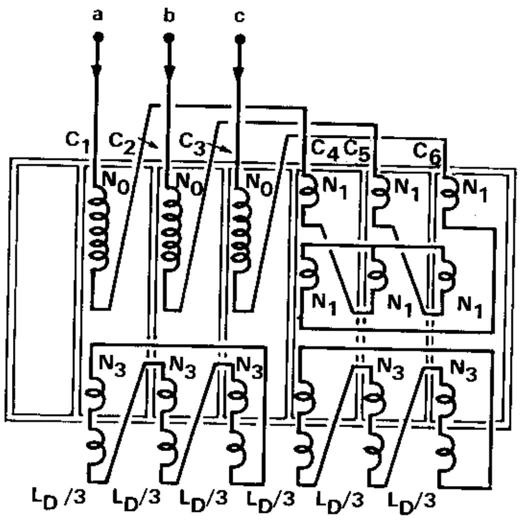
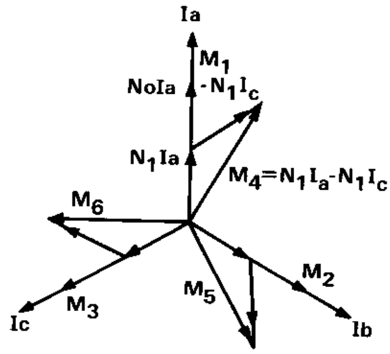


Fig. 2.4 Operating principle of saturated reactor, (a) basic element, (b) voltage versus current and (c) output characteristic.

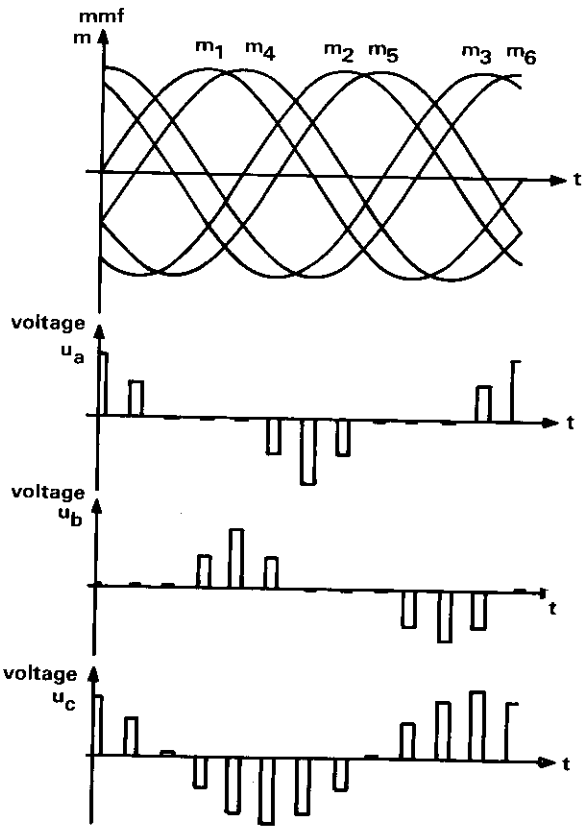
The current i lags the fundamental frequency component u_1 of the voltage u by 90 degrees. The peak magnitude $\hat{u}_1$ of the fundamental component u_1 is independant of the current i as long as saturation exists. Therefore the U-I characteristic is flat as shown (fig. 2.4c). The device therefore behaves like a voltage source with an internal voltage of $U_s = \hat{u}_1/\sqrt{2}$.



(a)



(b)



(c)

$N_0/N_1 = \sqrt{3}$

L_D : mesh loading reactor

Fig. 2.5 Twin-tripler saturated reactor

(a) basic circuit diagram
(b) mmf diagram
(c) mmf and voltage waveforms

The U-I characteristic of the device is in practice not perfectly flat in the saturated region because of the residual "air core" inductance of saturated iron, but is linear with a slope at voltages higher than U_s. Therefore, the saturated reactor performs as a reactive power source with an internal voltage U_s and saturated reactance X_s:

$$U = U_s + X_s I$$

The simple device described above is unsuitable for use in real applications because the voltage, the current or both are too distorted and contain high amounts of harmonics. In practice these harmonics are suppressed utilising multi-limbed core arrangements with mutually coupled windings.

The "twin-tripler" saturated reactor has a six-limb magnetic core with two return limbs and zig-zag windings as shown in fig. 2.5a.

The winding ratio N_0/N_1 is chosen such that the resulting magnetomotive forces (mmf) M_1, M_2, M_3 and M_4, M_5, M_6 are symmetrical but 30 degrees displaced as shown in fig. 2.5b, i.e. $N_0/N_1 = \sqrt{3}$.

Assuming sinusoidal symmetrical three-phase currents I_a, I_b and I_c large enough to saturate the limbs each magnetomotive force keeps its limb in saturation most of the cycle. The limb flux flips to the opposite saturation level when the magnetomotive force of the limb changes its polarity. A voltage pulse is induced in each turn of the limb winding, 6 voltage pulses are induced in each phase-to-neutral voltage and 12 pulses appear in the phase-to-phase voltages as shown in fig. 2.5c with 120 degrees displacement. The fundamental component of the induced voltage (phase-to-neutral) has the magnitude

$$U_s = \frac{16}{\sqrt{2}.\,T} \cdot N_0 \cdot \emptyset_s$$

due to the 30 degrees displacement of the pulses.

Harmonic analysis reveals the characteristic harmonics to be of the order $(12n \pm 1)$ for n = 1.2... (i.e., 11th, 13th, 17th...). In reality, the phase currents, rather than the induced voltages, contain characteristic harmonics, since the sinusoidal voltages are imposed rather than currents. In order to minimize the magnitude of characteristic harmonics the magnetic circuit is designed to give a voltage pulse width equal to T/12 at the operating point. This can be achieved by adding delta connected windings, loaded by an inductance L_D.

Further reduction of harmonics is achieved by utilising a nine-limb core with zig-zag windings, called "Treble-Tripler" saturated reactor as show in fig. 2.6.

Under balanced system voltage conditions, the harmonics are of the order $(18n \pm 1)$ giving the lowest order or harmonics as 17th and 19th, etc., for n = 1,2, ... if mesh windings are not loaded with inductances L_D for further suppression and smoothing of uncompensated harmonics.

The basic-scheme of a saturated reactor compensator (SR) given in fig. 2.7, consists of a 6- or 9 limb saturated reactor of conventional transformer type construction (core steel, windings, oil-filled tank, cooling), designed for voltages up to 70 kV. The saturated reactor itself has an inherent internal reactance (slope of the U-I characteristic) of between 5% and 15% on the base of reactor rating, depending on design.

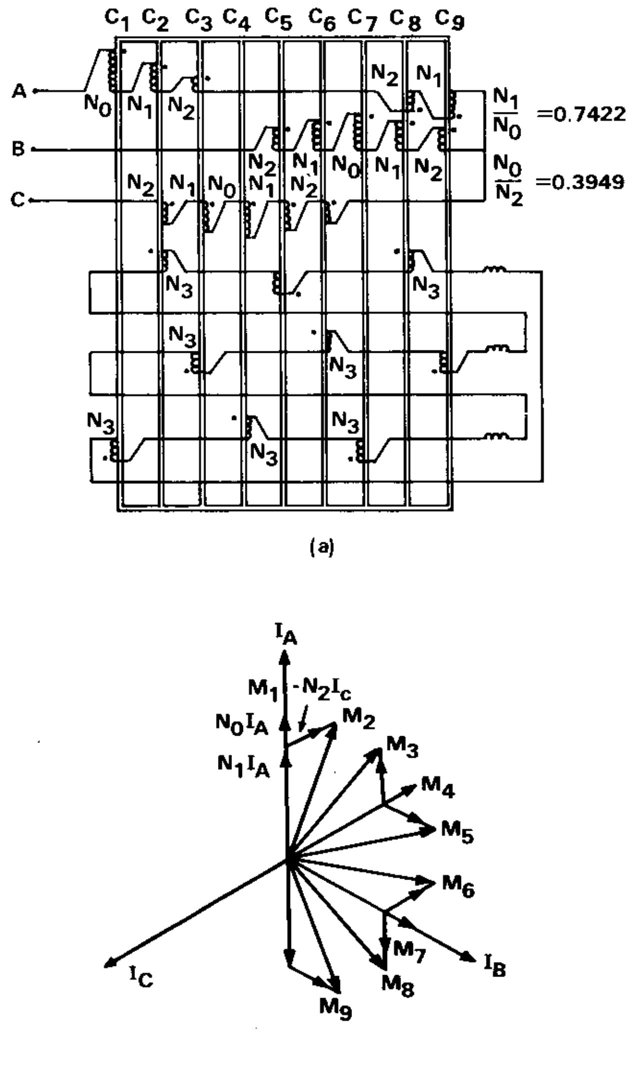


Fig. 2.6 Treble-Tripler saturated reactor, winding connections and mmf-diagram

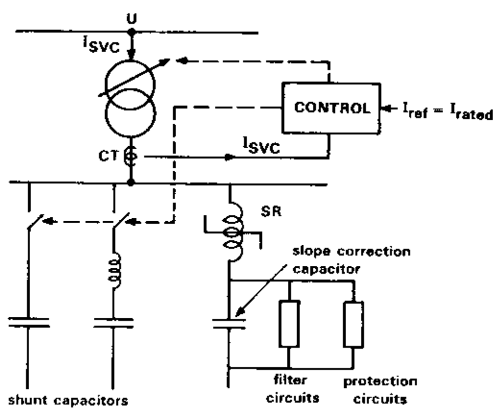


Fig. 2.7 Basic scheme of saturated reactor compensator

A standard transformer is used for coupling to HV or EHV systems. It is often provided with an on-load tap changer to enable adjustment of the operating point according to the system requirements.

Slope correction capacitors are connected in series with the saturated reactor to reduce the internal reactance X_s of the whole compensator, including transformer, to a required level. Damped bypass filters are always applied across these capacitors to damp oscillations at subsynchronous frequencies, as well as inrush current transients of the saturated reactor, in order to eliminate the risk of ferromagnetic resonance. The slope correction capacitor has to be protected by a protective device such as a non-linear resistor or a spark-gap against overvoltages.

Shunt capacitors, connected in parallel to the slope corrected saturated reactor, can extend the operating characteristic into the leading power factor region. These may be designed as filters if the system resonance conditions require such a measure.

The output characteristic (U-I) of the SR compensator is determined by its components. It can be represented as a reactive power source behind an internal reactance of the order 0 to 5% on the base of overall SR compensator installation rating (including the slope correcting capacitor and the transformer),as shown in fig. 2.8.

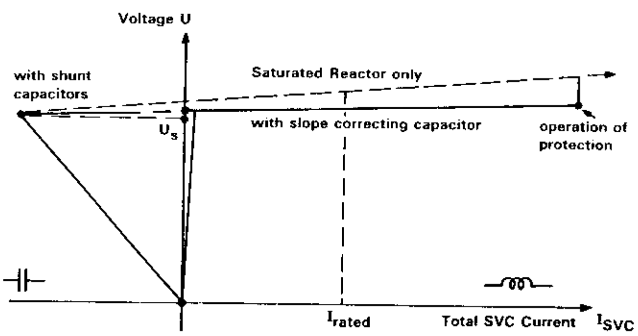


Fig. 2.8 Output characteristic of saturated reactor compensator

The characteristic is linear within the normal operating range. The characteristic can be shifted by tap changing and shunt capacitor switching, while the slope, as dictated by the slope correcting capacitor, remains constant unless the latter includes variable units. For this reason the SR compensators will only permit slow modification of parameters, if required in operation.

The dynamic response of the saturated reactor as such is fast, e.g. 1/36 of a cycle of supply frequency for the treble-tripler. However, the response of a SR compensator is slowed-down by the slope-correcting capacitor and its bypass filter to 2 to 5 cycles of supply frequency.

Harmonic generation is rather low due to internal compensation. Filters are not required in most applications. The internal harmonic cancellation is imperfect under unbalanced conditions.

Losses of SR compensators are quite high compared with reactors or transformers of comparable rating, being typically in the range of 0.7 % to 1 % of the MVA rating.

Saturated reactors, like transformers have a considerable temporary overload capability. Operation in the inductive range is unlimited and linear as long as internal protection of the slope correcting capacitor is not activated. This feature makes the SR most suitable for applications requiring reduction of temporary overvoltages, in addition to voltage stabilisation.

Typical applications of SR are :

- voltage stabilisation and temporary overvoltage reduction in AC systems
- flicker control in industrial systems
- HVDC link compensation

Saturated reactors have been built in sizes up to 150 MVar.

Energisation is by direct closure of the compensator circuit breaker.

Saturated reactor compensators are built from passive components based on traditional technology. They are reliable, maintenance-free and have a high overload capacity. For this reason, they have advantages in applications where these aspects are important.

2.5 THYRISTOR CONTROLLED REACTOR COMPENSATOR (TCR)

The basic elements of a TCR are a reactor in series with a bidirectional thyristor pair as shown in fig. 2.9a.

The thyristors conduct on alternate half-cycles of the supply frequency depending on the firing angle α. Full conduction is obtained with a firing angle of 90 degrees. In this case, the current is the same as that obtained if the thyristors were short circuited. The current i is essentially reactive and sinusoidal, lagging the voltage u by 90 degrees, as shown in fig. 2.9b. Partial conduction is obtained with firing

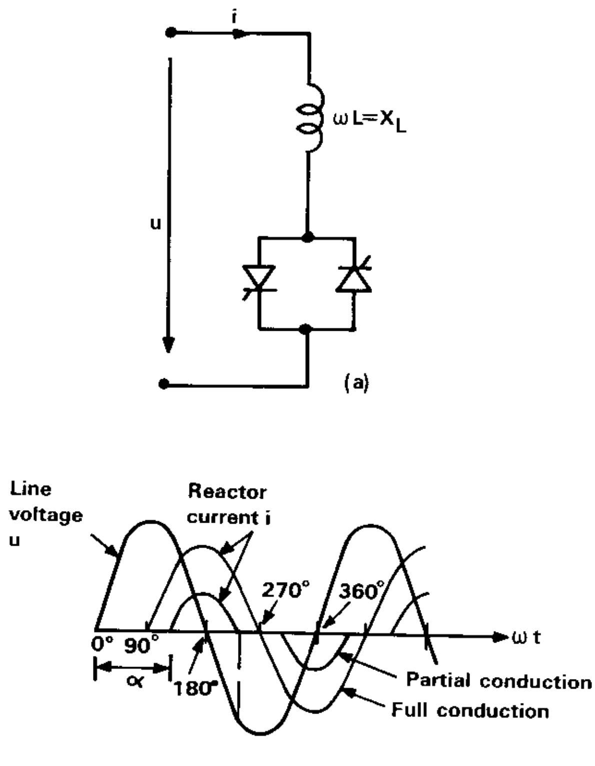


Fig. 2.9 Thyristor controlled reactor
(a) basic elements (b) current waveform

angles between 90 degrees and 180 degrees. Firing angles between 0 and 90 degrees are not permitted as they produce asymmetrical currents with d.c. components which are unacceptable. The effect of increasing is to reduce the magnitude of the fundamental harmonic component I_1 of the current. This is equivalent to an increase of the reactor inductance, i.e. the thyristor controlled reactor is a controllable susceptance $B(\alpha)$ with :

$$B(\alpha) = \frac{2(\pi - \alpha) + \sin 2\alpha}{\pi \cdot X_L}$$

where X_L is the reactance of the reactor. The TCR requires a control system which determines the firing instants (i.e., firing angle α) measured from the last zero crossing of the voltage u (synchronisation of firing signals) and issues the firing pulses to the thyristors based on control error signals, (e.g. voltage deviation, stabilising signals) or system requirements (e.g., susceptance B). The result is a U-I characteristic shown in fig. 2.10 which can be described by the equation :

$$U = U_{ref} + X_{SL} \cdot I$$

where X_{SL} is the slope reactance.

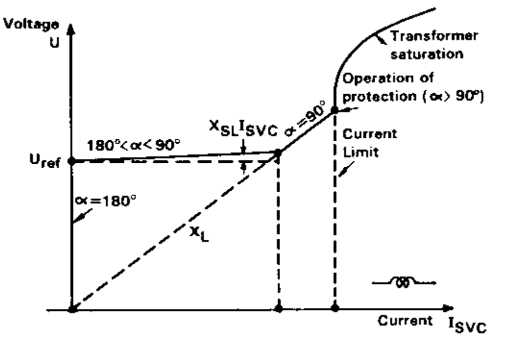


Fig. 2.10 Output characteristic of TCR with voltage control and current limiter including the step-down transformer

Due to the delay in conduction the TCR generates harmonic currents at 90 degrees < α < 180 degrees (see fig. 2.9b). Only odd order harmonics are generated is firing of the thyristors is symmetrical. The RMS value of the fundamental (I_1) and the nth harmonic current (I_n) components as a function of reactor current at full conduction (i.e. α = 90 degrees) is given by:

$$I_1 / I_L = \frac{1}{\pi} \left[2.(\pi - \alpha) + \sin 2\alpha \right]$$

$$I_n / I_L = \frac{4}{\pi . n . (n^2 - 1)} \left[\cos\alpha . \sin(n\alpha) - n . \sin\alpha . \cos(n\alpha) \right]$$

with n = 3, 5, 7... and $I_L = U/X_L$

Thereby for n = 1, 2, 3 harmonics of the order (6n+1) form positive sequence, of the order (6n-1) form negative sequence and of the order (6n-3) form zero sequence components. The TCR behaves like a harmonic current source and it is worth noting that maximum amplitudes of harmonics do not all occur at the same firing angle.

In a balanced three-phase system, where the three single-phase TCR elements are connected in delta (6 - pulse TCR) as shown in fig. 2.12, only harmonics of the order (6n ± 1) exist as shown in fig. 2.11. The reactor is usually split into two units in each delta arm, with one unit on either side of a valve, in

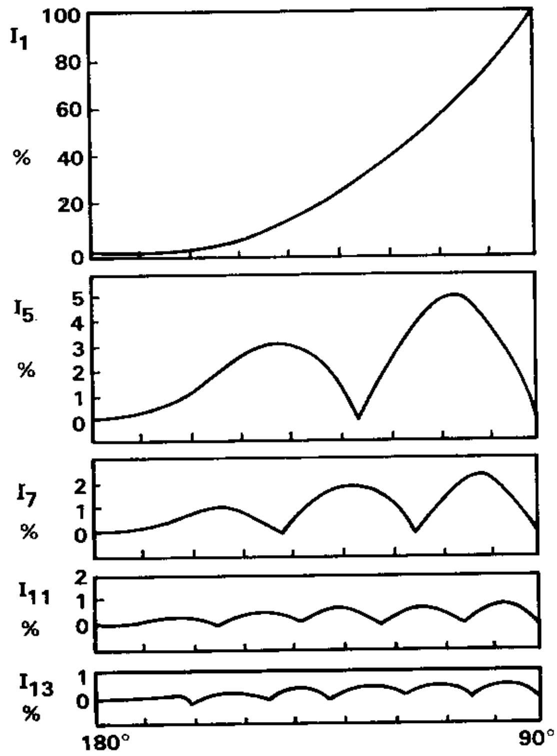


Fig. 2.11 Fundamental and harmonic currents of a three-phase delta connected TCR shown in fig. 2.12

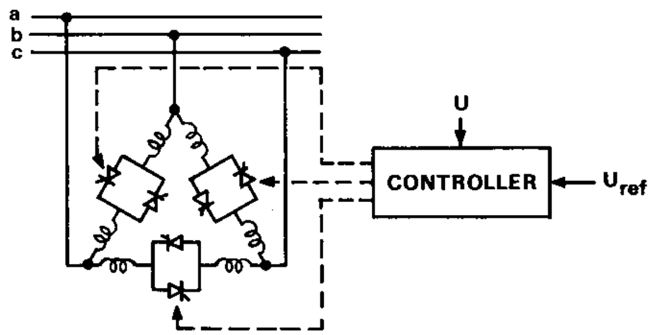


Fig. 2.12 6-pulse TCR

order to limit thyristor fault currents.

Under balanced system conditions the zero sequence current harmonics of the order 3, 9, ... circulate in the closed delta and are absent from the line currents (see fig. 2.11).

Further elimination of harmonics can be achieved by using two 6-pulse TCRs of equal rating, fed from two secondary windings of the step-down transformer, one connected in wye and the other in delta forming a 12-pulse TCR as shown in fig. 2.13.

Both TCR units are controlled with equal firing angles. Since the applied voltages have a phase difference of 30 degrees, the harmonic currents of the

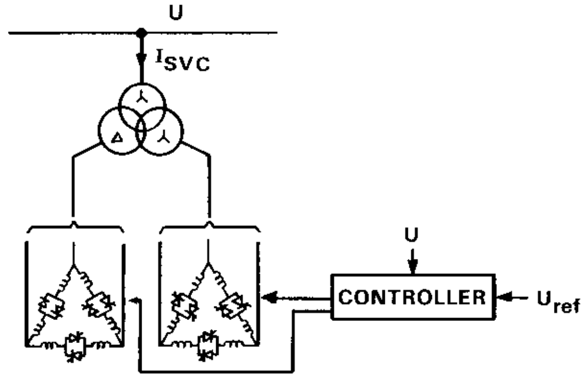


Fig. 2.13 12-pulse TCR

order [6(2n-1)±1] will be cancelled in the transformer. The characteristic current harmonics injected into the system are of the order (12n±1) i.e. 11, 13, 23, 25 .... etc.

Another approach to harmonic current reduction, other than filtering, is to use two 6-pulse sequentially controlled TCR units of half rated output to achieve the same overall reactive output. This arrangement effectively reduces the harmonic currents to 50% of a single TCR installation of full rating as shown in Section 5.5.2.

The thyristor controlled transformer compensator (TCT) is a special kind of 6-pulse TCR. It is a transformer with a 100 % leakage reactance, with windings connected in wye-delta and bidirectional thyristors pairs across the secondary windings, as shown in fig. 2.14.

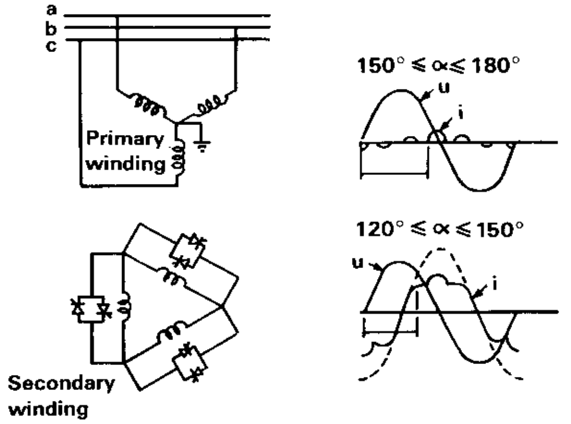


Fig. 2.14 Thyristor controlled leakage transformer, winding arrangement and characteristic waveforms

This concept was developed to reduce both the cost of the reactor/transformer complex and the secondary fault currents.As there is no secondary busbar any shunt capacitor must be connected at the primary voltage or through a separate step-down transformer. Harmonic generation is the same as a 6-pulse TCR compensator.

The basic scheme of a thyristor-controlled reactor compensator (TCR) consists of a 6- or 12-pulse TCR, and a controller including the thyristor firing/firing pulse synchronising system, the regulator, and the measuring system as shown in fig. 2.15.

Shunt capacitor banks can be added to filter harmonics and to extend the output characteristic into the capacitive range. A step-down transformer is required in HV or EHV applications as the TCR voltage is limited for technical and economic reasons to 50 kV or below.

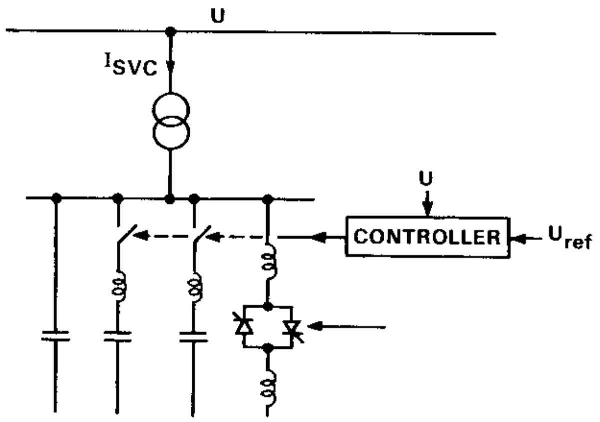


Fig. 2.15 Thyristor-controlled reactor scheme with switched or fixed capacitors (TCR+MSC+FC)

The shunt capacitor bank may be divided into several three-phase groups, fixed or separately switched by a circuit breaker. Each group can be a series tuned, or high-pass filter (reactor in series with the capacitor) to provide a shunt path for the harmonics generated by the TCR to flow into and to avoid harmonic resonances with the power system.

Filters are usually designed for 5th, 7th and occasionally to 2nd, 3rd, 11th and 13th harmonic depending on TCR type and system characteristics. A capacitor bank consists of many units connected in series and parallel in order to meet the specified reactive power requirements as well as the operating voltage. The bank is usually divided into two wye connected groups for economic reasons and for ease of protection arrangements.

The output characteristic (U-I) of a typical voltage controlled TCR with fixed or switched capacitor(s) is given in fig. 2.16. The operating range is determined by the rating of the components and by the overload rating of the TCR. Facilities for adjusting the reference voltage U_{ref} and slope (typically 0 to 5 %) are provided.

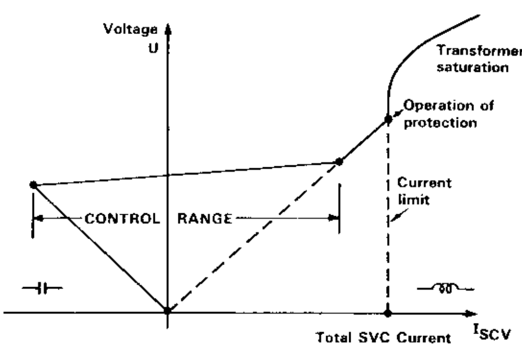


Fig. 2.16 Output characteristic of a TCR with capacitor

The dynamic response of the TCR as such is fast,less than 5-10 ms, but the delays in measurement and control circuits as well as the system impedance may impose settings that give slower response times for control loop stability reasons of typically around 3-10 cycles of supply frequency. A fast response setting for a low system impedance (i.e., strong power system) could lead to instability when the impedance becomes high under transmission circuit outage conditions (i.e., weak power system). However, a fast response for various system contingencies could be achieved utilising adaptive controllers as described in Chapter 7.

Harmonic generation of TCR schemes is dependent on the TCR type, filter arrangement used, TCR and power system operating conditions. Voltage unbalance, tolerances in firing angles and major TCR components may lead to generation of additional harmonics of the order 2, 3, 9, ... These non-characteristic harmonics are usually below 2 % of the TCR rating. With systems having parallel resonance close to the fundamental supply frequency, harmonic instability may occur due to controller feedback or synchronisation. Filters in the measurement and controller circuits can suppress these harmonics.

Losses of TCR schemes depend on layout and operating point as shown in fig. 2.17. TCRs with fixed capacitors have losses typically in the range of 0.5 to 0.7 % of the MVA rating.

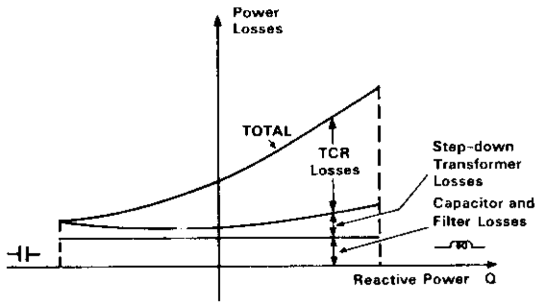


Fig. 2.17 Power losses for TCR with capacitor and filter

The overload capacity of the TCR is determined by the thyristors. At system voltages above the point corresponding to the minimum firing angle $\alpha = 90$ degrees, the control will be at the limit, the TCR will behave as a linear reactor with currents depending only on the system voltage. To avoid excessive thyristor heating, the firing angle α has to be increased to limit the current. At still higher voltages, the step-down transformer will begin to saturate and its magnetising current will increase rapidly; this may reduce the overvoltage but can also give rise to ferroresonance. Special protection measures may be required, involving surge arresters, circuit breaker operation, and firing of thyristors in all three phases based on a particular overvoltage level.

The TCR scheme can be subjected to an overcurrent if the thyristor is fired with a firing angle α of less 90 degrees by the protection or control scheme during a transient overvoltage condition (see fig.2.18).

The current will have a dc component and delayed zero current crossings, resulting in increased thyristor losses and heating.

Energisation of the TCR is by direct closure of the compensator circuit breaker with control signals suitably delayed to enable synchronisation of thyristor firing.

Typical applications of TCR are

- voltage stabilisation and temporary overvoltage reduction in AC systems
- stability improvement in AC systems
- damping of power oscillations
- load balancing in AC systems
- HVDC link compensation.

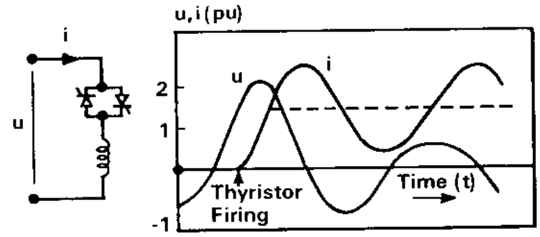


Fig. 2.18 TCR overcurrent and overvoltage problem

The TCR type compensators are very flexible with regards to their parameter settings and modifications. Maintenance requirements are small. Space requirements for reactors, filters and capacitors are large. The reliability is high. TCRs in use range up to hundreds of MVar and are utilised in both HV and EHV system applications.

2.6. THYRISTOR SWITCHED CAPACITOR COMPENSATOR (TSC)

The basic elements of a TSC are a capacitor in series with a bidirectional thyristor pair and a small reactor as shown in fig. 2.19.

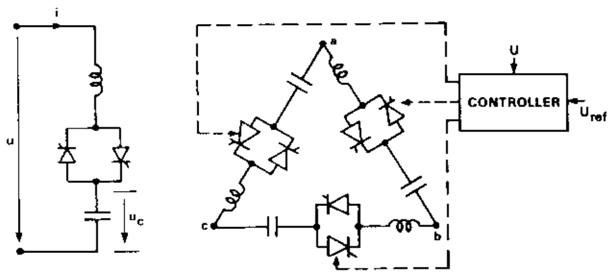


Fig. 2.19 Thyristor switched capacitor (TSC), single and three phase elements

The purpose of the reactor is to limit switching transients, to damp inrush currents and to form a filter for harmonics coming from the power system or from any parallel connected SVCs (e.g., TCR). In three-phase applications the basic TSC elements are connected in delta. The TSC also has a control system that determines the firing instants and issues the firing pulses to the thyristors according to the requirements. The instant of switching determines the switching-in transients as follows :

- minimum transients in the current i will occur if the thyristor is fired at the instant the capacitor voltage u_C equals the peak of AC system voltage u (i.e., voltage across the thyristor is equal to zero)
- large transients in the current will occur if firing occurs at zero system voltage or maximum voltage exits across the thyristor.

Favourable switching-in instants are shown in fig.2.20.

In practical TSC circuits, there must always be sufficient series inductance to keep the di/dt of the worst switch-in transient within the limits given by the capability of the thyristor. Transients are quickly damped due to system losses. Usual practice is to allow switching-in at the minimum thyristor voltage only (point-on-voltage-wave switching) by supplying

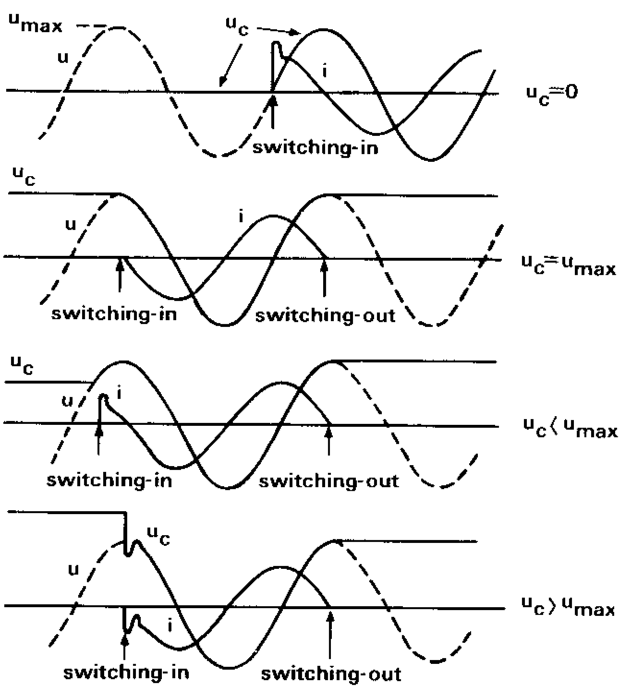


Fig. 2.20 Capacitor switching with minimum transients

the necessary information through the controller for the most appropriate firing instant.

The firing control usually sends a single firing pulse or a train of firing pulses or a continuous gating signal to the thyristors as long as capacitive current (susceptance) is requested by the controller. After the thyristor ceases conduction at zero current the capacitor remains charged at peak system voltage. These trapped charges are drained by discharge devices associated with the capacitors. Such trapped charges do not inhibit rapid reconnection of the capacitor as a firing pulse can be applied as soon as the system voltage is of the same polarity as the capacitor voltage as shown in fig. 2.20.

The basic scheme of a thyristor switched capacitor compensator (TSC) consists of a number of parallel, delta connected TSC elements and the controller (thyristor firing/firing pulse synchronising system, the regulator and the measuring system) as shown in fig. 2.21. A step-down transformer is also required in HV and EHV applications as the TSC voltage is limited to 30 kV or below for technical and economic reasons.

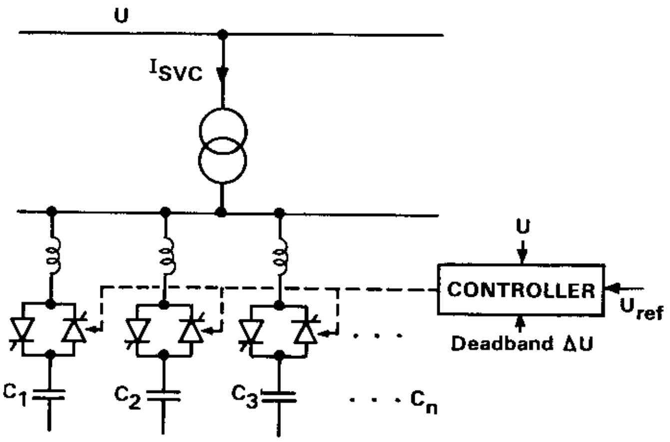


Fig. 2.21 Thyristor switched capacitor scheme (TSC)

The choice of the step-down transformer secondary voltage can considerably influence the overall TSC cost. It also determines the type of firing pulse system to be used. This in turn determines the thyristor valve voltage and current stresses which have to be accommodated by appropriate valve design and protection elements (ref. 350, 357).

The output characteristic (U-I) of a TSC compensator is discontinuous and determined by the rating and number of parallel connected units. Therefore the voltage support provided is discontinuous, as shown in fig. 2.22, i.e. the TSC as a reactive power source is controllable in discrete steps only. The voltage U is thus controlled in the range $[U_{ref} + \Delta U/2]$ where ΔU is the deadband.

The dynamic response of the TSC as such is fast and typically around 0.5 to 1 cycle of supply frequency, but delays in the measurement and control circuits, may impose settings that give slower response for control stability reasons of typically around 3 to 10 cycles of supply frequency. The comments made on the response of TCR schemes in the previous section also apply to TSC schemes.

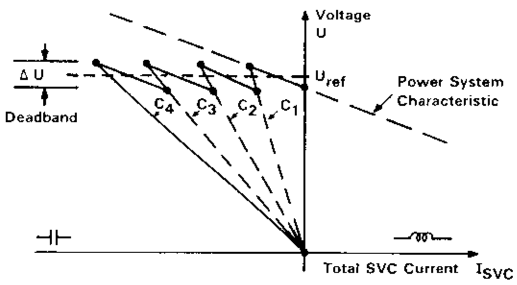


Fig. 2.22 Output characteristic of a TSC scheme under voltage control with deadband ΔU

Harmonic generation of the TSC is zero, but there is a danger of series resonance with the power system at harmonic frequencies and careful co-ordination of the series reactor impedance with respect to the TSC rating is required.

Losses of TSC schemes are less than TCR losses but higher than pure capacitor losses with typical losses shown in fig. 2.23.

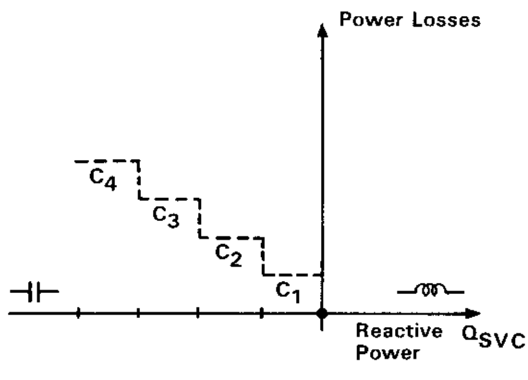


Fig. 2.23 Losses of a TSC scheme without a step-down transformer

The overload capacity of the TSC is determined by the thyristors and capacitors. An overvoltage problem does not exist as long as the control and protection is properly co-ordinated disconnecting the TSC under overvoltage conditions as required (ref. 357). The controller could also be blocked during large system disturbances to avoid the aggravation of overvoltages which may arise due to the re-energisation of the capacitor following fault clearance.

The thyristors of a TSC scheme can be subjected to an internal overvoltage problem if the thyristor is discontinuously fired (misfired) accidentally or due to inadequate design by the control or protection device, by a single pulse, at periods of maximum voltage difference across the thyristors as shown in fig. 2.24.

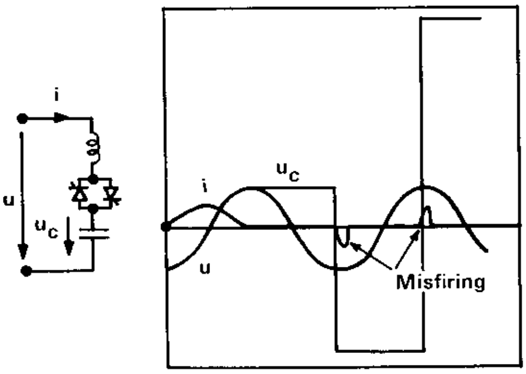


Fig. 2.24 TSC misfiring problem

The accidental firing (misfiring) of the thyristor when the AC system u and capacitor u_c voltages are opposite (i.e. at maximum voltage accross the thyristor) can result in a large surge current of high frequency, extinguishing shortly after the firing pulse and cause high voltage stresses across the capacitor and the thyristor. This problem can be minimised by the control system by prohibiting firing of thyristors at periods of maximum voltage across the thyristor and by applying continuous firing signals under overvoltage conditions or by other suitably co-ordinated protective means.

Typical applications of TSC schemes, which usually take advantage of minimum losses in standby operation, are :

- voltage support following large system disturbances
- damping of power oscillations
- voltage control
- load balancing.

TSCs in use range up to hundreds of MVar and are used in both HV and EHV system applications.

2.7 HYBRID COMPENSATORS (TCR + TSC)

The step change in voltage resulting from the switching of capacitors in TSC schemes can be smoothed by means of a TCR of equivalent rating, connected in parallel.

The basic scheme of a (TCR+TSC) compensator consists of thyristor switched capacitor banks of equal rating connected in parallel with one or more 6-pulse thyristor controlled reactor units each rated equivalent to one TSC unit, together with a fixed or mechanically switched capacitor bank, a filter capacitor bank (if required), a controller and a step-down transformer (if required), as shown in fig.2.25.

Typically, two of the abovementioned basic 6-pulse compensator units, each connected to the delta and wye connected secondary windings of a three winding transformer, form a 12-pulse system with compensation of 5th and 7th harmonics (see Section 5.5.2.).

The hybrid scheme can be tailored to the power system requirements such that, e.g., total losses during a characteristic operating period, capital and operational costs, harmonic generation and filter requirements can be minimised.

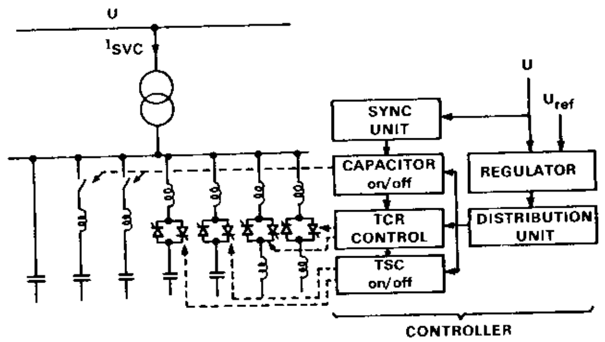


Fig. 2.25 (TSC+TCR+MSC+FC) type static var compensator

The controller of a hybrid (TCR + TSC) type compensator has to co-ordinate the operation of the constituent units according to a pre-determined control strategy in a similar manner to the following example. System phase voltages at the compensator terminals are converted into a DC signal. This signal, representing the amplitude of the system voltage, is subtracted from the reference voltage to obtain the error signal which is fed to the regulator to derive the compensator susceptance demand B_{ref}. Additional control signals derived from power flow, system frequency, etc. can be added to the error signal to control the voltage for system damping enhancement purposes. The B_{ref} is a measure of the reactive power (or current) needed to maintain a desired voltage at the compensator terminals. In the control co-ordination unit, the B_{ref} signal is converted to digital and analogue signals, to enable switching of TSC units and phase control of the TCR units respectively in order to match the susceptance requirements. The TCRs are controlled such that the harmonic currents are reduced. The control system also contains synchronising units which ensure the exact timing of the thyristor firing pulses. The reference signals for the TCR pulse generators are the zero crossings of the system voltages across the reactors. The reference signal for the TSC pulse generators are voltage minima across the thyristor valves.

The output characteristic (U-I) of the hybrid (TCR + TSC) compensator is the basic characteristic which has been described in Section 2.2 (see fig. 2.16).

The dynamic response is the same as for TCR or TSC schemes which is typically around 3 to 10 cycles of supply frequency or slightly slower depending upon the control system settings.

Harmonic generation can be minimised in the same manner as that described for TCR and TSC schemes.

Losses are dependent on the particular arrangement chosen, an example of which is given in fig. 2.26. The losses can be made very small at zero reactive power output, but are markedly increased as the capacitive or inductive output increases.

The overload capability of the hybrid (TCR + TSC) type compensator is the same as that of its constituent components.

The (TCR + TSC) type compensator represents only one of the hybrid compensator types possible. In practice, it is possible to combine and co-ordinate the characteristics of many types of SVCs, with existing reactive compensation equipment characteristics on the power system, to achieve an economic solution matching the power system needs. Further information on the practical combinations achieved using the (TCR+TSC) type compensator as a building block can be found in Chapter 8.

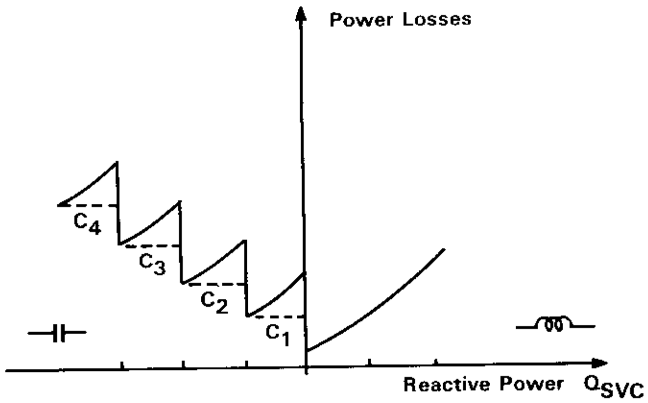


Fig. 2.26 Losses of a TSC-TCR compensator with 4 TSC and 2 TCR units

2.8 SELF AND LINE-COMMUTATED CONVERTOR COMPENSATORS (SCC AND LCC)

The basic elements of an SCC or LCC type of compensator are a static convertor and a voltage or current source as shown in fig. 2.27.

The convertor produces or consumes reactive power using semiconductor switching devices. In theory, such compensators do not require reactors or capacitors for reactive power generation as long as the compensator has an internal voltage or current source.

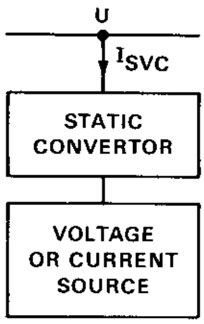


Fig. 2.27 Schematic configuration of SCC or LCC compensator

Two basic approaches are possible for a convertor compensator; one uses an inverter which converts DC voltage (or current) to AC voltage (or current) at fundamental frequency while the other employs a frequency changer which produces AC voltage (or current) at the fundamental frequency from an AC source whose frequency may be different. A battery, capacitor, reactor, high frequency generator or LC tank circuit may be used as a voltage or current sources. There are a wide variation of the combinations of static convertors and sources (ref. 167). Currently only the self-commutated convertor (SCC) and the line-commutated convertors (LCC) are in use (ref 305).

The SCC consists of semiconductor valves arranged to form a multiphase switching convertor circuit on the secondary winding of a transformer. The semiconductor valves have the capability of being turned "on" and "off" by control action which produces self or forced commutation. The switching convertor is controlled to draw variable inductive or capacitive current from the three phases of the power system.

The LCC consists of thyristor valves arranged to form a multi-phase switching convertor circuit on the secondary winding of a transformer. The thyristor valves are commutated by the line voltages at the convertor terminals. The switching convertor circuit is operated to draw variable inductive current from the three phases of the power system. Fixed capacitors may be added to extend the operating range into the capacitive region.

Basic structure of a self-commutating convertor (SCC) compensator is given in fig. 2.28.

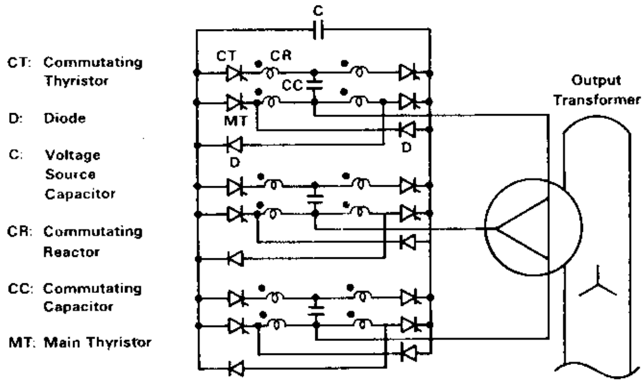


Fig. 2.28 SCC compensator

Such a compensator generates a square wave voltage across the corresponding winding of the compensator transformer by forced commutation of the charged storage capacitor. Several such three phase invertor units are applied to generate emf's which are phase displaced and interconnected in series or parallel by means of the transformer winding. The resultant internal emf has a quasi-sinusoidal waveform and is controlled to be in phase with the system voltage so that only reactive power flows across the leakage reactance of the transformer. When the internal voltage is equal to the system voltage the compensator is floating; when the internal voltage is greater the compensator generates reactive power, when less the compensator absorbs reactive power.

The output characteristics (U-I) of the SCC compensator is similar to the TCR/TSC compensator. However, the operation at undervoltage conditions is limited due to the possibility of commutation failure.

The dynamic response of the control system is similar to that of the TCR/TSC compensator or slightly faster.

The harmonics can be cancelled by utilising multiphase convertor configurations. A 36-pulse SCC compensator based on the six inverters mentioned above connected in series is schematised in fig. 2.29. In this scheme, only harmonics of $(36n \pm 1)$ order will remain, and no harmonic filter is required.

The losses of a SCC compensator are presently around 2 % of the output under maximum inductive or capacitive output conditions.

The overvoltage performance depends on the switching devices utilised. The SCC compensators are more sensitive to overcurrent than the TCR/TSC compensators because of the current limits of their valves.

Operation under unbalanced conditions is dependent upon the magnitude of the unbalance and may be limited due to possible commutation failure. Operation at undervoltage conditions may also be limited for the same reason.

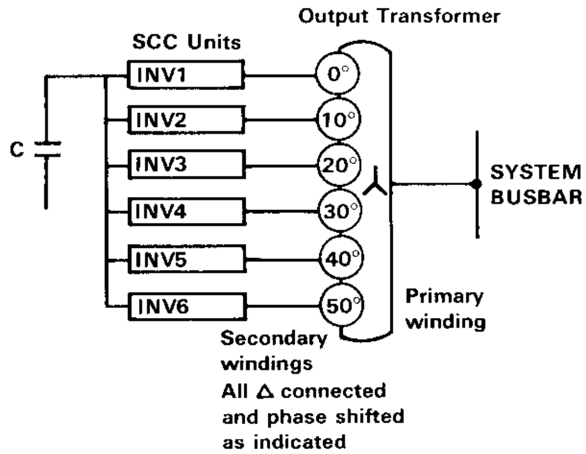


Fig. 2.29 36-pulse SCC compensator

The SCC/LCC compensator provides significant space saving. The commutating reactance is some 10 to 15% on the compensator rating.

Experience acquired with this system (fig. 2.29) has demonstrated its feasibility for fast acting reactive compensation of a.c. power systems especially following faults near the SCC/LCC compensator (ref. 245, 269).

SCC compensators are capable of being used for many applications e.g. reactive power compensation, improving of power transfer capability, improving system transient capability, and enhancing system damping.

2.9 A COMPARISON OF STATIC VAR COMPENSATORS

There are many factors which affect the performance and hence the application of different types of SVCs to solve specific power system problems. Important performance measures are :

- continuous or discontinuous adjustement of reactive power output, voltage reference values, slope and operating limits
- adjustability of control system parameters, active or inherent control
- individual phase control, phase balancing ability
- speed of response
- sensitivity to frequency variations
- sensitivity to under or overvoltages
- overload and overvoltage limitation capability
- loss characteristic, at zero output and over total operating range
- harmonics generated
- filter requirements
- equipment cost, space requirements
- reliability.

Some of these measures such as reliability, maintenance requirements, equipment costs and space requirements are difficult to quantify. A comparison of the SVC types discussed in this chapter, based on selected performance measures, is given in Table 2.1.

A comparison of the typical loss characteristics for different types of SVCs is given in fig. 2.30. (TSC + TCR + MSC + FC) schemes are more flexible with respect to loss minimisation.

Table 2.1 : Comparison of SVC's

	SR-FC	TCR-FC TCT-FC	TSC	TCR-TSC-FC	SCC LCC
Control range	Inductive and capacitive	Inductive and capacitive	Capacitive only	Inductive and capactive	Inductive and capacitive
Susceptance adjustment	Continuous inherent	Continuous active	Stepwise active	Continuous active	Continuous active
Control adjustability - voltage control - stabilizing signals - individual phase balancing	Poor Limited No No	Good Yes Yes Yes	Limited Limited No Limited	Good Yes Yes Yes	Good Yes Yes Yes
Speed of response	Fast,system and bypass filter dependent	Fast, system/ control dependent	Fast, control dependent	Fast, system dependent	Very fast, control dependent
Generation of harmonics	Very low	Low, filter required dep. system condition	None	Very low, filter required dep. system condition	Low
Limitation of overvoltages and overload capability	Very good	Good	None	Limited	Poor
Sensitivity to voltage and frequency deviations	Yes	No	No	No	No
Losses	Moderate	Medium, increase with lagging current	Small, increase with leading current	Small, medium depending on lay-out	Moderate
Direct EHV connection	No	TCT yes	No	No	No
Energization	Fast,direct	Fast with control action	Fast with control action	Fast with control action	Fast with control action

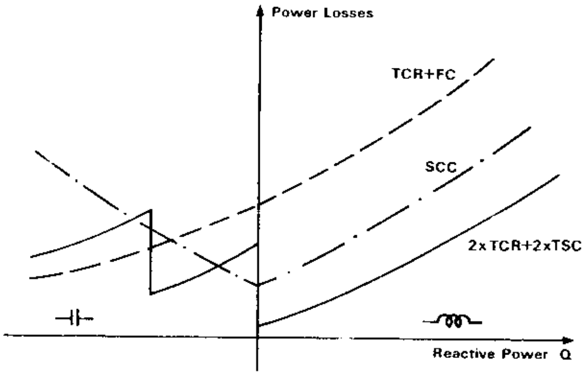


Fig. 2.30 Loss characteristics of SVCs

The result of this comparison can be summarised as follows :

- thyristor controlled or thyristor switched type schemes are most suited for applications which require flexible control capabilities
- combinations of mechanically switched capacitors (MSC) with thyristor switched capacitor (TSC) and thyristor controlled reactor (TCR) type compensators have lowest losses but mechanical switching reduces response time and does not allow rapid repeated operation
- no appreciable differences exist in the speed of response between different basic types of static var compensators currently available
- saturated reactor, thyristor switched reactor (TSR) and capacitor (TSC) type compensators release the minimum amount of harmonics to the power system followed by the 12-pulse thyristor controlled reactor (TCR)
- schemes using saturated reactors have higher overload and overvoltage capabilities than thyristor controlled or thyristor switched SVC types
- TCR compensators have simpler control schemes than (TCR + TSC) and other hybrid types of compensators while saturated reactors due to their inherent control characteristics have no external controller requirements.

Further information on the control strategies for specific power system applications and future trends can be found in Chapter 7 while technical details of SVC installations around the world can be found in Chapter 8.

CHAPTER 3

POWER SYSTEM STUDIES RELATED TO STATIC VAR COMPENSATOR APPLICATIONS

3.1. INTRODUCTION

Studies carried out as part of the power system planning process by the utilities must include an evaluation of the reactive power compensation requirements. Compensation alternatives to be evaluated may include series capacitors, shunt capacitors and reactors, synchronous compensators and static var compensators (SVCs).

Power system studies related to SVC applications in particular are required to :

- coordinate the economic and technical requirements of a utility and to identify the problem to be solved by SVCs
- determine the required rating and operating characteristics of the SVCs for the identified application
- evaluate the use and the benefits of SVCs in comparison with other alternatives.

The number and nature of studies carried out depend entirely on the objectives being considered. In establishing the objectives, it is worthwhile to differentiate between the usual stages of system development, namely :

- early planning
- detailed planning
- design
- operation.

In the early planning stage of the power system development, the reactive power requirements and the appropriate location of the SVCs are assessed, based on a relatively wide time horizon for the power system development in terms of loads, generation, and network configuration. The planning process is required to be iterative, as the configuration and the development strategy of the power system can be appreciably affected by the application of SVCs. Important studies at this stage are load flow and transient stability studies.

Load flow studies will provide information on the approximate rating of and appropriate locations for installing the SVCs. Transient stability studies will indicate the reactive power requirements to achieve a certain improvement of the power transfer capability while maintaining satisfactory system stability performance.

In the detailed planning stage, the power system performance will be evaluated in detail in order to prepare the necessary SVC performance specifications. System demand variations, fault levels, contingencies, voltage criteria, loss evaluation criteria, stability criteria, etc., have to be considered in carrying out detailed studies. These studies will provide information on the following characteristics of the SVCs :

- steady-state operating characteristics
- appropriate operating regimes to meet system requirements under abnormal operating conditions resulting from system disturbances
- continuous and short term overload capabilities
- control and protection requirements
- step-down transformer and tap-changer requirements
- harmonic performance requirements.

The detailed planning studies will result in a set of performance specifications which may not necessarily include a definition of the type of SVC for the particular application.

The selection of an appropriate SVC to meet the performance specifications and to carry out studies (if required) is best placed with the manufacturer, in the design phase. In some cases utilities may prefer to select the SVC type, based upon previous experience, close co-operation with the manufacturer in carrying out design studies is required to ensure the final design fully meets performance specifications.

In system operation studies, the appropriate SVC operating regimes must be verified, taking into account the system constraints and contingencies. Studies and tests carried out for verification purposes form part of the acceptance procedure for the SVC.

Table 3.1. summarizes the types of studies which may be required at various stages of power system development. Studies required for the design of SVC equipment are not covered in Table 3.1 since these are normally the responsibility of the SVC manufacturer. However, the utility should inform the manufacturer about all procedures, power system/plant performance criteria and standards which may affect the SVC design. It should be noted that not all of the studies shown Table 3.1 are required in all SVC applications.

Table 3.1 : SVC Application study requirements at various system development stages

power system development stage / Studies	early planning	detailed planning	operation
load flow	x	x	x
large disturbance (transient stability)	x	x	x
small disturbance (steady-state stability)	-	x	-
subsynchronous resonance	-	x	-
network harmonics	-	x	-
electromagnetic transients	-	x	-
fault level	-	x	x
coordination, optimization, loss and cost evaluation	x	x	-

The SVC application studies require appropriate power system models and study methods covering the particular problem to be solved by the SVC application. There are various tools available to study the SVC performance and to develop data for the performance specifications. These include digital computer programs, analogue, hybrid and physical models, each with appropriate simulation and parameter optimisation capability.

Experience to date indicates that computer programs for simulation and optimization are sufficient in the early and detailed planning stages to identifiy size, location requirements, and performance specifications. In some cases, e.g., where the SVC has the main purpose to control overvoltages in the power system, other models such as analogue or physical models provided with a general purpose real-time SVC controller can also be useful in assessing the effectiveness of the SVC and to draw general requirements for the SVC control and protection.

3.2 LOAD FLOW STUDIES

The objective of a load-flow study, for a power system with given network configuration, demand, generation, transmission line, transformer, series and shunt compensation parameters, is to determine the node voltages, the active and reactive power flow in transmission lines and transformers, the power losses, the power of the slack generator and the reactive power of generators and shunt elements. The standard load flow study assumes balanced steady-state conditions in the network.

In cases where the SVC is applied for load balancing, a three-phase load flow model of the power system and the SVC is desirable. If this is not available then a conventional equivalent sequence component model is required. In some cases the detailed analysis of the unbalance can be restricted to the SVC and the load. In such cases the rest of the network can be represented by a balanced equivalent, with equal impedances in each one of the three-phases.

The load flow problem can be described by a set of nonlinear equations resulting from the balance of the active and reactive power in each system node. These equations are solved by means of appropriate computer programs. In load flow programs a controlled SVC is a reactive power source which can be represented by a PV-node with zero active power (P = 0) and reactive power limits (Q_{max} and Q_{min}) at the point of connection. An uncontrolled SVC may be represented by a constant susceptance (shunt impedance) at the point of connection. More detailed descriptions of SVC models for load flow studies are included in Section 4.2 of Chapter 4.

The objectives of the load flow studies related to SVC applications are :

- to determine the appropriate location and the preliminary rating of the SVC
- to provide information on the effects of the SVC on the system active and reactive power flows and voltages under normal and abnormal system operation as well as contingency conditions
- to provide the initial conditions for system studies investigating large disturbance (transient stability) and small perturbation (steady-state stability) studies based on the power system configuration, loading and generation conditions.

Table 3.2 summarizes the load flow studies related to SVC applications. The SVC characteristic parameters determined from these studies are explained in detail in Chapter 5.

3.3. LARGE DISTURBANCE (TRANSIENT STABILITY) STUDIES

These time-domain studies are used to determine the performance of a generating plant during and after system fault conditions and to evaluate the effect of the system, generator, generator control, protection facilities and various performance enhancement measures (e.g., voltage support , series and/or shunt compensation, braking resistors, fast valving etc.) on the transient stability limit and on the damping of oscillations following such large distrubances.

The power system is modelled by a set of differential and algebraic equations describing the large disturbance dynamic behaviour of the system. Using the initial conditions from a load flow study, the above mentioned system equations can be solved by means of nu-

Table 3.2 : Load Flow Studies Related to SVC Applications

Power System Problem	Purpose of SVC	Purpose of Load Flow Study	Typical System Operating Conditions	Type of System Model	Typical SVC Model
Voltage Instability	Avoid voltage collapse	Determination of $Q_{C\,min}$, U_{min} $B_{C\,rated}$	Peak load, min. Q generation contingencies	Single-phase equivalent (positive sequence) load flow, balanced loads and constant frequency	PV-bus with or without Q limits i.e. Q_{max} and Q_{min}
Power Transmission Capability Enhancement	Voltage control	Determination of $Q_{C\,min}$, U_{min} $B_{C\,rated}$	"	"	"
Transient Stability and Damping Enhancement	Voltage support, damping of oscillations	To provide initial conditions for large disturbance studies	Various configurations, loadings, contingencies	"	"
Subsynchronous Resonance Damping and Suppression	Positive damping of SSR	"	"	"	"
		To determine characteristic impedance		Admittance-type load flow, variable frequency	Shunt susceptance
Reduction of Continuous or Temporary Overvoltages	Limitations of overvoltages	Determination of $B_{L\,min}$, U_{OV} U_{max}	Load rejection, min. Q generation, light load contingencies	"	Shunt susceptance: $B_{L\,min}$ Separate PV-bus: U_{ref}, X_{SL} = SL
Load Balancing	Balancing of load reactive compensation, voltage control	Determination of $Q_{C\,min}$, Q_{Lmax} per phase	Max. and min. load min. short-circuit impedance	3-phase load flow, unbalanced loads, network parameters	Shunt susceptance per phase or PV-bus with or without Q constraints

merical integration and algebraic manipulation. The power system model for large disturbance studies should include :

- network series impedances and shunt admittances
- generator models with voltage regulators and speed governors
- loads with constant admittance (Y), frequency and voltage dependant admittance (Y(f,U)), constant current (I) or constant active and reactive power (P) and (Q)
- HVDC links with relevant controls
- SVCs with relevant controls.

The SVC is represented as a controllable susceptance or equivalent voltage or current source with a suitable controller in these studies. For most applications it is sufficient to model only the positive sequence behaviour of the SVC. More detailed information on SVC models for stability studies is given in Section 4.3 of Chapter 4.

The objectives of the large disturbance studies related to SVC applications are :

- to determine the required rating of the SVC especially in the capacitive range, from the excursions of the reactive power during disturbances
- to determine the effect of the control range limits
- to evaluate the effect of SVCs on the damping of oscillations
- to determine the appropriate control parameters and signals for adequate transient and damping performance
- to evaluate the effect of various SVC locations and ratings on the transient stability limits, in order to achieve effective minimisation of the investment required.

It is recommended to use an SVC model without susceptance or reactive power limits, i.e. a voltage source model, in the initial phase of the study and to apply more sophisticated models in the detailed planning stage.

Table 3.3 summarises the large disturbance (transient stability), small perturbation and subsynchronous resonance studies related to SVC applications. The SVC characteristic parameters determined from these studies are explained in detail in Chapter 5. Small perturbation studies and subsynchronous resonance studies are described in more detail in the following sections.

3.4 SMALL DISTURBANCE (STEADY-STATE STABILITY) STUDIES

Small disturbance studies are carried out to examine the possibility of low frequency power system oscillations due to lack of damping and to evaluate various measures for providing additional damping.These measures include use of system configuration and loading changes, generator control, voltage support, and supplementary control signals. The analysis can be performed using time-domain simulations, as used for large disturbance studies. The possible drawbacks of the time-domain simulations are the computing requirements and the numerical stability problems. Methods involving eigenvalue calculations, frequency dependent transfer functions or frequency-scanning methods are also powerful tools. These are based on a linearization of the dynamic power system model at a specific operating point. For SVC applications, the small perturbation study will provide information on the choice of SVC rating and appropriate control characteristics for improving the damping performance of the power system.

Table 3.3 : Large disturbance (transient stability), small disturbance (steady-state stability) and subsynchronous resonance studies related to SVC applications

Power System Problem	Purpose of SVC	Purpose of Study	Typical System Operating Conditions	Type of System Model	Typical SVC Model
Transient instability (Loss of synchronism following large disturbances) insufficient damping	Voltage support, transient, stability limit and damping improvement	Determination of SVC rating: $Q_{C\ min}$, U_{min} B_{C} rated Control parameters, signals, location of SVC	Peak or light load, min Q generation, outage contingencies. Fault type, location and duration according to system design criteria used	Balanced (pos. sequence) network, generator with inertia, damping control, load, no transformer terms in the power system and generator stator equations	Controlled current source (pos. sequence) or susceptance
Steady-state stability (Damping of low frequency power system oscillations)	Damping of power oscillations, reactive compensation to improve generator control	Determination of SVC operating point, control signals, parameters, structure	Peak or light load, min Q generation, outage contingencies	Linearized Balanced (pos. sequence) network, generator (inertia damping, control, load)	Controlled current source (pos. sequence) or susceptance
Damping of subsynchronous resonance	Damping of generator shaft oscillations, voltage control reactive compensation	Determination of SVC rating: $Q_{L\ max}$, U_{rated} Control signals, parameters, structure	Nominal load, power system tuned to SSR and/ or typical contingencies	Balanced (pos. sequence) generator shaft, inertia, damping, control, load all transformer terms eg di/dt, dφ/dt	Controlled current or susceptance source (pos. sequence) with transformer terms, converter time delay

3.5 SUBSYNCHRONOUS RESONANCE STUDIES

Subsynchronous resonance (SSR) may occur in power systems with series compensated transmission lines and thermal generation. In these systems there is a certain risk of adverse interactions between the electrical system and the generator shaft system. These interactions may result in sustained torsional oscillations causing damage to the generator rotor and shaft system. Subsynchronous resonance (SSR) studies are performed to evaluate the effectiveness of an SVC in damping or preventing subsynchronous oscillations in a power system.

The SSR studies are generally carried out in the time domain. Numerical integration is applied to the differential equations describing the network, generators and generator-turbine shaft train(s). Small perturbation methods (e.g., eigenvalue analysis) can also be applied equally effectively. Regardless of the method, the transformer terms representing rates of changes of variables with respect to time (e.g. di/dt, $d\phi/dt$) in the equations describing the generator and the power system have to be adequately included to represent the SSR-modes. Particular attention has to be paid to the modelling of the mechanical behaviour of the generator-turbine shaft train, taking into account the inertias, torsional parameters and mechanical damping of individual rotor sections.

The subsynchronous resonance studies should provide information on :

- adequacy of the SVC rating
- appropriate control system and its parameters
- benefical effects of the SVC in controlling and preventing subsynchronous resonance.

3.6 ELECTROMAGNETIC TRANSIENT STUDIES

An abrupt change of the steady state, such as the actuation of a switch, inception of a fault, or change of a reference value, will induce transients in an electrical power system. Although a power system is in a quasi steady-state most of the time, it must be designed to withstand the stresses which usually occur during transients. These stresses can include transient overvoltages, overcurrents and distorted waveforms. These effects may cause breakdown of insulation, saturation of transformers, mechanical or thermal damage to plant and maloperation of measurement, control and protection systems.

Since the transients involve interaction of magnetic and electrical fields, these phenomena are called electromagnetic transients. SVCs are able to limit temporary and some transient overvoltages by their control or inherent characteristics. It is therefore important to model the SVC in detail, if the fast transients are of interest and if interaction with other power system elements is possible. Power frequency overvoltages can be evaluated, as a first approximation, by using load flow type (i.e., positive sequence, P-V-node) models for the SVCs.

Studies to evaluate the real-time behaviour of SVCs in a power system during transient disturbances can be performed using analog, hybrid or physical models (TNA) and/or digital computer programs. The advantage of the TNA-type models is primarily in the possibility of using the actual SVC control equipment and carrying out a large number of studies in a short time period.

Since the time domain of interest extends from microseconds to seconds, the models for the network elements, generators, and SVCs need to be quite sophisticated. Appropriate modelling of saturation, losses, voltage drops and unsymmetric operation under unbalanced system conditions is important. More information on SVC models for electromagnetic transient studies is included in Section 4.4.

The objectives of the electromagnetic transients studies related to SVC application can include :

- verification of the effect of the SVC on system transients, especially on overvoltages (a specification problem)
- determination of the stresses on the SVC equipment during transient disturbances (partly a design problem)
- verification of the adequacy of the SVC rating for transient disturbances
- optimization of the control system structure and parameters
- the determination of the effect of voltage distortions on the SVC performance, especially on the measurement and the control system response
- provision of training for the utility staff in the design and operation of the SVC.

The results of the studies are used to derive requirements to be included in the SVC technical specifications for the particular application.

3.7 HARMONIC PERFORMANCE STUDIES

Many types of SVC utilising thyristor-controlled or saturated reactor elements generate harmonic currents. The objective of a harmonic performance study is to determine the effect of harmonics generated by the SVC on the power system and its elements, to determine the interaction of the SVC with the system, the SVC performance under balanced and unbalanced operating conditions and to evaluate countermeasures such as filters. In order to carry out these studies network harmonic characteristics at the point of SVC connection, existing levels of harmonics and appropriate standards on acceptable harmonic levels need to be adequately known.

Since harmonic distortions in the system result from the interaction between SVCs and the system, all system contingencies which may affect system frequency response should be evaluated. Any tolerances in the parameters of the power system model should be considered to make sure that system parallel resonance points do not coincide with characteristic harmonics from the SVC. Harmonics generated by SVCs are largely dependent on the operating point within the SVC characteristic. A conservative approach is to use the maximum values of harmonics generated within the spectrum irrespective of the operating point. Time domain simulations will provide more realistic results of the interaction between the SVC and the system.

As long as the harmonic content in the system voltage and/or current is small, the power system can be described by linear equations with frequency dependent parameters which means that any interaction between the individual harmonics will be disregarded. The characteristic and non-characteristic harmonics generated by SVCs can be considered simply as zero, positive, and negative sequence current sources if :

- the effective impedance of the network as seen by the SVC from the point of common coupling does not have parallel resonance(s) near one of the generated harmonics
- the control does not amplify the harmonics due to resonance
- the thyristor control and synchronisation is operating properly.

Harmonic performance studies are generally carried out by means of digital computer programs on a linear, quasi-stationary (complex), balanced representation of the system with harmonic current sources. Harmonic impedance approximations have to be used for the representation of the power system if detailed data is not available. Time domain simulation can be used in cases where interaction between the SVC and other power system components may occur leading to possible harmonic magnification, high inrush currents, control interaction and non-characteristic harmonics. Thus appropriate modelling of the SVC controls is of importance. The use of TNA with the actual SVC controller is a good approach provided the network is properly represented.

The objectives of harmonic performance studies related to SVC application can include the determination of :

- the network harmonic characteristic (i.e., impedance versus frequency) required for the specification and design of filters
- the effects of SVC generated harmonics on the power system and its elements
- the overall filter requirements and the countermeasures to reduce harmonics to acceptable levels.

The results of such harmonic performance studies provide the input to appropriate SVC design studies.

3.8 FAULT LEVEL STUDIES

The objective of fault level studies is to determine the short circuit current for symmetric or unsymmetric faults or the short-circuit impedance at the point of the SVC connection for various network and system demand conditions. In modelling the network the admittance approach can be used. The generators and motors can be represented by simplified models with transient parameters. The study, besides giving the most suitable rating of circuit breakers, provides relevant information for the overcurrent and fault protection coordination as well as the initial determination of SVC controller parameters.

3.9 COORDINATION, OPTIMISATION, LOSS AND COST EVALUATION STUDIES

In order to ensure the correct choice of SVC rating and appropriate coordination of SVC output within the power system, optimisation and coordination studies are carried out as part of the load flow, transient stability and steady-state stability studies in the detailed system planning stage. The optimisation studies which can be carried out by successive load flow or appropriate optimal load flow studies provide information on the adequacy of the chosen SVC rating to meet the particular voltage and system contingency criteria, under system steady-state conditions prior to and following system contingencies. The appropriate SVC rating selected from these studies needs to be checked to ensure it satisfies the transient and steady-state stability performance requirements envisaged for the SVC. Iterations on sets of these studies will yield the most appropriate i.e., optimal rating of the SVC satisfying all criteria and performance requirements. These studies can also yield appropriate information on the coordination of SVC output under various system demand and contingency conditions with other reactive power sources in the system and especially in the vicinity of the SVC. This would ensure that SVC does not act in conflict with other reactive power sources.

An examination of the time duration of particular power system operational and/or contingency condition permitting the outage of the whole or part of the SVC will provide insight to the availability requirements.

The information for loss evaluation studies is generally obtained from the many load flow studies carried out in the detailed planning stage. These studies will need to assume the SVC with the chosen rating in service under various system conditions in order to establish the most common operating points/regimes of the SVC together with the corresponding duration of operation under such conditions. This information would be valuable to the manufacturer in designing the SVC with minimum losses under most common operating regimes. Following the completion of SVC design by the manufacturer, the loss characteristics of the SVC will be made available to the utility together with the equipment cost to enable an overall tender evaluation based upon costs of equipment and SVC losses over the expected life.

3.10 SUMMARY

The power system studies carried out for SVC applications do not differ substantially from studies carried out for conventional reactive compensation alternatives such as switched capacitors and reactors and synchronous compensators. The speed of response of the SVC due to inherent or control characteristics makes it a powerful tool in terms of overall power system design. In this sense it is necessary to carry out sufficient studies covering as wide a planning horizon as possible in determining the functional requirements of the SVC.

The study and analysis techniques are well established and the inclusion of appropriate SVC models, described in Chapter 4, should ensure satisfactory evaluation of the SVC functional as well as performance requirements.

CHAPTER 4

MODELLING OF STATIC VAR COMPENSATORS IN POWER SYSTEM STUDIES

4.1 INTRODUCTION

Power system studies required to evaluate the need and develop specifications for static var compensators (SVCs) have been described in Chapter 3. It is clear from the information presented in Chapter 3 that the power system and SVC modelling requirements for these studies are dependent on the type of study being performed. The objective of this chapter is to describe these modelling requirements in more detail for the various types of studies.

For each type of study, there are basic modelling requirements which must be satisfied. This chapter describes the general assumptions which are associated with the basic model, extensions and refinements to the model for specific analyses, and techniques for implementing the model in typical study tools available. Examples of the model application are included where appropriate.

4.2 MODELS FOR LOAD FLOW STUDIES

4.2.1 General Requirements

SVC models for load flow studies should represent :

- the steady-state, fundamental frequency, balanced behaviour of the SVC, i.e., the static characteristic expressing total reactive SVC current as a function of the SVC terminal voltage at nominal frequency, balanced terminal voltages, etc., including control limits.

This model is sufficient to evaluate the steady-state fundamental frequency behaviour of any SVC, both with active and inherent control.

Three-phase modelling is required only in applications where the SVC is installed to balance voltages, reactive or active power loads, i.e., when unbalanced networks and loading conditions are to be analysed.

4.2.2 Description of Basic Model

The loads or generators connected to system busbars are represented in standard load flow programs as :

- loads or generators with specified active (P) and reactive power (Q) - (PQ-node)
- generator with specified node voltage (U) and active power (P) where the reactive power (Q) is not specified, but varies within set limits - (PV-node)
- shunt elements with specified admittance (G+jB) or complex power (P+jQ) connected to nodes.

These standard load flow program features are used in modelling a generalised SVC.

The steady-state characteristic of a generalised SVC describes the relationship between the terminal voltage (U) and the total reactive current (I), both within and outside the control range as shown in fig. 4.1.

The load flow representation depends on whether the SVC is operating within or outside the control range.

With the reactive power Q flowing into the SVC at the point of common coupling, and (B) the equivalent susceptance of the SVC, the sign conventions for the load flow analysis will be as follows :

$Q > 0$ or $B < 0$ means that the SVC is behaving like an inductor

$Q < 0$ or $B > 0$ means that the SVC is behaving like a capacitor

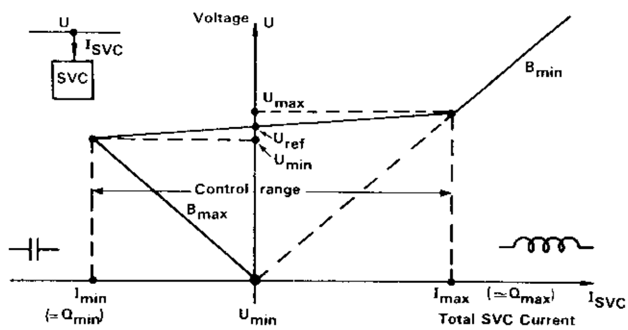


Fig. 4.1 Basic SVC characteristic

4.2.2.1 SVC Operating within the Control Range

$(I_{min} < I_{SVC} < I_{max}, U < U_{min})$

If the slope SL of the steady-state characteristic is zero, the SVC is represented as a PV-node ($P = 0$ and $U = U_{ref}$) at the point of coupling to the system. Otherwise, the SVC is represented as a PV-node at an auxiliary bus with ($P = 0$ and $U = U_{ref}$). A reactance of (X_{SL}) equivalent to the slope SL (X_{SL} in pu = SL in pu) is added between the auxiliary node and the point of coupling to the system (SVC-node) to represent the slope of the characteristic. The node at the point of common coupling is a PQ-node with initial conditions $P = 0$ and $Q = 0$, as shown in fig. 4.2.

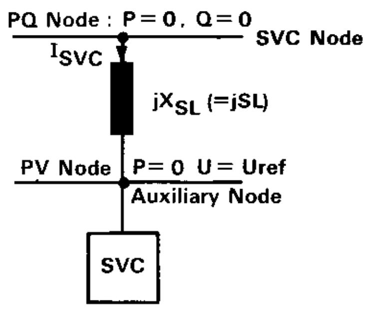


Fig. 4.2 SVC model with slope for operation within control range

4.2.2.2 SVC Operating Outside the Control Range

$(U < U_{min}$ and $I_{SVC} > I_{max})$

The SVC is represented as a shunt element with the susceptance (B), depending on the operating point (see fig. 4.3) :

for $I_{SVC} > I_{max}$: $B = B_{min} = - Q_{max}/U^2_{max}$

for $U < U_{min}$: $B = B_{max} = - Q_{min}/U^2_{min}$

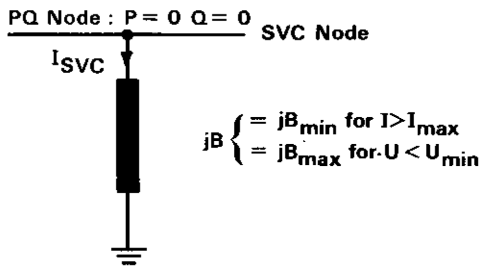


Fig. 4.3 SVC model with slope for operation outside control range

The result of the load flow calculation will be the reactive power Q at the point of common coupling (i.e. HV side of the SVC step down transformer) necessary to maintain the voltage U according to the SVC characteristic for a given network and loading situation.

These basic models are sufficient to determine the required SVC rating irrespective of the SVC type and to evaluate the effect of the SVC without considering transformer saturation.

It should be noted that, the PV-node with Q-limits (Q_{min} and Q_{max}) type representation, is not appropriate for representing an SVC under overload conditions. With such a representation the behaviour will be incorrect outside the control range as illustrated in fig. 4.4.

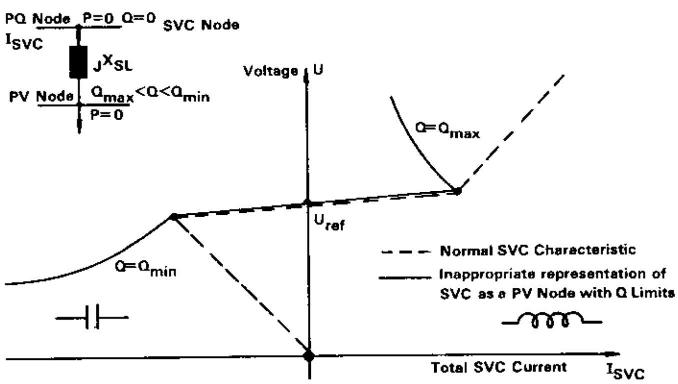


Fig. 4.4 Illustration of inappropriate SVC model for load flow studies

4.2.3 Extensions and Refinements to the Basic Model

More detailed models should consider both the slope of the static characteristics in the control range and the limits of the characteristic in the uncontrolled range in one model so that no external interaction is required during the simulation.

This feature does not exist in a standard load flow program. It requires a modification of the node type. There are several ways to provide a node element having the standard SVC characteristic shown in fig.4.1

4.2.3.1 Modelling as Voltage Controlled Susceptance

Depending on the voltage U at the SVC node, the susceptance (B) is increased or decreased stepwise according to the error ($U - U_{ref}$) until one of the B_{max} or B_{min} limits is violated. The accuracy of the model is limited by the number of steps in (B) as shown in fig. 4.5.

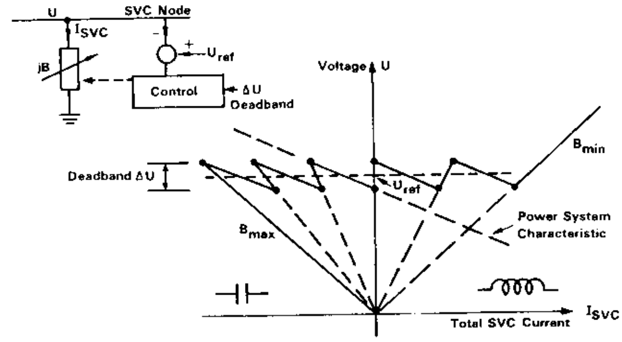


Fig. 4.5 SVC model for load flow and time domain simulation with stepwise control of susceptance (B) (see fig. 2.22)

4.2.3.2 Modelling by Functions Q (U)

The dependency of the reactive power output Q of the SVC on the terminal voltage U as represented by the static characteristic shown in fig. 4.1 which can be expressed either in tabulated form or as an analytical expression and included in the load flow equations. In load flow programs based on the Newton-Raphson algorithm, this is accomplished by including the derivative of the SVC reactive power with respect to voltage ($\partial Q/\partial U$) in the Jacobian matrix. The value of this derivative will be updated at every step of the iterative solution procedure, based on the computed voltage at the SVC node. No problems are generally encountered with this technique as long as appropriate convergence control is used.

The dependency of the SVC reactive power output Q on the terminal voltage U is given by the following expressions for the static characteristic shown in fig. 4.1.

$Q = (U - U_{ref}) \cdot U / X_{SL}$ within the control range

$Q = -B \cdot U^2$ outside the control range with $B = B_{max}$ or B_{min}

4.2.3.3 Modelling as Controlled PV- and PQ-node

The basic SVC model shown in fig. 4.2 can be complemented with a control procedure, controlling the nature of the SVC load at the auxiliary node.

Based on the SVC current, which can be calculated as the current between the SVC node and the auxiliary node, the control procedure will decide whether the load at the auxiliary node will be a PV-node or a constant admittance load as shown in fig. 4.6.

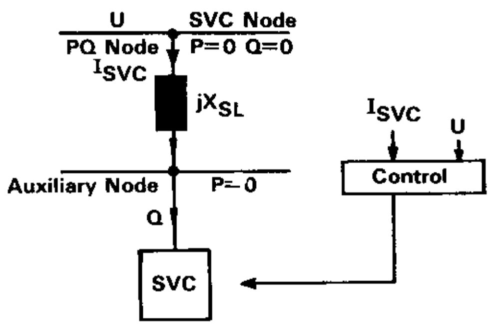


Fig. 4.6 SVC modelled as a controlled load

As long as the SVC is operating within the limits I_{max} and U_{min}, the auxiliary node will be of the PV-type with P = 0 and $U = U_{ref}$.

A PQ-type of load will be used with P = 0 and unspecified voltage U if the SVC is operating outside the limits I_{max} or U_{min}. The reactive power Q is dependent upon the voltage U (calculated in the previous iteration) and the SVC overloading. For $I_{SVC} > I_{max}$, the reactive power Q is set $Q = -B_{min} \cdot U^2$, while for $U < U_{min}$ is set to $Q = -B_{max} \cdot U^2$. The node type has to be switched back to the PV-type as soon as the SVC is back to its normal operating range during the next iteration.

4.3 MODELS FOR LARGE AND SMALL DISTURBANCE STUDIES

4.3.1 General Requirements

SVC models for small disturbance, transient and dynamic stability studies should represent the positive sequence system behaviour, including control action. Electromagnetic transients in the network and SVC components can be ignored in these studies as long as the disturbances being evaluated are the result of electromechanical oscillations.

SVC models for subsynchronous resonance studies,must accurately represent SVC characteristics under steady-state, dynamic and transient conditions. Thus similar SVC models to those used in electromagnetic transient studies are recommended for subsynchronous resonance studies.

4.3.2 Description of the Basic Model

Digital computer programs for transient stability and small disturbance studies are based on the node admittance approach using lumped elements with nominal frequency parameters to represent the network. Generators are represented as current sources modelled by Park's equations with detailed representation (e.g., damper circuits, saturation) depending on the requirements. Generator control models include adequate representation of the small and large disturbance behaviour. Loads are represented by constant or controlled susceptance or current sources.

The basic model of the SVC follows the classical representation of generator control. This generalised basic model which is described in terms of thyristor controlled/switched type SVCs is also applicable to all other type SVCs with appropriate modifications to the block diagram.

The basic model consists of the following elements as illustrated in fig. 4.7 :

- a voltage and current measuring and filtering system (H)
- an SVC regulator (G_1) including possible additional signals fed to the reference point or directly into the thyristor controller
- elements (A_1) and/or (A_2) to represent the effect of additional control signals used for system damping improvement, etc.
- a model of the thyristor control (G_2) with limit and normalising functions for the output, according to the rating of the SVC
- a synchronising control unit (G_3) acting on the voltage phase angle to synchronising firing pulses
- an SVG-model (or interface with the power system) consisting either of a controlled susceptance or a controlled current source.

In studies concerned with electromechanical oscillations, the effect of thyristor valve firing pulse synchronising controls (phase-locked loops) on the overall control response can be neglected. However, if this is considered necessary then representation of these effects through the element (G_3) is possible.

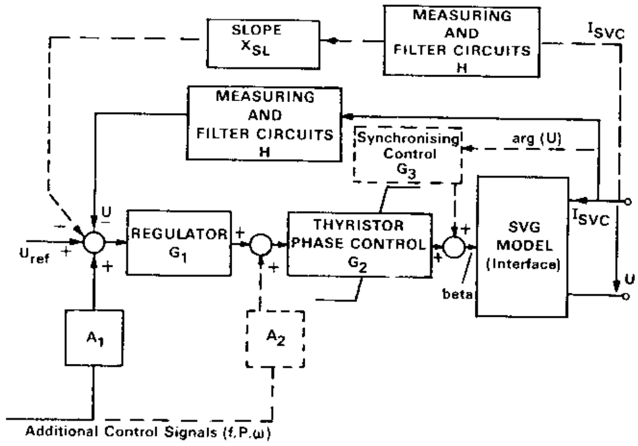


Fig. 4.7 Basic SVC model for small and large disturbance studies

The characteristics of the measuring and filter circuits can be approximated by the transfer function :

$H = 1/(1 + sT_m)$

if no specific filters with appreciable time constants are applied in addition to the filters associated with the measuring circuits.

The transfer function G_1 of the SVC regulator (AVR) can be represented by :

$G_1 = K\ (1 + sT_1)\ /\ (1 + sT)\ (1 + sT_2)$

for a proportional type control and

$G_1 = K\ (1 + sT_1)\ /\ sT\ (1 + sT_2)$

for an integral type control system, each containing a lead-lag compensation term.

In case of an integral type voltage controller the slope SL is incorporated into the SVC characteristic by a current feedback ($X_{SL} \cdot I_{SVC}$), or reactive power feedback term ($X_{SL} \cdot Q_{SVC}$) in practice, as shown in fig. 4.7. In case of proportional type voltage controller the current feedback is not required as the slope is modelled by the gain K.

Additional control signals related to system frequency or power flow may be incorporated into the overall control by means of the transfer functions (A_1),(A_2), etc.

The control representation should include the correct representation of integrator action (non-wind-up, see definition 9.6.14) and all limits applicable to transfer function blocks and control circuit quantities. If such limits are not correctly represented, serious errors are likely to be experienced in studies, due to extra time delays associated with incorrect representation of limits.

The thyristor phase control is represented with the transfer function

$G_2 = (\ s^{-sT_d})\ /\ (1 + sT_b)$

where T_d is the gating transport delay and T_b is an additional time constant representing the effect of the thyristor firing sequence control.

The non-linear relationship between the SVC output (B) and the firing angle is compensated by means of a linearising function in the thyristor phase control *circuits. The above transfer function for the thyristor* phase control is therefore linear taking due account of this compensation.

The output of the thyristor phase control block is limited such that the control signal (beta) into the SVG model remains within the limits :

$$1 \geq (beta) \geq B_{min} / B_{max}$$

with :

$$B_{max} = - Q_{Crated}/U^2_{rated} = - Q_{min}/U^2_{min}$$

$$B_{min} = - Q_{max}/U^2_{max}$$

according to the rating.

The firing pulse synchronising controls can be modelled by a second-order delay, represented by the transfer function

$$G_3 = s(1 + sT_s)/ \left[K_s + s(1 + sT_s)\right]$$

acting on the control signal (beta) depending upon the normalised voltage phase angle, arg (U), according to the SVC design.

The SVG model (or interface) has to convert the output signal of the control (beta) into a controlled network element connected to the SVC node.

There are two ways to model the SVG or interface it with the network :

(a) as a variable susceptance $B = (beta).B_{max}$ (fig. 4.8a), such that the SVC current I_{SVC} depends on the control output (beta) and the voltage U :
$I_{SVC} = j(beta).B_{max}.U$

(b) as a controlled current source (fig. 4.8b), with the same characteristic :
$I_{SVC} = j(beta).B_{max}.U$

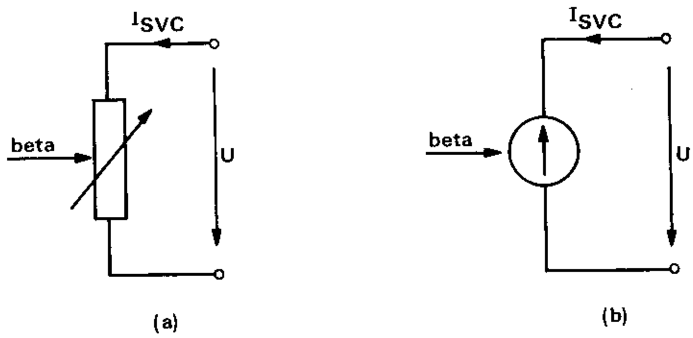


Fig. 4.8 Basic SVG models for small and large disturbance studies (a) susceptance model (b) current source model

In terms of overall SVC simulation the susceptance and current source models are equivalent. However, considerable differences exist with their implementation in computer programs. For the model in fig.4.8a the admittance matrix has to be updated if (B) changes, while the model in fig. 4.8b permits the use of constant admittance matrix.

The parameters of the basic model have to be selected according to the SVC rating and performance criteria taking into account the power system behaviour under various operating conditions and the SVC response under such conditions.

The basic SVC model shown in fig. 4.7, is suitable for modelling the electromechanical transient performance of any type of SVC in conjunction with the response of the network model. Typical values for the various SVC model parameters are given in Table 4.3.1.

Table 4.3.1 :Typical parameters for SVC models

Parameters	Simplified SVC	TCR, TSR, TSC LCC, SCC	SR
K	40... 400	40... 400	1/SL
T	0,05..0.15s	0.05..0.15s	0.015..0.02s
T_1	0	0.5s	-
T_2	0	1.0s	-
T_d	0	0.001s	-
T_b	0	0,003..0.006s	-
T_m	0	0.001..0.005s	-
K_s	0	30	-
T_s	0	0.06s	-

Values of 40 to 400 are typical for the gain K with the input of the controller $(U-U_{ref})$ expressed in per unit (pu) on the base of the SVC rating. High values of K may cause control instability, depending on the equivalent power system reactance X_e.

Based on the simplified model as described in Section 4.3.4 an estimate of the gain K in pu can be derived by means of the following formula :

$$K \leq (1 - B_{max} \cdot X_e)\ 2/X_e$$

If the controller is a proportional type controller then the gain K defines the slope of the static characteristic as :

$$X_{SL} = 1/K$$

omitting the current feedback $(-X_{SL}.I_{SVC})$ in fig. 4.7.

In small and large disturbance studies related to electromechanical problems with eigenfrequencies up to a few Hz the thyristor control block and the synchronising control can be ignored. The time constants T_1 and T_2 can be ignored in the initial phase to study.

At the start of the simulation, the current I_{SVC} or the susceptance B and the control value (beta) have to be determined according to the initial conditions given by the load flow study.

The performance accuracy of the basic SVC model is limited to electromechanical oscillations as the transformer terms (di/dt) in the network equations (i.e., the dc-components in the currents), are neglected. Thus any interaction between the control system and the network at harmonic and sub-harmonic frequencies is disregarded by this model.

Any transmission system resonant frequencies close to the fundamental may need to be filtered as they may adversely effect the control system response.

The model can also be used for subsynchronous resonance studies provided the transformer terms (di/dt) are represented in the network equations.

4.3.3 Simpler SVC Models

For first swing, post-fault transient stability studies where the damping of the electromechanical oscillations is not important, a simpler SVC models can be used with either :

- a steady-state characteristic expressed as a function of voltage i.e. $I_{SVC} = f\ (U)$
  or
- a switched shunt reactance, generally a capacitor, which is voltage dependent
  or
- a simplified basic model with a proportional control-

ler : K = 20...100, T = 0, and (beta) with or without limits.

In the case of a model with limits, the size of the SVC can be selected by means of load flow studies considering the power system peak loads at which maximum generator voltage angles across the system are expected.

4.3.4 Simplified Transfer Function Block Diagram for SVC and Power System

For power system stability studies related to the voltage control at the point of the SVC connection to the system, a simplified block diagram of the SVC and the power system might be sufficient. This simplified system might be used to verify the adequacy of the control parameters.

For this situation the power system is represented by a source voltage E, in series with a equivalent system reactance X_e in pu, normally derived from the three-phase short-circuit fault MVA infeed from the power system at the SVC busbar as follows.

$X_e = (U^2_{rated}/ S_C) \cdot$ (MVA base)

where S_c = three-phase short-circuit fault MVA infeed at the SVC node U_{rated} = nominal line-to-line voltage
MVA base = Base MVA used in the power system study

The reactive current output of the SVC (either capacitive or inductive) produces an "in-phase" voltage drop $(-X_e \cdot I_{SVC})$ which means that, with the source voltage E at a constant value and the SVC not on closed-loop control, the terminal voltage will vary depending on the reactive current drawn by the SVC as shown in fig. 4.9.

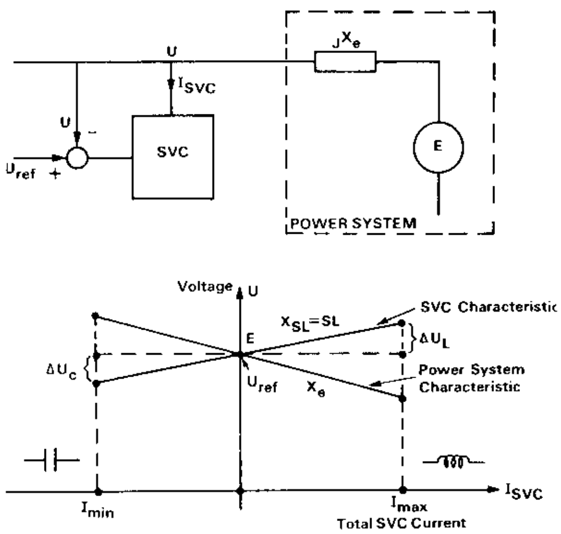


Fig. 4.9 Simplified power system model and SVC characteristic

The voltage variation at the SVC node within the SVC control range $I_{min} < I_{SVC} < I_{max}$ is defined by the combination of :

(i) The power system characteristic; representing the voltage variation due to the equivalent power system reactance by the equation

$$U = E - X_e \cdot I_{SVC}$$

and

(ii) the SVC control characteristic; representing the compensation provided by the SVC in response to voltage variations by the equation

$$U = U_{ref} + X_{SL} \cdot I_{SVC} = U_{ref} + SL \cdot I_{SVC}$$

Assuming $E = U_{ref}$ the power system and SVC control characteristics intersect at zero SVC current as shown in fig. 4.9. It is clear that with the SVC control range if $U_L = X_{SL} \cdot I_{max}$ i.e., if $X_{SL} = X_e$ then the SVC provides full compensation, if however, $X_{SL} < X_e$ then the SVC provides partial compensation for the voltage drop due to the power system characteristic. Full compensation by the SVC allows flat voltage control of the voltage U while partial compensation results in a voltage characteristic with a droop related to the slope reactance (i.e., slope of the SVC control characteristic) defined as :

$$SLOPE = SL = X_{SL} = \Delta U_c/I_{min} = \Delta U_L/I_{max}$$

The resultant voltage control achieved by full and partial compensation are illustrated in fig. 4.10.

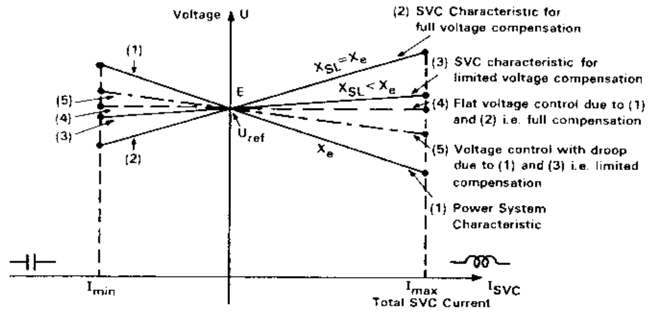


Fig. 4.10 Control of voltage U obtained with SVC characteristic adjusted to full or limited voltage compensation ($E = U_{ref}$)

The block diagram of the closed loop voltage control for the SVC, having the characteristic given in fig. 4.10, is shown in fig. 4.11 with G and H as defined in Section 4.3.2.

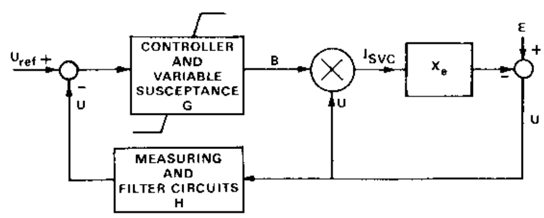


Fig. 4.11 Block diagram of SVC with closed-loop terminal voltage control

A simplified block diagram of the closed-loop voltage control can be derived assuming the terminal voltage U deviates only slightly from its nominal value U_{rated} as shown in fig. 4.12.

The transfer functions G and H of the simplified system shown in fig. 4.12 can be generalised as follows in per unit (pu) on the base of SVC rating :

$$G = K(1+sT_1) \cdot e^{-sT_d} / (1+sT)(1+sT_2)$$

$$H = 1/(1+sT_m)$$

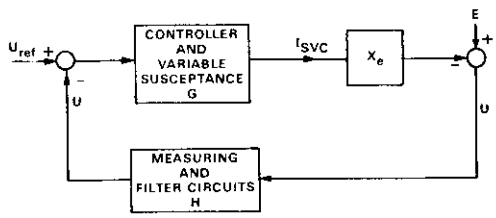


Fig. 4.12 Simplified block diagram of SVC with closed-loop terminal voltage control for $U = U_{rated}$

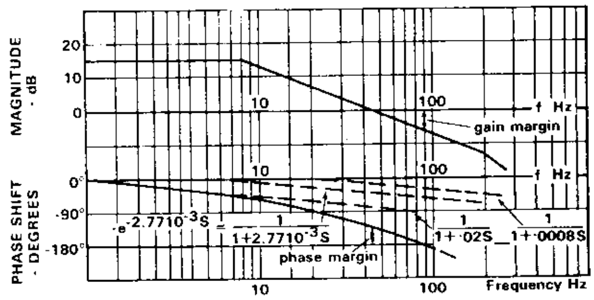


Fig. 4.13 Magnitude and phase shift of the open loop transfer function $(G.X_e.H)$ for the SVC and power system given in the example

The slope of the steady-state characteristic is related to the transfer function gain K by :

$$K = 1/X_{SL} = I_{min}/\Delta U_C = I_{max}/\Delta U_L$$

Defining $I_{base} = Q_{rated}/(\sqrt{3} \cdot U_{rated})$ and $U_{base} = U_{rated}$ then the gain K in pu and the external reactance X_e is given by

$$K(pu) = (I_{Cmax} \cdot \sqrt{3} \cdot U^2_{rated})/(U_C \cdot Q_{rated})$$

$$Xe\ (pu) = Q_{rated}/S_c$$

where

Q_{rated} = rated reactive (capacitive or inductive) power output of the SVC (MVar)

U_{rated} = rated line-to-line voltage of the SVC (kV)

S_c = three-phase short-circuit fault MVA infeed at the SVC node

I_{min} or I_{max} = maximum capacitive or inductive current of the SVC (kA).

A small change in the terminal voltage ΔU, as a function of the source voltage change ΔE and reference voltage change ΔU_{ref} can be expressed as :

$$U = (\Delta E + G \cdot X_e \cdot \Delta U_{ref})/(1 + G \cdot X_e \cdot H)$$

This indicates that the equivalent system reactance X_e representing the power system has as important an effect on the dynamic behaviour of the SVC, as the control gain K. Therefore, the value of the gain K which can be used is limited, especially in weak power systems with a large equivalent reactance X_e, to ensure stable response from the SVC control system (see also Section 7.2). In more detailed studies the frequency dependency of X_e has to be considered as well, especially in cases where parallel resonances may already exist at or near even harmonic frequencies (2nd, 4th, etc.) in the power system.

Example : Consider an SVC connected to a power system with the following data :

SVC : Q_{rated} = 45 MVA

X_{SL} = 0.2 %   T = 0.02s T_m = 0.0008s

$T_1 = T_2 = 0$ T_d = 0.0027s   0.0055s

Power System : S_c = 4000 MVA

the above equations yield a steady-state gain K = 500 pu and an equivalent system reactance X_e=0.01125 pu on the base of SVC rating.

Plots of the magnitude and phase shift of the open loop transfer function $(G.X_e.H)$ for the above example, as a function of frequency are shown in fig. 4.13. As the combined SVC and control system was found to be stable, no phase compensator network was required in the controller (i.e., $T_1 = T_2 = 0$).

The response of a (TSC + TCR) type compensator, with a single (TSC) bank and characteristics given in the example, to a step-like voltage change is shown in fig. 4.14 with T_d = 5.55ms.

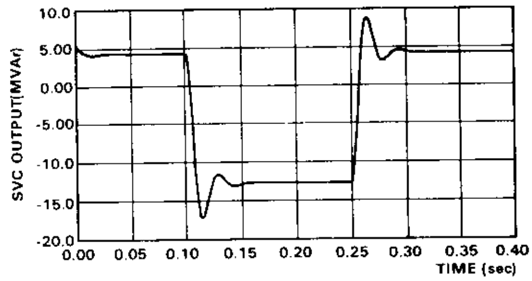


Fig. 4.14 Response of the (TSC + TCR) type compensator, with a single (TSC) bank and characteristics given in the example, to a step-like change in the source voltage E, with the main regulator time constant T_d=5.55msec

Calculations on the SVC and control system characteristics can be carried out on any base MVA chosen for a particular power system study. However, care will need to be taken to calculate all quantities on the same basis for consistency of results.

4.4 MODELS FOR ELECTROMAGNETIC TRANSIENT STUDIES

4.4.1 General Requirements

SVC models for electromagnetic transient studies must accurately represent the SVC characteristics for steady state, dynamic, and transient conditions. Studies in the specification development and design stages must evaluate the interaction between the SVC and the network for many different transient conditions. The time frame of interest for these conditions ranges from microseconds to many seconds. Important conditions to be evaluated, which require detailed representation of SCVs within the network, include :

- system switching events, such as transmission line switching, transformer switching, filter switching, etc.
- fault initiation and fault clearing, including unsymmetric faults
- load rejection
- interaction of the SVC controls with the power system, which can result in harmonic resonance conditions.

The appropriate tools for studying SVC performance under electromagnetic transients conditions include analogue, hybrid (partly analogue and partly digital) and completely digital models. Analogue or hybrid models for the power system and the SVC might consist of :

- power system components (lines, transformers, generators, etc.) simulated by means of physical elements (resistors, inductors, capacitors, etc.) and/or electronic devices (generators, circuit-breakers, arresters, etc.)
- combination of physical elements/electronic devices with digital assemblies like minicomputers, microprocessors etc., for simulating controls and power system components.

Fully digital simulations are carried out by suitable computer programs.

Important requirements for the power system representation in electromagnetic transient studies include :

- three phase representation
- accuracy over a wide frequency range
- representation of non linearities of system elements and controls
- time domain simulation
- accurate modelling of system elements (generators, transformers, transmission lines, cables, SVCs, controls, breakers, HVDC converters, filters, etc.)

Modelling of system elements for electromagnetic transient studies has been described in the technical literature. This section will concentrate only on SVC models for these studies.

4.4.2 Description of Basic Models

As indicated above, for electromagnetic transient studies all the SVC components must be accurately represented in the time domain. Representation can be completely analogue, a combination of analogue and digital, or completely digital depending on the simulation tool being employed. Important characteristics of each component which must be represented are described in the following sections.

4.4.2.1 Inductive and Capacitive Elements

The inductive and capacitive elements in the SVC can include reactors (TCR, TSR, or MSR), capacitors (FC, TSC, or MSC), transformers (TCT), or saturated reactors (SR). In completely digital simulations, these devices are represented by differential equations which are solved using numerical integration techniques, such as the trapezoidal rule. With power system simulators, analogue or electronic models can be employed.

4.4.2.2 Linear Reactor Models

Models of linear reactors are applied to represent :

- thyristor controlled or thyristor switched reactors
- current limiting reactors used in TSC banks
- reactors used as filter components
- mesh and mesh-loading reactors used as components of saturated reactors
- leakage and saturation effects in transformers and reactor-transformers

Physical reactor models utilise magnetic cores with air gaps making their remanent (residual) magnetism negligible. The quality factor of such reactors (X/R up to 50) is adequate in many applications. Improved reactor models employ electronic negative resistance circuits for compensation of excessive copper losses of the reactor windings.

Digital models for reactors use the appropriate differential equations to represent the linear inductance and resistance of the reactor.

4.4.2.3 Saturated Reactor Models

Basic models of twin-tripler and treble-tripler saturated reactors consist of both saturated and linear reactors. A typical treble-tripler reactor model is shown in fig. 4.15.

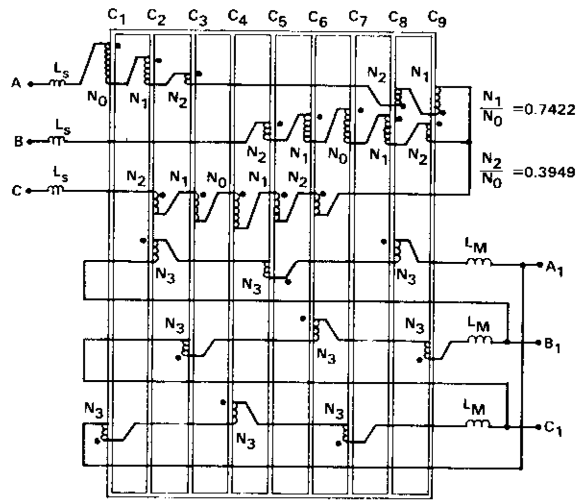


Fig. 4.15 Treble-tripler saturated reactor model

It consists of nine saturable reactors with their cores and windings (N_0, N_1, N_2 and N_3) scaled down to provide a saturation knee-point at the voltage level around the simulator operating voltage. Three linear reactors (L_S) are added to the saturation reactance to achieve the required impedance (5% to 15% on rating). The mesh reactors (L_M) are modelled by three other linear reactors or an appropriate more detailed model connected to the terminals A_1, B_1 and C_1.

In physical models, the saturable elements are modelled with actual saturable cores made of appropriate magnetic material to give the required magnetizing characteristics while tapped windings can be employed to vary the saturation knee-point. Copper and core losses of these saturable cores can be somewhat higher than in reality, resulting in greater damping of transients. Because the core characteristics are fixed it is usually difficult to obtain precise modelling of a given saturation characteristic. However, the approximation obtained is usually sufficiently accurate. Improved models of saturated reactors employ electronic negative resistance circuits to compensate for excessive copper losses.

In digital models, the saturation characteristic is generally represented by a piecewise linear U-I curve (or B-H curve), either with or without hysteresis. At each time step, the program must iterate to a solution which satisfies this and other non-linearities in the system. This permits more accurate modelling of the magnetising and saturation characteristic. In electromagnetic transient studies utilising digital models, the time step must be selected carefully such that possible numerical instabilities around the knee-point of the curve are avoided.

4.4.2.4 Transformer Models

Basic physical transformer models consist of interconnected saturable and linear transformers and reactors. Examples of physical models are illustrated in fig. 4.16.

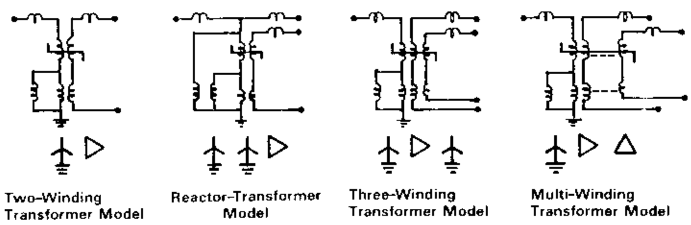


Fig. 4.16 Transformer models

Each three-phase model consists of three saturable and three linear transformers with their windings connected in series. Three linear reactors are connected in parallel to the linear transformers to reduce the net reactance to the required saturation reactance of the transformer model. Linear reactors in series with the transformer windings are used to achieve the desired leakage reactance. The individual windings are interconnected according to the transformer connection (i.e., wye-delta, delta-wye, etc.).

The physical model of the reactor-transformer incorporates three additional linear reactors connected in parallel with the saturable and linear transformers in order to decrease the magnetising reactances of the model to the desired level.

The transformer models for SCC and LCC compensators employ saturable and linear transformers with multiple secondary windings interconnected to provide the required number of three phase windings, phased equidistantly within the range of 0 to 60 electrical degrees.

As with saturated reactors, physical models of transformer saturation characteristics must necessarily be approximations of actual characteristics. Approximation can include inaccurate characteristics around the knee-point and higher than actual losses. Approximations achievable with digital models are generally sufficient for evaluation of both dynamic and transient SVC performance. Improved physical models employ electronic negative resistance circuits to compensate for copper losses. Further improvement can be obtained by using three limb cores instead of three individual cores for better modelling of transformer inrush current phenomena.

Another technique makes use of a combination of linear and saturable reactances and semi-ideal transformer. The transformer as well as the power system modelled is viewed from the terminals of one winding. Arrangements of such elements for representing a three-phase autotransformer with a delta winding are shown in fig. 4.17. These models are sufficiently accurate in most cases.

In the lower diagram of fig. 4.17 the reactance in series with one of the delta connected windings of the semi-ideal transformer accounts for the zero sequence flux behaviour of three limb core transformers.

Digital transformer models must include accurate representation of the linear leakage reactance characteristics, coupling between transformer terminals corresponding to the winding configuration, and the saturation characteristics. The model can be achieved with a multi-phase coupled inductance matrix and piecewise linear representation of the saturation characteristics.

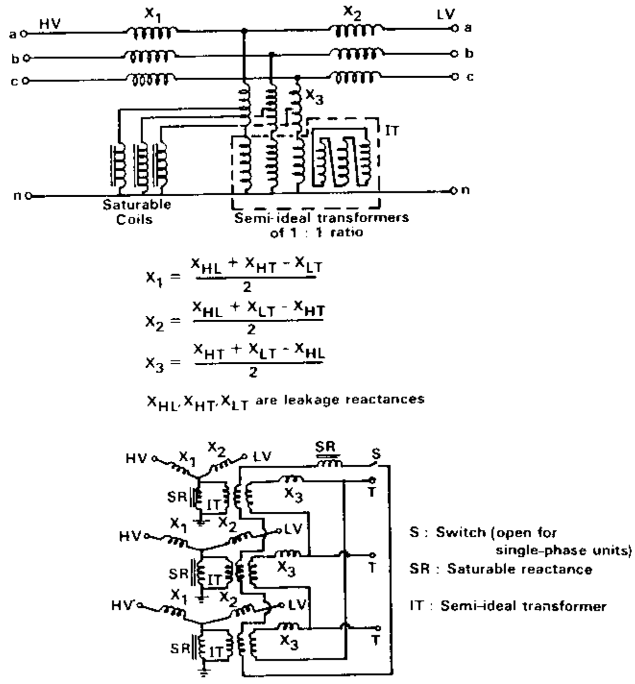


Fig. 4.17 TNA representation of an autotransformer

4.4.2.5 Capacitor Models

Physical models of capacitors in SVC capacitor banks consist of actual low loss capacitors of appropriate voltage rating for the simulator being employed.

Digital models of capacitors consist of the differential equation defining the voltage versus current characteristic.

4.4.2.6 Thyristor Valve Models

Physical models of thyristor valves generally consist of actual bidirectional thyristor pairs. The model thyristors must have a relatively negligible holding current compared with their full conduction current. Equivalent snubber circuits are modelled by passive components.

Gate turn-off (GTO) thyristor valves are beginning to be applied as self-commutated devices in SCC compensators. These valves are modelled either by small GTO thyristors or by field effect transistors (FET) which require simpler gate control circuits. Diodes are connected in series with the transistors to prevent reverse conduction.

Voltage drops across thyristors (1 volt), triacs (1 volt), and diodes (0.6 volts) are fairly constant. Field effect transistors (FET) exhibit an internal resistance of 0.1-1 ohm, resulting in a voltage drop proportional to current. In proportion to the physical model operating voltage, the thyristor valve model voltage drops are generally higher than those encountered in actual equipment. In addition, nonlinear thyristor valve models generate a small amount of harmonics which are negligible compared with the main harmonic generation of the TCR, TCT, SCC and LCC type SVCs. Despite these inaccuracies, the basic thyristor valve models are sufficiently accurate for most dynamic and transient SVC performance studies.

Improved models of thyristor valves employ electronic circuits for compensation of voltage drops across the basic thyristor valve models by means of a negative resistance. An example is given in fig. 4.18.

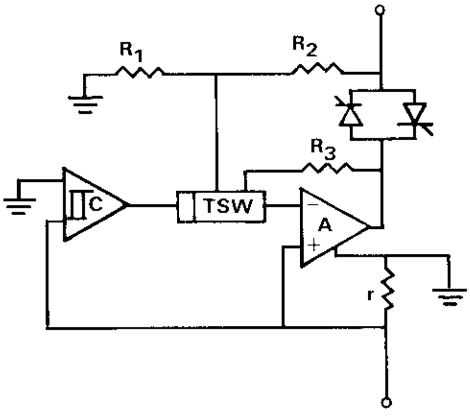


Fig. 4.18 Electronic circuit for compensation of thyristor voltage drop and reactive element losses

The operational amplifier provides the compensation voltage. The compensation is switched in or out depending on whether or not the thyristors are conducting. The same circuit also compensates for excessive losses in associated reactor or transformer windings because it functions as a negative resistance equal to $-R = r.\ (R_1 + R_2)/R_1$.

Other solutions might be adopted where electronic devices can be utilised as general purpose switches to represent AC breakers or thyristor valves. An example of a practical solution of this type is shown in fig. 4.19 where the power section of the device consisting of a diode bridge is fed by a controlled current source. A much smaller current flowing from the TNA meets the small forward voltage drop of the diode bridge given that the diodes are identical. While the control section may introduce some errors depending on the solution adopted, by utilising the internal control logic the current source can be properly started or stopped, closing or opening the switch provided.

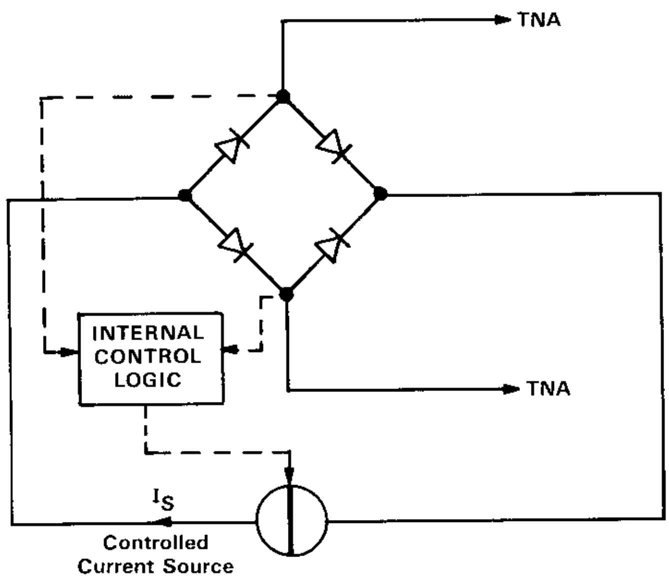


Fig. 4.19 General purpose electronic switch

This solution allows operation with very small current because there are no problems introduced by the holding current.

In digital simulations, thyristors can generally be modelled as ideal switches with appropriate controls. However, precautions must be taken in the modelling to avoid numerical oscillations around the current zeros. During digital simulation of thyristor commutation, the point of zero current will not normally fall on a time increment. This results in a current discontinuity which, in combination with a series inductance, can lead to numerical oscillations.

The numerical oscillation problem can be resolved by using self-adjusting time step techniques which can be costly in computing time or in at least two other ways by :

- improved physical modelling of the thyristor circuits. The most obvious improvement is the addition of snubber circuits. The RC time constant of the snubber circuit should be at least two time steps.
- "smoothing" the offending signals. In circuits involving inductors, the oscillations can be damped with the addition of a dissipative resistor across the inductor. The system would be critically damped if the resistor is sized so that $2L/Rt$ (t = **time step** size) is equal to unity.

4.4.2.7 Control Circuit Models

The SVC controls can be represented by the actual physical controls, by electronic or analogue equivalents of the controls, or by completely digital control models. Even with real time simulations, microprocessor technology permits accurate modelling of SVC controls almost entirely in software.

Actual SVC control modules, supplied by the manufacturer, can be interfaced with analogue simulators that operate in real-time. This is advantageous in the design and acceptance stages to assure that the actual controls operate properly for all system conditions and contingencies.

In the initial stages of analysis, it is beneficial to have a more general control system representation so that overall controller requirements can be evaluated for the system being studied. A digital control system representation provides the greatest degree of flexibility at this stage. The essential components of the control are described in the following sections (see fig. 4.20).

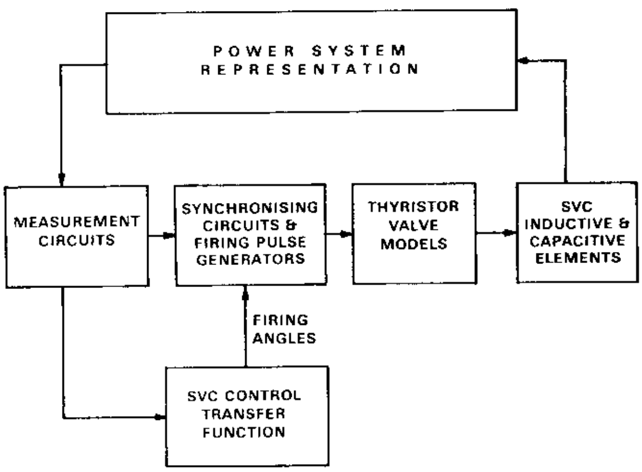


Fig. 4.20 Components of control circuit module

4.4.2.7.1 Measurement Circuits

The measurement circuits are required to provide the control system with the necessary input signals. The measurement circuits should be structured so that either individual phase or three-phase average signals can be used by the control. Important control signals include :

- individual phase and three-phase average voltages
- individual phase and three-phase average currents
- individual phase and three-phase average reactive power.

A block diagram giving an example of a flexible measurement circuit representation is given in fig.4.21. The signals shown as outputs in this figure can be inputs to analogue-to-digital (A/D) conversion circuits for digital control representations.

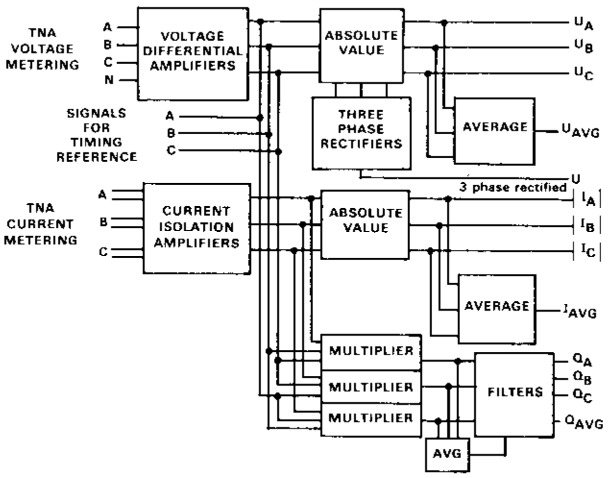


Fig. 4.21 Measurement circuits for general SVC control module

The measurement circuits are an integral part of the overall transfer function of the SVC control, usually including a low-pass filter for the input signals. This filter can be implemented in the measurement circuit hardware as variable RC filters, or in software as part of the overall transfer function.

Measurement circuits can be implemented for digital simulations in a similar manner. In this case it is easy to supply the control system with any power system quantity and to process it by the arithmetic/logic functions which the program must have to enable appropriate representation of controls.

4.4.2.7.2. Main Control Transfer Function

The overall control system characteristic can be represented as a transfer function which accepts one or more control variables as inputs from the power system and provides a signal proportional to the required compensation as an output. The control variables used and the transfer function will depend on the application. A generic control system model must be able to represent the important control system characteristics for any application. The output of the controller is a signal proportional to the total SVC susceptance. This is used by the "Gate Pulse Generator" circuits to generate actual firing pulses for the thyristors.

The primary requirements of a digital control system model are accuracy and flexibility. Z-transform techniques may be used to develop equivalent digital algorithms (difference equations) for analogue transfer functions. Errors can be introduced due to finite sampling time (alias frequencies in the response) and due to inaccuracy in representing the variables involved.

The sampling time which can be used depends on a number of factors :

- the time required to perform the multiplications and additions which make up the difference equation. Hardware to perform mathematical functions can increase the speed of these operations.
- the time required to perform additional control system functions. These include linearising the output of the transfer function, decoding the transfer function output into actual firing angles and switching commands, implementing current feedback loops, and implementing override control functions.
- the time required to sample the input signals. This depends primarily on the conversion speed and the multiplexing time of the A/D circuits being used.

Since the response time of the SVC controls is normally on the order of 1-2 cycles of the fundamental frequency and the controls must be able to respond to fast changes in the input signals, a sampling time of one millisecond or less is required to accurately simulate the SVC controls in real time.

In terms of flexibility, the control system model should have at least the following capabilities :

- simulation of multiple transfer functions for the main control according to transfer functions provided in Section 4.3.2
- operation with a variety of different input signals, as described above for the measurement circuits
- handling of various reactor and capacitor configurations, including both switched and controlled reactors, thyristor and breaker switched capacitors, and both 6-pulse and 12-pulse operation
- representation of special characteristics of SVC control systems; such as circuits for linearising the controller output when calculating firing angles, circuits for balancing positive and negative TCR current pulses, and circuits for override controls. All of these special circuits can have important effects during transient events.

The limitation of a generalised control system model is that it cannot represent all the details of the actual SVC controller supplied by the manufacturer. The generalised model is well suited for initial evaluation of control system requirements and SVC/power system interaction. Actual SVC controller is recommended for use in the final analysis especially if there are questions regarding the SVC performance.

In digital simulations, the control system representation is the same as described above, except there is no requirement for real time simulation. This allows the time step size to be specified independent of computation requirements.

4.4.2.7.3 Synchronising Circuits/Gate Pulse Generators

Synchronising circuits are required in the SVC control to provide reference signals for the gate pulse generators. This unit should generate and supply pulses to the valves in a correct relationship with the voltage across them so that :

- proper firing is achieved during transient conditions with distorted voltage waveforms to ensure satisfactory performance under such conditions,
- generation of non-characteristic harmonics is

minimised.

Synchronism with the network voltages can be achieved following different philosophies depending on the degree of reliance upon the actual system voltages that is adopted for generating pulses. Digital programme simulation of such control section is relatively simple because any type of synchronising and pulse generator system can, in principle, be modelled. General purpose analogue or hybrid controls are generally much less flexible in this respect. Nevertheless these models, whatever the philosophy on which they are based, should reflect the present state-of-the-art.

As an example, fig. 4.22 illustrates a general phase-locked loop circuit which can be used in SVC control models.

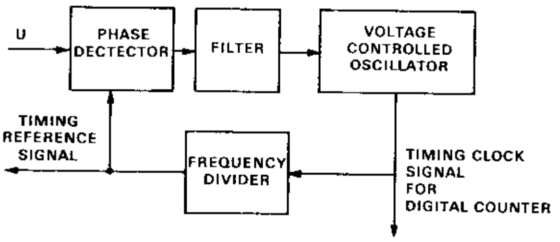


Fig. 4.22 General phase-locked loop model for digital control system representation

The phase-locked loop provides both a reference signal indicating the point of voltage zero crossing (fundamental frequency component only) and a timing signal phase-locked to the fundamental frequency for actually counting the desired firing angle. Counters are then used to actually generate the firing pulses.

4.5. MODELS FOR HARMONIC PERFORMANCE STUDIES

4.5.1 General Requirements and Assumptions

SVC and power system models for harmonic performance studies should permit the evaluation of the following system concerns and phenomena :

- voltage and current distortion and telephone interference, etc.
- interaction between the SVC components, the filters and the network
- filtering of harmonics.

Sufficiently accurate modelling to study many of these problems can be achieved with the following assumptions :

- the superposition principle can be applied to evaluate multiple harmonic sources
- the SVC harmonic generation characteristic can be represented by ideal zero, positive or negative sequence harmonic current sources with respect to the network
- a linear system representation can be used at each harmonic frequency
- accurate load representation may be required to obtain a realistic level of harmonic distortion for filter design.

4.5.2 Description of the Basic Model

The basic model of an SVC for harmonic performance studies consists of an ideal harmonic current source (single-phase or three-phase symmetrical) with a given current spectrum I_n. The magnitudes of the currents I_n and the order n of the harmonics are dependent on the type of SVC and its operating conditions. A typical harmonic current spectrum of a 6-pulse TCR is shown in fig. 4.23.

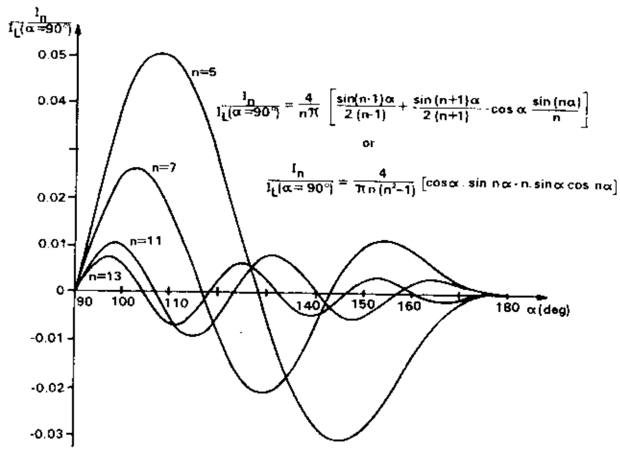


Fig. 4.23 Harmonic currents I_n of a 6-pulse TCR related to the firing angle and the maximum fundamental frequency reactive current I_L at full conduction (also see fig. 2.11)

Typical levels of characteristic harmonics for different SVC types, assuming balanced power system and symmetric ideal operating conditions for the SVC, are given in Section 5.5.2. These harmonic levels are obtained assuming a sinusoidal voltage source and no harmonic contribution from external sources.

Non-characteristic harmonics of the order (i.e. dc current, see Section 7.6), 2, 3, 4, 6, 9 and 12 can also occur due to asymmetry of SVC components such as reactors and step-down transformers, asymmetry of thyristor firing angles, or unbalances in the system voltages. The magnitude of the non-characteristic harmonics can be estimated if the unbalances are known. A range of typical values is given in fig. 4.24.

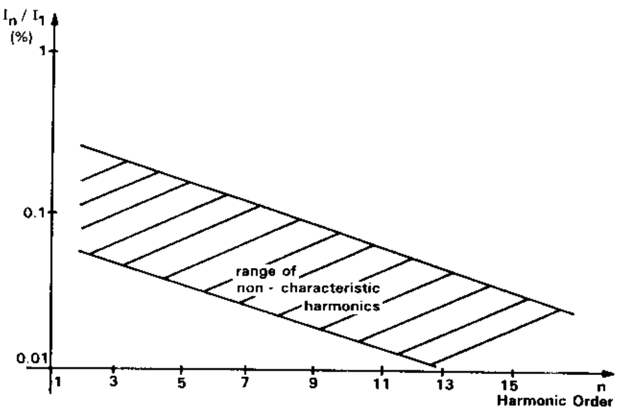


Fig. 4.24 Typical non-characteristic harmonics of TCR

The response of the power system to harmonics generated by the SVC depends on the order of harmonics and the system characteristics. The basic model of the power system consists of nodes and connecting elements (lines, transformers, shunts) as shown in fig. 4.25.

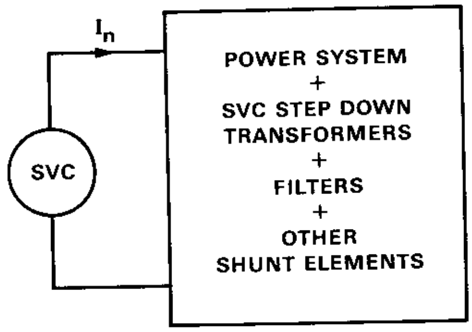
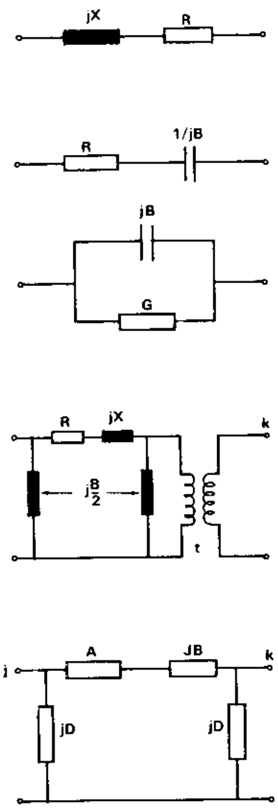


Fig. 4.25 Basic model for harmonic performance studies



Filter or Circuit Elements

$X = 2\pi f_1 nL$

f_1 = fundamental frequency

$B = 2\pi f_1 nC$

Transformer:

$X = X_\ell . n . U_n^2/S_n \quad X_\ell = 2\pi f_1 L$

$B = -I_e S_n/(U_n^2 . n)$

$R_1 = P_{cu} U_n^2/S_n = L/t_c$

t = Uni/Unk transformer turns ratio

X_ℓ transformer leakage reactance (p.u.)

I_e transformer magnetising current (p.u.)

P_{cu} transformer copper losses (p.u.)

S_n transformer MVA rating

U_n nominal voltage

R_o DC resistance

R_1 transformer resistance (pu) at fundamental frequency

t_c transformer leakage time constant from Fig. 4.27

Transmission Line

$A = R = f(n)$

$B = Z \sin(2\pi f_1 n\sqrt{LC})$

$D = (1/Z) \tan(\pi f_1 n\sqrt{LC})$

$Z = \sqrt{L/C}$

Fig. 4.26 Modelling of network elements for harmonic studies

Special attention must be paid to the proper modelling of lines, transformers, loads, and reactor impedances (losses), including appropriate frequency dependency. An example illustrating the frequency dependency of the time constant of the transformer leakage impedance is given in fig. 4.27.

Frequency dependent parameters for transmission line models can be obtained from standard data or computed by suitable programs based on the physical dimensions of transmission towers, conductor configuration and ground resistivity. Carson's equations can be used to determine the frequency dependence of the zero sequence parameters.

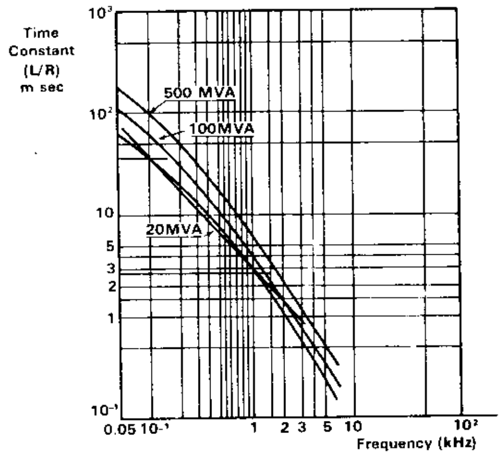


Fig. 4.27 Frequency dependence of time constant (L/R) of the leakage impedance of transformers (typical values, inductance assumed to be constant)

Generators are modelled by one port circuits with the subtransient, transient or synchronous reactance and resistance according to the study. TCRs other than the one under considerations can be modelled by a fixed shunt susceptance depending on their types and operating points. The capacitive part of the remote SVC has to be modelled by a constant capacitance.

If the harmonic performance has to be evaluated considering other harmonic sources beyond the SVC under consideration, these sources can be simultaneously applied to the network. The current source model can satisfactorily account for the behaviour of most of these harmonic sources such as HVDC links, industrial loads, and so forth. The phase angle displacement among the injected currents at different locations and for each harmonic order is an important parameter and different combinations of angles should be evaluated to verify the acceptability of the system harmonic levels. A conservative evaluation of system harmonic levels will be obtained if all harmonic sources are assumed to be in phase.

If multiple SVCs are present in the system, they can be represented simultanously by harmonic current sources, reasonably assuming that the waveshape of the current flowing in the harmonic producing components of the SVC is not altered by the rest of the system. Filters and capacitors of the SVCs have to be fully represented.

4.5.3 Extensions and Refinements to the Basic Model

Extension of the basic model should permit evaluation of interaction between the SVC, the control system, transformer saturation and the power system.

For this level of simulation, detailed models such as those described in Section 4.4. are required. In such cases either scaled extended models on a simulator such as a TNA or hybrid computer, or more accurate digital models, using step by step simulation in the time domain, should be employed.

CHAPTER 5

FUNCTIONAL SPECIFICATION OF STATIC VAR COMPENSATORS

5.1 INTRODUCTION

This chapter describes the preparation of a functional specification for an SVC satisfying the requirements of a particular power system application. Following the definition of technical requirements and subsequent studies confirming broad characteristics of the SVC, a functional specification, enabling a manufacturer to tender for the equipment, is required. In this chapter the information that needs to be included in the functional specification to ensure adequate information exchange between the supplier(s) and the utility is presented in detail. A successful information exchange is important for clear understanding of the technical requirements and for equitable assessment of the tenders.

The chapter is divided into four main sections, with:

- Section 5.2 describing the broad user requirements for the particular application within the network,
- Section 5.3 describing the detailed user specifications to define the SVC characteristics enabling the choice of the SVC type,
- Section 5.4 describing the information to be provided by the manufacturer to enable adequate adjudication of the tender,
- Section 5.5 describing relevant standards applicable to major SVC components and other useful information on SVC performance.

5.2 SPECIFICATION OF BROAD USER REQUIREMENTS AND SYSTEM DETAILS

In order to enable a manufacturer to offer the most suitable equipment, the broad requirements of the particular application, together with a description of the network particulars which would influence this choice, should be supplied to the SVC manufacturer.

5.2.1 Nature of the Particular SVC Application

The user should provide a clear statment of the particular problem the SVC is intended to solve. Clear definition of the intended application (transmission systems, industrial or HVDC) together with the problem area(s), namely,

- improvement of voltage regulation and control
- improving the balance of loading between individual phases
- power transfer capacity improvement
- transient stability performance enhancement
- system damping performance enhancement
- reduction of temporary overvoltages
- subsynchronous resonance damping improvement
- provision of reactive power to AC-DC converters.

will define the broad SVC control and capability requirements. As the intended application determines the performance and operating characteristics, detailed information about the envisaged role of the SVC, over a particular power system development period, will be very useful. In the following sections the specification of the SVC rating for the most common applications is described in detail. However, in load balancing and subsynchronous resonance damping applications the specification of rating may have to include special considerations and thus expressed in a different manner.

5.2.2 Characteristics of SVC Envisaged

5.2.2.1 Type of SVC

User preference for a particular type of SVC, for the envisaged application, with the reasons leading to this particular preference should be clearly communicated to the manufacturer.

5.2.2.2 Range of Controlled Reactive Power

The output of the SVC can be defined as follows as shown in fig. 5.1 :

a) At rated line to line voltage U_{rated}, the rated total reactive power output is defined as Q_{Lrated} in the inductive and Q_{Crated} in the capacitive range.

b) For the inductive range the maximum total reactive power output Q_{Lmax} occurs at the maximum voltage U_{max} and, for the capacitive range the minimum total reactive power output Q_{Cmin} occurs at the minimum voltage U_{min}.

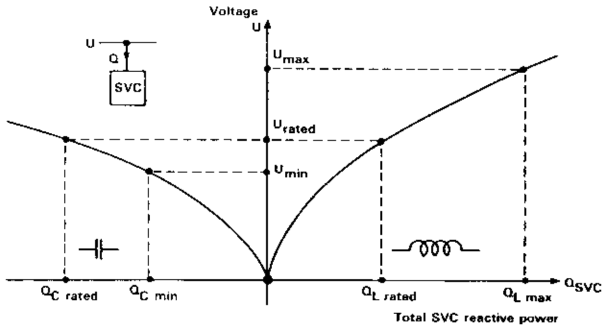


Fig. 5.1 Definition of the rated SVC output

On a fixed impedance basis the above mentioned SVC reactive power output quantities are related as follows :

$$Q_{Lrated} = Q_{Lmax}\left(\frac{U_{rated}}{U_{max}}\right)^2 \qquad Q_{Crated} = Q_{Cmin}\left(\frac{U_{rated}}{U_{min}}\right)^2$$

5.2.2.3 Utility Loss Evaluation Procedure

The cost of SVC losses incurred during the operation of the equipment on the system has a significant influence in determining the final cost of the SVC to the user. These losses need to be evaluated for the range of specific operating conditions envisaged for the SVC. For loss evaluation purposes, the SVC losses should therefore include the losses in individual components such as the transformer, reactor(s), capacitor(s), thyristor valves, cooling system and auxiliary equipment forming the particular SVC installation.

The basis for evaluating the SVC losses should be clearly stated by the user. Specification of the total SVC loss characteristic P_L as a function of tive power output does not allow optimisation of SVC design. The following method is preferred as it allows flexibility in optimising the SVC design and thus reducing the total SVC cost. The user may specify a stepwise SVC reactive power output duration characteristic $\Delta t_i = f(Q_i)$, over a given period $\Sigma \Delta t_i$

and the capitalised value K of the losses P_L. On this basis the cost of the total SVC losses P_L are calculated as :

$$\text{Cost of Losses} = K \frac{\sum P_L(Q_i, Q_k) \cdot \Delta t_i}{\sum \Delta t_i}$$

where $P_L(Q_i, Q_k)$ represent the average losses in the portion Q_i to Q_k SVC output range at nominal voltage and zero slope.

A typical loss curve for a TCR/TSC type SVC is given in fig. 5.2 as a function of SVC output. The horizontal dotted lines passing through points P_{LA}, P_{LB} and P_{LC} indicate the mean losses for SVC operation in the corresponding reactive output range. Thus, if the SVC operates for a time period of Δt_A in the reactive output range 'A', Δt_B in the reactive output range 'B' and Δt_C in the reactive output range 'C' then the cost of total SVC losses for the total time period are calculated as

$$\text{Cost of losses} = K. \frac{[P_{LA} \cdot \Delta t_A + P_{LB} \cdot \Delta t_B + P_{LC} \cdot \Delta t_C]}{(\Delta t_A + \Delta t_B + \Delta t_C)}$$

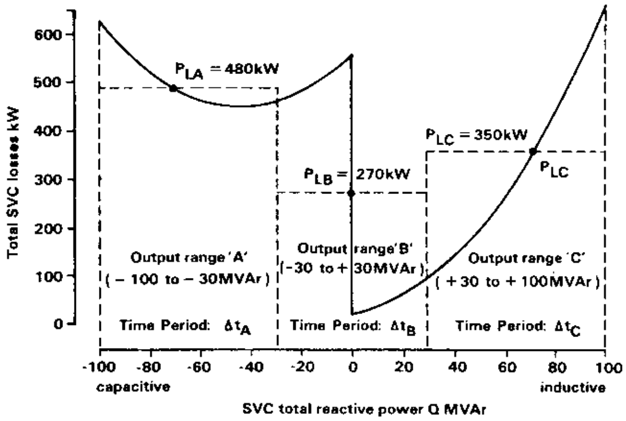


Fig. 5.2 Typical losses for a TCR/TSC type SVC of 100 MVar rated capacity both in the inductive and capacitive range

Applying the information presented in fig. 5.2 and assuming that $\Delta t_A = 0.2$ p.u., $\Delta t_B = 0.55$ p.u. and $\Delta t_C = 0.25$ p.u. representing the per unit periods of SVC operation in the output ranges A, B and C respectively then

$$\text{Total Cost of Losses} = K \frac{(480 \times 0.2 + 270 \times 0.55 + 350 \times 0.25)}{(0.2 + 0.55 + 0.25)}$$

with K expressed in a specific monetary unit per kW of SVC losses.

5.2.3 Network Details

The location and operating environment of the SVC within a network largely influences the design offered by the manufacturer. The essential and optional details of the network which should be supplied to the manufacturer, can be summarised as follows :

5.2.3.1 Network Characteristics at the Point of SVC Connection

- system configuration (single line diagram) including point of SVC connection
- nominal system voltage and frequency, range of deviations U_{max}, U_{min}, f_{max}, f_{min}, including magnitude and duration of such deviations
- voltage unbalance and magnitude of negative sequence voltage
- transient and temporary overvoltages, magnitude and duration (time characteristics)
- insulation level, overvoltage and existing surge arrester levels
- system grounding conditions
- method of line protection and autoreclosing applied
- existing and expected minimum and maximum three phase fault levels over as wide a period of network development as possible (including fault levels under envisaged abnormal system operating conditions under which the SVC may be required to operate).

Optional :

- system impedances as seen from the SVC location as a function of relevant frequencies (from fundamental to the highest relevant harmonic), to enable for the manufacturer to evaluate, filter and control system requirements
- existing or anticipated levels of harmonic voltage distortion and harmonic currents from other sources
- acceptable harmonic distortion levels.

5.2.3.2 Environmental Characteristics

- maximum and minimum temperatures
- altitude
- solar, snow and ice, humidity, wind, air pollution and seismic conditions
- acceptable audible noise and electromagnetic interference levels in and around the SVC installation.

5.2.3.3 Site Conditions and Method of Connection

- available site area, access and transport limitations
- auxiliary power available; voltage, frequency, and power rating with tolerances; ripple content for dc auxiliaries
- availability of cooling water and water drain facilities
- method of connection of the SVC to the system explained in detail by means of a single line diagram, showing the proposed connection to the transmission line, busbar, transformer secondary or tertiary winding.

5.3 SPECIFICATION OF STATIC VAR COMPENSATOR CHARACTERISTICS

The reactive power requirements for a given nominal rating can be met by various types of SVCs described in Chapter 2. However, each type of SVC possesses its own particular operating characteristics. To enable the suppliers to arrive at the most suitable SVC type and design to meet the particular need, the nominal rating, overload capability, control and dynamic performance, harmonic and specific equipment requirements need to be clearly stated. In this section, these characteristics are examined in detail for various types of SVCs currently available, together with factors influencing the choice of these characteristics.

5.3.1 SVC Characteristics

5.3.1.1 Definition of the SVC Type

If preference exists for certain type of SVC, detailed information should be given on :

- type and configuration of the SVC
- control mode for both continuously controlled and switched components.

5.3.1.2 Nominal Rating and Overload Capability

A static Var compensator (SVC) usually consists of a transformer connecting a combination of thyristor controlled, saturated or fixed reactors; fixed or thyristor switched capacitors; self or line commutated inverters to the power system.

Nominal rating and overload capability of an SVC are defined by a voltage-current characteristic, as seen from the point of connection of the SVC to the system, for example :

- primary side of the coupling transformer
- secondary side of the coupling transformer if the SVC is connected to a tertiary winding.

All other components, e.g. harmonic filters and other fixed unswitched inductive or capacitive components, associated with the SVC must be included, in deriving this characteristic, as they have an influence on the SVC rating.

The maximum allowable tolerance of the SVC output has to be specified by the user at nominal voltage, frequency and temperature or will be chosen by the manufacturer according to existing standards applicable to individual components of the SVC. When specifying the SVC output tolerances, it is important to note that individual component tolerances specified by International Electrical Commission (IEC) Standards are 0 to 10 % for capacitors and ± 5 % for reactors. The nominal ratings of the components (SVC transformer, reactors, capacitors and thyristors, etc.) will be determined by the manufacturer to meet the specification.

5.3.1.3 Nominal Rating and Overload Capability of Thyristor Switched Reactors (TSR), Thyristor Controlled Reactor (TCR), and Thyristor Switched Capacitor (TSC) Type SVCs

Rating for normal continuous operation for the thyristor switched or controlled types of SVCs can be defined as follows, and as shown in fig. 5.3 :

(a) at rated line-to-line voltage U_{rated} the rated total reactive power output in the

- inductive range :

$$Q_{Lrated} = \sqrt{3} \cdot U_{rated} \cdot I_{Lrated} = U^2_{rated} \cdot B_{Lrated}$$

- capacitive range :

$$Q_{Crated} = \sqrt{3} \cdot U_{rated} \cdot I_{Crated} = U^2_{rated} \cdot B_{Crated}$$

(b) at the maximum line-to-line voltage U_{max}, the maximum total reactive power output in the inductive range :

$$Q_{Lmax} = \sqrt{3} \cdot U_{max} \cdot I_{Lmax} = U^2_{max} \cdot B_{Lrated}$$

at the minimum line-to-line voltage U_{min} the minimum total reactive power output in the capacitive range :

$$Q_{Cmin} = \sqrt{3} \cdot U_{min} \cdot I_{Cmin} = U^2_{min} \cdot B_{Crated}$$

Given either U_{rated}, Q_{Lrated}, Q_{Crated} or U_{max}, Q_{Lmax}, U_{min}, Q_{Cmin} the nominal susceptances B_{Lrated} and B_{Crated} can be determined. The definitions (a) and (b) giving the SVC rating for normal continuous operation are equivalent.

The range of normal continuous operation is limited by the :

- maximum current I_{Cmax} in the capacitive range
- maximum current I_{Lmax} in the inductive range, as determined by the rating of the feeding transformer, the thyristor valves, etc.
- maximum and minimum values of the slope of the voltage control characteristic SL_{max} and SL_{min}
- maximum reference voltage $U_{ref\ max}$
- susceptances B_{Lmin} and B_{Crated}.

The SVC shall be designed to operate continuously anywhere within the shaded area of the voltage-current characteristic defined by these limits, as shown in fig. 5.3.

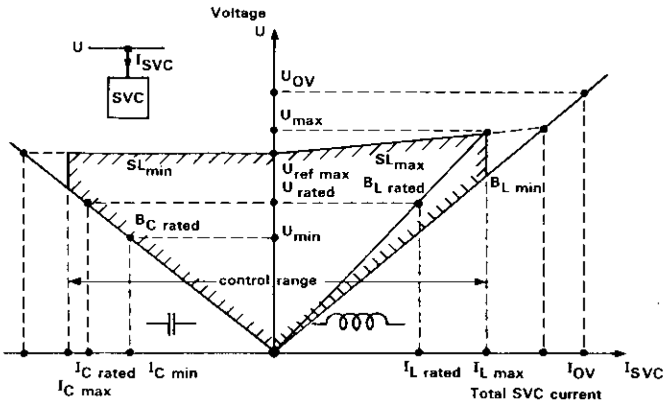


Fig. 5.3 Operating characteristics of TSR, TCR and TSC type SVCs

The overload capability can be defined only for the inductive range. In the uncontrolled region, the SVC voltage-current characteristic is determined by the minimum susceptance B_{Lmin} which can have a value lower than B_{Lrated}, depending upon the SVC rating.

The overload capability in the inductive range is defined by the :

- peak value of the maximum transient overvoltage U_{OVmax}
- RMS value of the maximum temporary overvoltage U_{OV}(RMS) (see fig. 5.3).
- magnitude versus time-duration characteristic of the overvoltage U_{OV}, which may be given as a stepwise linear function as shown in fig. 5.4 including the repetition rate of the overvoltage as it affects the accumulated thermal transients of the SVC equipment
- minimum susceptance B_{Lmin} (or equivalent I_{Lmin} at U_{OV} (RMS)).

When selecting the SVC characteristic, the following points have to be kept in mind :

- a high susceptance B_{Lmin} (i.e., low reactance) in the inductive range results in a higher transient overload capability, lower reactor costs and, higher magnitude harmonics under normal conditions

- the limitation of the current in the capacitive range I_{Cmax} results in capacitor and transformer savings.

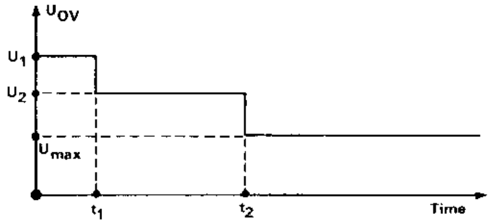


Fig. 5.4 Time-duration characteristic of the overvoltage U_{OV}

5.3.1.4 Nominal Rating and Overload Capability of Line-Commutated Convertor (LCC) and Self-Commutated Convertor (SCC) Type SVCs

The rating for normal continuous operation for these SVC types is defined as follows, and as shown in fig. 5.5. At rated line-to-line voltage U_{rated} and, line current I_{Lrated}, the rated total reactive power output in the :

- inductive range :

$$Q_{Lrated} = \sqrt{3} \cdot U_{rated} \cdot I_{Lrated}$$

- capacitive range :

$$Q_{Crated} = \sqrt{3} \cdot U_{rated} \cdot I_{Crated}$$

The voltages U_{max}, $U_{ref\ min}$, $U_{ref\ max}$ and the slopes SL_{min}, SL_{max} define the range of continuous operation for this type of SVC shown by the shaded area in fig. 5.5

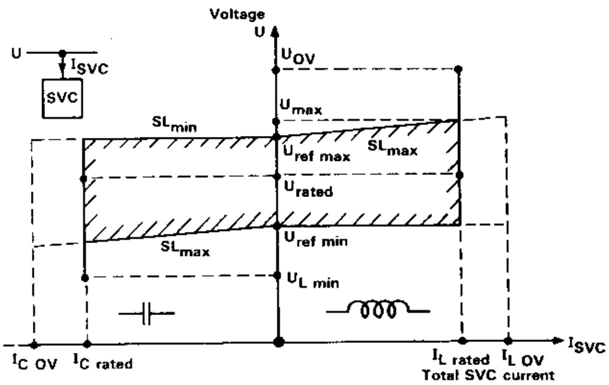


Fig. 5.5 Operating characteristics of SCC or LCC type SVCs

The overload capability is defined by $I_{L\ OV}$, $I_{C\ OV}$, $U_{L\ min}$ and the peak value of maximum transient overvoltage $U_{OV\ max}$. The duration of the overvoltage $U_{OV\ max}$ is time dependent as shown in fig. 5.4.

5.3.1.5 Nominal Rating and Overload Capability of Saturated Reactor (SR) Type SVCs

The rating for normal continuous operation for this type of SVC is defined as follows and as shown in fig. 5.6. Rated reactive power output in the :

- inductive range :

$Q_{Lrated} = \sqrt{3} \cdot U_{max} \cdot I_{Lrated}$ at maximum line-to-line voltage U_{max}

- capacitive range :

$Q_{Crated} = \sqrt{3} \cdot U_{min} \cdot I_{Crated}$ at minimum line-to-line voltage U_{min}

The reference voltages $U_{ref\ max}$, $U_{ref\ min}$ and the slope SL_{min} define the range of continuous operation for this type of SVC, as shown by the shaded area in fig. 5.6.

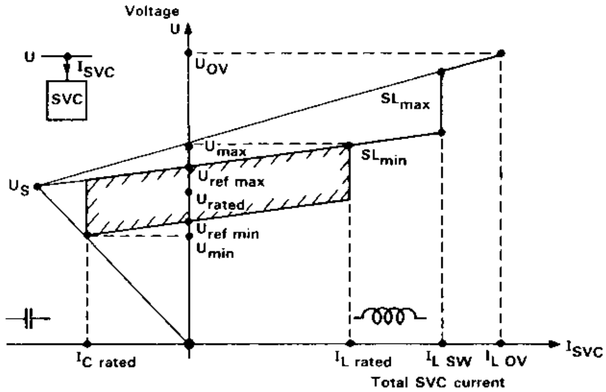


Fig. 5.6 Operating characteristics of SR

In the overload range, when the current exceeds the value I_{LSW}, the slope-correcting capacitor of the SR may be wholly or partly short-circuited by means of a protective device, e.g., spark gap or a non-linear resistor. The saturated reactor voltage-current characteristic thus has a maximum slope SL_{max} with an origin defined by the voltage U_S.
The permissible time duration of the overvoltage U_{OV} is determined by a magnitude versus time-duration characteristic shown in fig. 5.4.

5.3.2 SVC Control Characteristic

5.3.2.1 Modes of SVC Control

In specifying the mode of control for SVCs it is important to note that there are substantial differences between various types of SVCs.

Through the use of an external controller, active continuous or stepwise control of any SVC consisting of any combination of TSR, TCR, TSC, SCC, LCC, TCT and SR type SVC elements can be realised. Of the many types of SVC only the saturated reactor (SR) type has inherent control characteristics.

The structure of an active SVC control system is illustrated in fig. 5.7, which consists of the following modules :

- a measurement module (M) forming the SVC main control signal (voltage, current, reactive, etc.)
- an SVC control module (C) varying the SVC output according to the particular control requirements
- a supplementary control module (SC) bringing the additional control signals for performance enhancements such as damping and reactive power control.

Since the main and supplementary control signals and their processing by the SVC control system have a direct bearing on overall SVC performance, any control specification should indicate the facilities available or preferences for deriving these signals at a particular point(s), e.g., high voltage, low voltage or tertiary terminals of the SVC transformer.

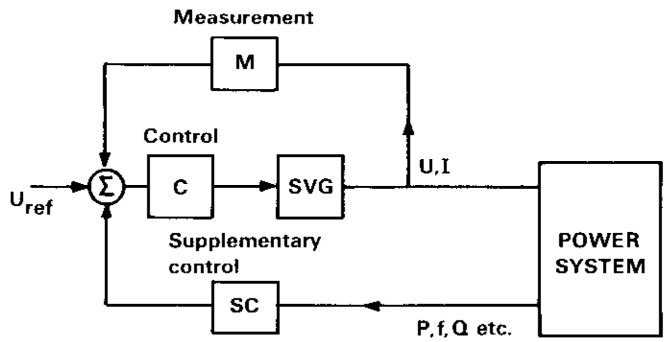


Fig. 5.7 SVC Control structure

Depending upon the design of the control modules, the SVC may perform the following individual and combined control functions.

- three-phase average or positive sequence voltage control based on
  * average magnitude
  * positive sequence voltages
- individual phase voltage control based on
  * individual phase voltages
  * positive and negative sequence voltages
  * negative sequence voltages (phase balancing).

By judicious use of supplementary control signals

- reactive power control based on reactive power measurements
- damping control based on active power, speed, frequency or phase angle change measurements

can also be obtained.

5.3.2.2 Static and Dynamic Characteristics of SVC Control System

The "static characteristic" of the SVC control is shown in fig. 5.8. This characteristic is defined by :

(i) the reference voltage U_{ref} at zero SVC current output as well as the maximum and minimum values of this reference voltage $U_{ref\ min}$ and $U_{ref\ max}$

(ii) the slope of the voltage control characteristic SL as well as the maximum and minimum values of the slope reactance SL_{max} and SL_{min}, where

$$SL = \frac{\Delta U \text{ (at rated current)}}{U_{rated}}$$

and the equivalent slope reactance X_{SL} within the SVC control range (i.e., on the base of the SVC rated reactive output) is given by :

$$X_{SL} = \frac{SL \cdot U_{rated}}{\sqrt{3} \cdot I_{rated}} \text{ ohms or } X_{SL} = SL \text{ in pu}$$

The SVC control range is defined by the maximum continuous inductive and capacitive currents (I_{Lmax}, I_{Cmax}) and the overall accuracy of the controlled voltage is within specified limits, usually expressed as a percentage (e.g., + 1%) using the nominal reference voltage as base voltage.

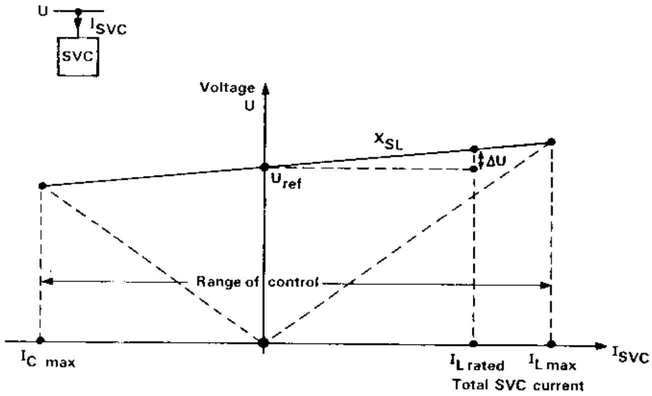


Fig. 5.8 Static control characteristic of an SVC

SVCs with stepwise control based upon TSC, TSR and combinations of these components possess a static characteristic with a bandwidth of ΔU_{ref}. The step size of the switched components should therefore be chosen such that the controlled voltage can be kept within the specified bandwidth, which should be based upon the users system voltage control criteria.

The "dynamic characteristics" of the SVC control system are defined by the SVC output change (i.e., SVC current, susceptance or corresponding controlled busbar voltage change) in response to a small step change in any control signal or quantity (e.g., reference voltage, reactive power, etc.) in the linear range of the SVC. Such a dynamic response characteristic is illustrated in fig. 5.9. This response can be specified by

- response time : time to achieve 90% of the excursion value of the output
- settling time : time to settle within ± 5 % of the final value
- maximum overshoot of the output.

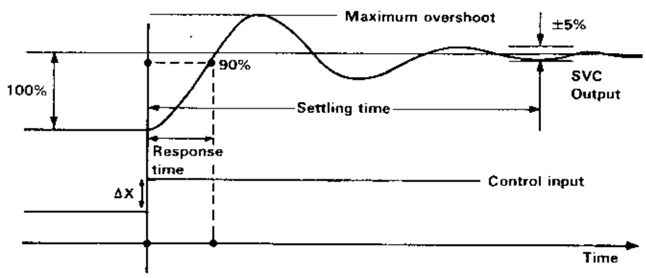


Fig. 5.9 SVC response to small step changes at the control input

The response should be determined for each control loop or module, e.g., a slower response can be expected from a supplementary reactive power control loop, than that obtainable from the main voltage control loop. The response time obtained is dependent upon the SVC operation conditions and network characteristics, i.e., system fault level at the SVC point of connection to the system. Therefore, either a minimum response time or several different response times based upon specific SVC and system operating conditions, should be specified. The response of the SVC to large disturbances cannot, in general, be specified, but certain control and switching actions may be blocked following system faults to prevent large swings in SVC output following fault clearance.

Preferences for remote and supervisory control facilities required should be given together with control co-ordination requirements. The latter is especially important in locations containing other reactive compensation installations in addition to the SVC. At such sites, requirements for master and slave control arrangements needs to be clearly indicated.

5.3.3 Harmonics

The magnitude of the SVC generated harmonics which can be tolerated can be specified based upon the following criteria.

- Individual voltage distortion factor (D_n) due to the n-th harmonic

$$D_n = U_n / U_{rated} \approx U_n / U_1$$

- Total voltage distortion factor ($D_{r.s.s}$)

$$D_{r.s.s.} = \frac{1}{U_1} \sqrt{\sum_{n=2}^{\infty} U_n^2} = \sqrt{\sum_{n=2}^{\infty} D_n^2}$$

- Maximum voltage deviation (D_{arith})

$$D_{arith} = \frac{1}{U_1} \sum_{n=2}^{\infty} U_n = \sum_{n=2}^{\infty} D_n$$

- Telephone influence factor (TIF)

$$TIF = \frac{1}{U_{rated}} \sqrt{\sum_{n=1}^{\infty} (K_n \cdot P_n \cdot \frac{U_n}{U_1})^2} = \sqrt{\frac{\sum_{n=1}^{\infty} (I_n \cdot W_n)^2}{I_{rated}}}$$

- Total harmonic current factor (IT)

$$IT = \sqrt{\sum_{n=1}^{\infty} (K_n \cdot P_n \cdot I_n)^2} = \sqrt{\sum_{n=1}^{\infty} (I_n \cdot W_n)^2}$$

where

U_{rated} = rated phase-to-neutral voltage (RMS)

I_{rated} = rated line current (RMS)

f_1 = fundamental (nominal) system frequency

n = harmonic order

U_n = harmonic voltage of order n and frequency $f = f_1 \cdot n$ (RMS, phase-to-neutral)

I_n = harmonic current of the order n and frequency $f = f_1 \cdot n$ (RMS, line current)

U_1 = fundamental frequency rated system voltage (RMS, phase-to-neutral)

K_n = coupling coefficient of the harmonic frequency given by $K_n = 5\ f = 5 \cdot f_1 \cdot n$

P_n = weighting factor of the n-th harmonic according to EEI/BTS guidelines (based on harmonic voltages)

W_n = weighting factor of the n-th harmonic according to EEI/BTS guidelines (based on harmonic currents)

The calculations of telephone influence factor (TIF) and total harmonic current factor (IT) are based upon weighting factors p_n according to the Editson Institute (EEI) and Bell Telephone System (BTS) guidelines which are mainly used by utilities employing 60 Hz systems. Similarly, interference definitions based upon International Consultative Commission of Telephone and Telegraph Systems (CCITT) are used by utilities employing 50 Hz systems. The CCITT define telephone harmonic form factor (THF) and equivalent disturbing current (EDC) as follows :

- Telephone harmonic form factor (THF)

$$THF = \sqrt{\Sigma (K_f \cdot P_f \cdot \frac{U_n}{U_1})^2}$$

- Equivalent disturbing current (EDC)

$$EDC = \sqrt{\Sigma (K_f \cdot p_f \cdot I_n)^2}$$

where

p_f = weighting factor of harmonic n according to CCITT guidelines

K_f = a factor which may take a value of $f_1 \cdot n/800$, 1 or $800/f_1 \cdot n$ depending upon the impedance of the AC network and the coupling between the power and the telephone lines

n, f_1, U_n, U_1 and I_n are as defined previously

Amongst the above factors the most commonly used at D_n and $D_{r.s.s}$. The typical limits adopted in specification of these factors are given in Section 5.5. An allowance, for defined network harmonics which may exist, should be made, for example, by specifying the addition of a certain percentage allowance to each SVC generated harmonic or by assuming that all harmonic source are in phase, so that some safety margin can be provided within the harmonic filter rating.

Although many utilities specify D_n, $D_{r.s.s}$ and D_{arith} limits in a consistent manner, there are no recommended limits on TIF, IT, THF and EDC for static compensator applications. However, the weighting factors applied are given in Section 5.5 and some utility practices in specifying these factors can be found in Chapter 8.

5.3.4 Equipment Characteristics

The SVC specification should provide information on the following :

- coupling transformer :
  * nominal primary and secondary (optional) voltage, number of taps and tap step sizes. (It must be understood that the specification of the secondary voltage of the coupling transformer may affect the cost of the SVC considerably).
  * type of cooling preferred, temperature levels, overload-time characteristic
  * insulation levels
  * preferred bank arrangement (single or three-phase banks)

- capacitors and filters :
  * insulating fluid, temperature levels, overload-time characteristic
  * insulation levels, permissible steady-state and transient overvoltages
  * protection, fusing (internal or external), grounding
  * frequency of switching, discharge resistors, reactors or transformers required

- thyristor valves :
  * special requirements which may affect the choice of triggering, insulation level, redundancy, safety margin, thyristor failure monitoring, thyristor cooling, etc.

- relevant standards for components of the compensator (see Section 5.5)
- permissible audible noise and electromagnetic interference levels
- earthquake standards (if applicable)
- space available for the SVC and the components
- distance to substation control room
- protection, alarm, and failure signals
- metering system : local or remote quantities to be metered
- reliability characteristics : availability required at partial and/or total reactive power output, spare equipment requirements
- testing and commissioning procedures, including factory and site tests (see Chapter 6)
- loss determination and evaluation method

5.4 SVC DESIGN INFORMATION TO BE PROVIDED BY THE TENDERER

The following SVC design and performance details should be provided by the tenderer to ensure adequate assessment of tenders.

5.4.1 SVC Layout

- nominal rating with tolerances and overload capability of the SVC
- nominal impedances and tolerances of all SVC components at nominal frequency and temperature
- single line diagram of the SVC, space requirements, physical layout
- method of energisation and starting, including the reactive power load change at the instant of starting (due to transformer inrush currents, etc.), shut down procedure
- method of protection against internal failures, external and internal overvoltages and overloads
- type of grounding (if any) on the primary and secondary side of the SVC transformer
- permissible voltage and frequency deviations
- auxiliary power supply : voltages, frequency, loads, tolerances
- cooling system required : type, rating, limits, pressure, secondary cooling system availability
- explanation of the considerations leading to the dimensioning of the major SVC components including the expected SVC and control system response
- earthquake safeguards
- maximum unbalance of components (transformers reactors, capacitors), i.e., maximum deviation of the reactances of the individual phases from the mean of the three-phases and, appropriate standards used
- loss characteristic :calculated total losses as a function of reactive power output at specified system voltage, no-load and on-load losses of the individual components including relevant standards used
- filter design criteria : permissible voltage distortion and frequency deviation, losses, level of external harmonics considered, detuning conditions, component redundancy included
- reliability characteristics of the SVC, spare parts and maintenance requirements to comply with required reliability and availability
- characteristics of the thyristor valve : method of cooling and triggering, insulation levels, thyristor redundancy, transient overload capability

5.4.2 SVC Performances

- harmonics generated by the SVC at a given loading and given network condition
- radio interference level and screening requirements (definition and measurement according to IEC - International Special Committee on Radio Interference CISPR publication 1)
- SVC response time at minimum and maximum system fault levels according to fig. 5.9
- range of the voltage setpoint variation (%)
- SVC response to large disturbances, e.g., three-phase short-circuits, load rejection, etc., including control strategies for large disturbances
- possible interaction with adjacent compensation systems, measures to prevent interaction
- overload var absorption capability (performance with and without transformer saturation under system overvoltage conditions where the transformer is part of the SVC equipment)

5.5 DESIGN STANDARDS AND HARMONIC PERFORMANCE LIMITS

At present there is no single national or international standard which specifically deals with static var compensators. The components forming the SVC are, however, designed according to recognised national and international standards which are listed in this section.

Typical worst case characteristic harmonic currents available from different types of SVC and harmonic performance factor limits/criteria adopted by various countries are also indicated.

5.5.1 Relevant Standards for Major Components

Insulation Co-Ordination

ANSI	C 92.1 - 1982
CSA/ACNOR	CAN3 - C308 - M80

Power Transformers and Reactors

IEC	Publ. 71-3 (1982), 722 (1982) (Impulse Testing)
CAS/ACNOR	CAN3 - C88 - M 1979
ANSI	C57.12.00 - 1979, C57.12.90 - 1973 C57.16 - 1958 (R1971), C57.21 - 1971
IEEE	STD 262A (1977) (SC Tests) STD 262B (1977) (Dielectric Tests)
NEMA	TRI TR98 - 1978
IEC/CEI	Publication 76 (1976) (being revised) Publications 76-1 to 76-5 (1976) Publications 289 (1968) Publication 354 (1972)

Power Capacitors

CSA/ACNOR	C155 - 1975
ANSI/IEEE	STD 18 - 1980, C55-2 - 1973
NEMA	CP1 - 1976
CEI/IEC	Publication 70 (1967) Publication 143 (1972) Document 33 (BC) 55 (testing of capacitors with internal fuses)

Thyristors

ANSI	C34.2 - 1968 (R 1973)

CEI/IEC	Publication 146 (1973), Publication 147
CEI/IEC	Publication 700 (testing of semiconductor valves for high-voltage d.c. power transmission)
IEEE draft	IEEE guide for specification on HVDC thyristor valve testing

Control Systems

ANSI	C83-98, C83-107, C85-1 - 1963

General Definition of Terms

IEEE	STD 100 - 1977

Radio Interference

IEC	CISPR Publication 1 (1972)

Harmonic Distortion

IEEE	STD 519 - 1981

5.5.2 Typical Worst Case Characteristic Harmonic Currents for Symmetric Operation, Ideal Source No Harmonic Contribution from External Sources

Note : Generally, maximum amplitude of each harmonic will not be obtained at the same SVC operating point. IT_{max} has been calculated assuming maximum amplitude of each harmonic

Harmonic Order	Saturated Reactor (1)	(2)	Thyristor Controlled Reactor (6-pulse)	Thyristor Controlled Reactor (12-pulse)	Sequentially Controlled Reactor Two 6-pulse units
5	-	-	5%	-	2.5%
7	-	-	2.5%	-	1.25%
11	-	2%	1%	1%	0.5%
13	-	3%	0.7%	0.7%	0.35%
17	2%	-	0.4%	-	0.2%
19	3%	-	0.3%	-	0.15%
IT_{max}/I_{rated}	2%	-	.49%	.38%	.25%

(1) Treble-tripler
(2) Twin-tripler

Rating:
TCR: $I_{rated} = Q_{L\ rated} / \sqrt{3}\, U_{rated}$ SR: $I_{rated} = I_{max}$

5.5.3 Existing Harmonic Distortion Limits (Status 1982)

Normally one compensator, depending on the voltage level

	D_n	D_{rss}	D_{arith}	TIF	IT
Australia*	1% (odd) 0.5% (even)	1.5%	-	-	-
U.K.	1%	1.5%	2.5%	-	-
Sweden	0.7%	1%	-	-	-
Finland	1%	1.5%	-	-	-
USSR	-	5%	-	-	-
France (EdF)	1% (odd) 0.6% (even)	1.6%	-	-	-
Brazil (Chesf)	1% (odd) 0.6% (even)	1.5%	-	25	10,000
Canada					
New Brunswick	1%	-	4%	20	25,000
Hydro-Quebec	1%	-	4%	20	25,000
Manitoba Hydro	-	-	4%	25	50,000
BC Hydro	-	-	2%	50	-
USA					
AEP**	1%	4%	-	-	-
BPA	-	-	2%	15-20	5000-50000
South Africa	1%	3%	-	-	-

* Limits are specified for total distortion from all sources
** Guidelines currently being revised

5.5.4 Harmonic Weighting Factors

(See publ. 60-68, Edison Electric Institute and CCITT directives and IEEE Standard 519 - 1981)

Order n of Harmonic	Weighting Factor p_n (EEI/BTS)	Weighting Factor p_f (CCITT)	Weighting Factor W_n (EEI)
1	0.007	0.71	0.5
5	0.15	178	225
7	0.31	376	650
11	0.685	733	2260
13	0.862	851	3360
17	1.0	1035	5100
19	0.988	1109	5630
23	0.923	1035	6370
25	0.891	977	6680
29	0.841	881	7320
31	0.841	842	7820
35	0.841	775	8830

5.5.5 Harmonic Impedance Characteristics of Power Systems

Knowledge of the network impedances as a function of frequency Z(f) at the point of SVC connection is required for filter design and control system layout. As these characteristics are not always known, the following assumptions may be useful. The network impedance at a given frequency can be presumed to have any value within a circle in the complex impedance plane as shown in fig. 5.10. Typical values for R_2 and θ are 200 - 1000 ohms, and 75 - 80 degrees, respectively. R_1 represents the minimum value of network resistance.

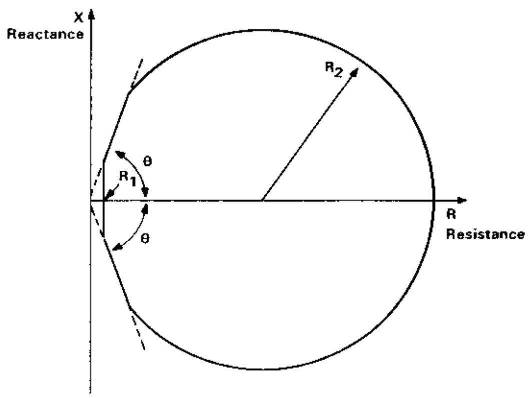


Fig. 5.10 Definition of network impedance characteristics at the point of SVC connection

For low order harmonics the impedance Z(f) is inductive. Z(f) can therefore be presented by a straight line as shown in fig. 5.11, where $Z(f_1)$ is the fundamental frequency network impedance corresponding to the fault MVA infeed at the point of SVC connection.

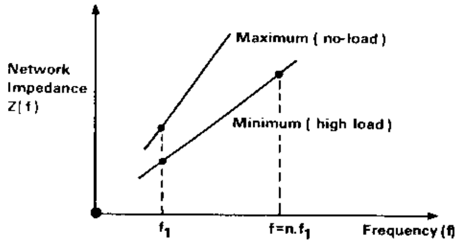


Fig. 5.11 Network impedance characteristics as a function of harmonic frequencies

In addition to the above considerations the existing harmonic distortion of network voltages has to be taken into account in the filter design and overall evaluation of SVC harmonics.

CHAPTER 6

GUIDELINES FOR TESTING OF STATIC VAR COMPENSATORS

6.1 INTRODUCTION

At present there is no single national or international standard which is specifically applicable to the manufacture and testing of static var compensators. Therefore only the standards applicable to the manufacture and testing of major components forming the SVC equipment have been used, in absence of a unique standard. Absence of a standard also meant that tests to establish the performance of the SVC equipment had to be specified and agreed between manufacturers and utilities on an individual installation basis. In this chapter, guidelines for testing both the major components and the total SVC installations based upon experience obtained with the SVC installations, to date, are provided. In providing these guidelines, it is assumed that for the manufacture and testing of minor components appropriate standards have been applied.

Two distinct sets of tests are recognised as necessary for static var compensators, namely, factory and site tests. For factory tests, guidelines are given for testing the major components or groups of SVC components. These tests can be carried out at the factory or at a test station equipped with appropriate facilities. For the site tests, guidelines on both commissioning and acceptance tests are provided.

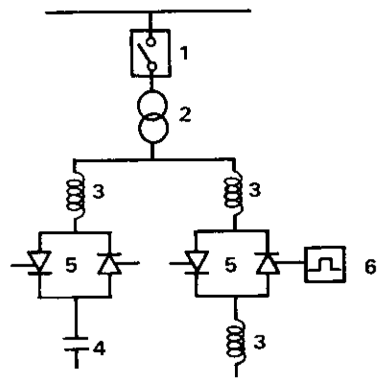
Throughout this chapter reference to the appropriate International Electrotechnical Commission (IEC) standards is made. For certain tests which are specific to certain types of SVC equipment not covered by IEC standards,but essential in determining equipment compliance with the specification, guidelines on the testing techniques adopted are also provided. In addition, the need for adequate testing of control, protection and monitoring equipment in both the factory and at site is recognised by providing appropriate guidelines.

6.2. FACTORY TESTS

In this section guidelines for testing different types of SVCs at the factory or at an appropriately equipped test station are described. These tests are designed to verify the performance of individual SVC components prior to shipment to the site and are classified as type or routine tests (see Section 9.6).

6.2.1 Factory Tests for Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR) and Thyristor Switched Capacitor (TSC) Type SVCs

The major components forming a TCR/TSR/TSC type SVC installation are shown in fig. 6.1.



1. Circuit breaker - 2. Transformer - 3. Reactor
4. Capacitor - 5. Thyristor valve - 6. Control and protection

Fig. 6.1 Major components of TCR, TSR and TSC type SVCs

6.2.1.1 Circuit Breaker

Type and routine tests according to IEC Publication 56.

6.2.1.2 Transformer

Type and routine tests according to IEC Publication 76.

6.2.1.3 Reactor

Type and routine tests according to IEC Publication 289.

6.2.1.4. Capacitor

Type and routine tests according to IEC Publication 70.

6.2.1.5 Thyristor Valve

The voltage and current stresses likely to be experienced by thyristor valves employed in various types of SVC installations have been briefly described in Chapter 2 (see Sections 2.5 and 2.6). The valve design will need to take full account of the likely stresses. The compliance of the valve design and manufacture with the performance specification can only be determined through the appropriate tests.

Currently there is no single national or international standard applicable to the testing of thyristor valves for TCR/TSR/TSC or other types of SVC installations. Thus in the absence of such a standard for the type and routine testing of such valves, applicable parts of IEC Publications 700, 71, 146 and 147 have been utilised. Due to significant differences between the SVC applications and the HVDC applications for which the IEC Publication 700 has been originally prepared, in many cases agreement between the manufacturer and utility had to be reached in the specific interpretation of the applicable tests. Therefore, the following suggested guidelines are indicative of what has been included in different specifications based upon the experience gained.

In recognition of the urgent need for a single international standard CIGRE Study Committee 14 Working Group 14-01 is currently reviewing both the SVC and HVDC applications with a view to making the appropriate recommendations available to IEC, as soon as possible. In view of this, the reader is requested to follow the progress of this work and take particular note of its conclusions. This item would then need to be revised based upon the conclusions of the WG 14-01 work.

6.2.1.5.1 High Voltage Insulation Tests on the Thyristor Valve Structure or Valve Base

For these tests, which are recommended as type tests, individual thyristors are short circuited prior to the test. The principal objectives of these tests are :

(a) to test for absence of disruptive discharge in the insulation of the valve base, cooling ducts, light guides and other insulating parts of the pulse transmission and distribution systems at the maximum test voltage,

(b) to verify that the partial discharge inception and extinction voltages are above the maximum operating voltage appearing on the valve base.

If the tests specified by the utility are found to be inappropriate by virtue of the valve design offered by the manufacturer, consideration should be given to alternative tests by which the above principal objectives may be met. Such alternative tests should be agreed between the utility and the manufacturer. Depending upon the application, it may be possible to eliminate some of the following tests on the valve base, subject to agreement.

For a three-phase valve :

- valve structure switching impulse withstand voltage test of individual phases to earth and between phases according to IEC Publication 71 and 60-2
- valve base lightning impulse test according to IEC Publication 71 and 60-2. It is usual to impulse test with 3 positive and 3 negative pulses of 1.2/50 µs waveform.
- valve structure power frequency withstand voltage test (for 1 minute) according to IEC Publication 71.

For a single-phase valve :

- valve base AC power frequency voltage test according to IEC Publication 700 power frequency, 1 minute duration
- valve base DC voltage test according to IEC Publication 700, 1 minute duration. This test is applicable only to TSC valves with trickle charge operation.

6.2.1.5.2 High Voltage Tests on the Main Thyristor Valve Circuits and Valve Terminals

The principal objectives of these tests, recommended as type tests, are :

(a) to determine how many electrical components in the thyristor string and associated circuitry fail during the test, if any,

(b) to test the absence of disruptive discharge in the insulation of the valve structure, cooling ducts, light guides, and other insulating parts of the pulse distribution and transmission systems at the maximum test voltage,

(c) to verify that the partial discharge inception and extinction voltages are above the maximum repetitive operating voltage,

(d) to demonstrate, in part, the immunity of the valvalve unit control to electromagnetic interference arising from within the valve and from outside the valve, unless the immunity can be adequately demonstrated by another test.

It is important to note that the individual thyristors are not short-circuited for these tests, the details of which need to be agreed between the utility and the manufacturer, as they depend upon the particular valve design. It may be possible to omit certain insulation tests, for example, the requirements for a valve DC voltage test may be waived or the possibility of disconnecting the individual thyristor voltage breakover type protection devices may be discussed.

These tests include :

- AC and DC voltage tests between valve terminals
- high voltage AC power frequency and impulse withstand tests on the main circuits of thyristor valves, with the protection facilities included in the SVC control system fully operational (active) or inhibited (passive).

The voltage tests between valve terminals are carried out according to IEC Publication 700 and include :

- AC power frequency voltage test
- DC voltage test which is applicable only to TSC valves with trickle charge operation.

For the purposes of these tests it may be sufficient to test only one phase of a three-phase valve with the other two phases at earth potential.

In order to ensure that the valve design includes sufficient margin above the protective level, high voltage power frequency and switching impulse voltage tests are carried out on each phase of a valve with the other two phases at earth potential and with protection circuitry (whether by control or by passive elements such as ZnO arresters) disconnected. These tests are carried out according to IEC Publication 700. However, care needs to be taken to adjust the duration of the power frequency tests in accordance with the damping (snubber) circuit design across the thyristors. Under high voltage power frequency test conditions, losses incurred in these circuits can be excessive, especially in the circuits for TSC valves which may cause damage to snubber circuits.

In valve designs, where protection forms part of the control system, impulse voltage tests are carried out to ensure correct operation of the protection system around the specified voltage level. Thus with the protection provided by the control system fully operational (active) it is usual to apply three pulses each of positive and negative polarity with the waveform 250/2500 µs for this test. In order not to exceed the rate of rise of valve current (di/dt) permissible for the valve, it is recommended that a series reactor as shown in fig. 6.2 is used in the impulse voltage tests where the protection provided by the control system is active.

In relation to the above-mentioned tests it is worthy to indicate that the standard switching impulse voltage waveshapes, commonly used for testing power system equipment, may represent much greater stresses during tests than those that can arise for the TCR/TSR/TSC type SVC equipment in service. By adhering to standard switching impulse voltage waveshapes, the utility may in some cases incur extra costs, depending upon the valve design. Standard waveshapes may not be generally appropriate for testing of certain valve designs. The relatively low impedance of such valves may prevent steep fronted voltage surges from appearing accross the valve under operational conditions. Such a low impedance may mean that, even if a standard lightning impulse is specified, it may be impossible to apply such an impulse across the valve while maintaining a sufficiently high surge generator impedance to limit valve stresses to realistic values. It is thus usual to impulse test such valves with three pulses each of positive and negative polarity with waveforms in the 20/200 µs to 250/2500 µs range.

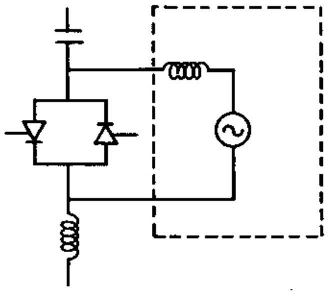


Fig. 6.2 Use of additional series reactor to limit di/dt during impulse voltage testing with protection provided by control system fully operational

6.2.1.5.3 Short-Time Withstand Current Tests

These tests, recommended as type tests, are to check the integrity of electrical connections forming the valve. In cases where valve frames are part of the valve design, an optional test for mechanical structure integrity is also recommended to verify that mechanical components do not suffer sustained deformation and the specified temperature as well as noise levels are not exceeded.

The short-time current tests are carried out by applying a power frequency AC current, according to a defined characteristic, to :

- the main busbars of the valve structure with the thyristors short-circuited
- the earthing device on the valve structure (if not insulated).

In each of the above tests the waveform of the current applied is recorded such that the current peak reached (usually expressed as an equivalent rms current for 't' seconds) can be analysed. The shape of the current characteristic is agreed between the manufacturer and the utility according to the duty cycle of the valve.

6.2.1.5.4 Periodic Firing and Extinction Tests

These tests, recommended as type tests, are carried out according to IEC Publication 700 typically for a duration of 30 minutes.

The principal objectives of the periodic firing and extinction tests are to check the adequacy of the thyristors and associated electrical circuits with regard to current, voltage and temperature stresses on the thyristors at turn-on under the worst repetitive stress conditions.

The tests may be performed on either the complete valve or on valve modules. The choice depends mainly upon the valve design and the test facilities available.

6.2.1.5.5 Non-Periodic Firing Test

The principal objectives of the non-periodic firing test are to check the adequacy of the thyristors with regard to di/dt stresses on the thyristors at turn-on under non-repetitive stress conditions.

The tests may be performed on either a complete valve or on modules depending upon valve design and test facilities available.

If the test is performed on modules, the equivalence of these module tests in respect of tests on a complete valve, will need to be adequately demonstrated. These tests are recommended as a type test.

For TSC valves protected by ZnO arrester, with current commutation from arrester to the valve when the arrester is conducting, the test should be performed at thyristor normal operating temperature. The time duration of the test is dependent on SVC circuit design and should be agreed between the utility and the manufacturer.

6.2.1.5.6 Fault Current Test

The principal objectives of the test are to demonstrate that the design of the thyristors, thermal design of the thyristor heat sink assembly and current sharing, if parallel connected thyristors are used, is adequate for the stresses occurring on the thyristor valve during short-circuit under the most onerous specified conditions.

The test is recommended as a type test which is usually carried out on thyristor valve modules. The test is carried out by injecting AC power frequency current of the appropriate magnitude agreed between the manufacturer and the utility.

6.2.1.5.7 Tests for Determining the Electrical Losses of a Complete Thyristor Valve

This test, recommended as a type test, is carried out according to IEC Publication 700. The losses as a function of rated current and no load losses are determined as follows :

- Conducting-State Losses up to Rated Current

For this test, a low voltage sinusoidal power frequency test source is used. By varying the valve conduction angle the valve current is varied from zero to rated current observing steady-state temperatures at each current level. Measurements at, at least four levels of current are recommended with the following quantities recorded at each current level :

Applied Voltage	Ambient Temperature
Valve Current	Cooling Medium Flow
Wattmetric Losses	Cooling Medium Temperature Rise

to enable full assessment of electrical losses.

If the loss determination is carried out by the calorimetric method, as is often the case with air cooling of the valve, then the valve should be insulated from the surroundings.

- No-Load Losses

The no-load losses are measured by applying rated power frequency voltage across the valve, with the firing angle (α) adjusted to 180 degrees. The applied voltage, the valve current and wattmetric losses are recorded. Since the no-load losses of the thyristor valves are very small, e.g. in the order 2-5 kW per valve, wattmeter readings may be difficult to evaluate and therefore unreliable. Thus it may be necessary to assess losses from recordings of current and voltage.

If valve losses at any firing angle (α) between 90 degrees and 180 degrees are of interest, these losses can only be accurately obtained either by calculation from recorded voltage and current or by calorimetric measurements.

6.2.1.5.8 Temperature Rise Test

This test, recommended as a type test, is carried out according to IEC Publication 700 to verify the compliance of thyristor junction temperatures with specification.

The thyristor valve is loaded with sinusoidal maximum current and the case temperature is measured on thyristors mounted in the position closest to outgoing cooling medium. The temperature to be measured with thermocouples on the thyristor casing. The following quantities are recorded :

Test Current
Incoming Cooling Medium Temperature
Temperature Rise
Ambient Temperature
Cooling Medium Flow

6.2.1.5.9 Cooling System Test

This test is recommended as a routine test to verify the integrity of the cooling system. It is especially relevant to liquid cooling systems (e.g., water, oil or glycol). A pressure test on the valve cooling system is carried out to ensure that no leakage or coolant droplets are detected on the valve. For this test, a test pressure of 10 bar or not less than 50% above the cooling system working pressure including the pressure surge for a 24 hour duration is generally recommended.

6.2.1.5.10 Insulation Tests on Auxiliary Circuits Built into the Valve

This is a recommended routine test which is carried out according to IEC Publications 255-5 and 245-2. It is usual to apply a 2.5 kVrms power frequency test voltage of 1 minute duration between auxiliary circuits and earth potential. Absence of flashover (s), insulation breakdown or thyristor failures indicates the integrity of the auxiliary circuit insulation used.

6.2.1.5.11 Voltage Distribution Along Series Connected Thyristors within a Valve

This is a recommended routine test to check the grading circuit parameters and thereby ensure that the voltage division between the series connected thyristors will be correct.

As a guideline, the voltage division between the series connected thyristors in steady-state should not deviate more than 5-10% from the mean value. A power frequency test should be performed for testing the damping (snubber) circuits. For DC testing, the voltage division figure obtained is dependent on the valve design, i.e., leakage current of the thyristors, presence of DC voltage sharing resistors, etc. In the former case the test must be performed at different temperatures.

6.2.1.5.12 Continuous Current Test

This is a recommended routine test to verify correct operation of the valve at continuous current. For the test, a low voltage power frequency source is used and the valve is operated at rated current for about 30 minutes to one hour.

6.2.1.5.13 Overcurrent Test

This is a recommended routine test to verify that the valve remains controllable for the specified load/overload current duty cycle. A test set up, similar to that used for the continuous current test, is used.

6.2.1.5.14 Mechanical Integrity Test

This is a recommended routine test for certain valve designs to verify that the mechanical arrangement provided to ensure correct contact pressure, is functioning within design tolerances.

6.2.1.5.15 Ancillary Electrical Checks

The following checks are found valuable in ensuring integrity of valve circuits prior to valve energisation :

- Check the off-state and reverse blocking voltage of each thyristor pair. It is recommended to test at rated power frequency voltage, for 1 minute.
- Check the voltage grading circuit. It is usual to test with a power frequency AC voltage of the order of 1000 volts, and monitoring the grading circuit current.
- Check all monitoring circuits for functional operation (pre-warning and alarm).
- Check that all of the thyristors turn on correctly in response to a firing signal.

6.2.1.6 Control and Protection System

It is recommended that the components forming the protection and control system are type and routine tested according to IEC Publications 146 and 147.

6.2.2 Factory Tests for Saturated Reactor (SR) Type SVCs

In this section, only the tests on saturated reactor units are described. Tests on other SVC components are carried out according to the appropriate standards described elsewhere in this chapter.

If due to the large size of the reactor it is not possible to achieve the rated current value (I_{Lrated}, see fig. 5.6) in the test facility, then the appropriate tests should be carried out at the site.

6.2.2.1 Routine Tests

For these tests the mesh loading of the SR is adjusted for satisfactory harmonic compensation by setting the mesh reactor tap to the preferred position. Appropriate amount of shunt capacitance is connected to the primary terminals to minimise the harmonic distortion of the supply voltage. The following routine tests are then carried out.

(i) Winding Resistance Test

The resistance of each phase of the main reactor is measured.

(ii) Magnetising Characteristics

The SVC line current is increased in as small steps as possible, up to at least the rated current, to obtain a plot of line voltage against line current at the supply frequency. The line current step changes should not exceed 15% of the SVC rated current.

(iii) Electrical Losses

The power losses are measured up to the rated current at ambient temperature and rated supply frequency.

(iv) Harmonic Content of Line Current

The harmonic content of line current is measured at approximately 25%, 50%, 75% and 100% of rated current to evaluate the harmonics due to the SVC. Oscillographic record of line current, mesh winding current and supply voltage waveform is made to support the analysis.

(v) Overvoltage Test

A three-phase voltage of three times the supply frequency voltage magnitude is applied to the line terminals (neutral terminals linked and floating) with the supply neutral earthed according to shunt reactor test standards (IEC 289).

(vi) Pressure Test

The appropriate supply frequency voltage is applied according to shunt reactor test standards (IEC 289) between HV windings, with other windings earthed. The test is repeated for the mesh windings by applying the appropriate voltage with other windings earthed.

(vii) Impulse Test

An appropriate magnitude of impulse voltage is applied according to shunt reactor test standards (IEC 289) on each phase terminal with the other two phases earthed and the neutral floating.

(viii) Noise Test

These tests are carried out according to the details agreed between the utility and the manufacturer. It is usual to carry out tests at approximately 10% and 100% rated current.

(ix) Insulation Resistance Tests

The insulation resistance is measured and the average oil temperature recorded for the reactor main windings, mesh reactor windings and current transformer windings with all other windings earthed in each case.

(x) Overvoltage Tests

Supply frequency voltage of 2.5 kV to earth is applied to test current transformer secondaries. Similarly, frame to core, frame to earth, and core to earth tests are carried out at 4 kV d.c. if possible.

6.2.1.7.2 Type Tests

These tests can be summarised as follows :

(i) Temperature Rise Test

The temperature rise test is usually carried out as nearly as possible in accordance with the standards. The test procedure is agreed between the utility and the manufacturer taking account of the facilities available for close adjustement of operating conditions during the test.

(ii) Impulse Test

The routine impulse tests previously described can be carried out as a type test in a similar manner but with a chopped wave test included, if required.

(iii) Cooler Noise Level Test

The test are carried out with all fans operating to establish compliance with specified standards.

(iv) Cooler Losses Test

The power losses of coolers with all pumps and fans in operation at rated voltage is measured.

6.2.3 Factory Tests for Self-Commutated Converter (SCC) and Line-Commutated Converter (LCC) Type SVCs

The self or line-commutated converter type SVCs are relatively new and as yet have not been widely applied. Thus, currently, there is no single national or international standard applicable to testing these SVCs. For the testing of the converter itself applicable parts of IEC Publications 146, 146-2 and 700 can be utilised. Other tests which are basically similar to TCR/TSR/TSC type SVC tests need to be carried out according to a procedure agreed between the utility and the manufacturer. In many cases it may only be possible to carry out type and routine tests on the subassemblies at the manufacturers works. Thus, the site tests may need to include some tests to verify correct interactions between the subassemblies.

6.3 SITE TESTS

In this Section guidelines on various site tests carried out on different types of SVC following the delivery of the equipment to site are described. These tests include commissioning tests and system tests carried out to verify the performance characteristics of the SVC installation within the power system.

6.3.1 Site Tests for Thyristor Controlled Reactor (TCR), Thyristor Switched Reactor (TSR) and Thyristor Switched Capacitor (TSC) Type SVCs

6.3.1.1 Reactance Symmetry Test

This test is carried out to verify that reactance of each phase of the TCR/TSC type SVC is within a certain defined tolerance. With the SVC operating at various levels of current up to the rated current, the three-phase currents on primary and each secondary of the SVC transformer are measured. Typically, if the currents measured do not differ by more than 1% from the mean rated current, the phase balance of the SVC is deemed satisfactory. This assumes that system voltage prior to the introduction of the SVC is a balanced three-phase sinusoidal voltage. If significant voltage unbalance is present, then subsequent analysis must take due account of its effect, on the phase balance measured with the SVC in operation.

6.3.1.2 Thyristor Equal Firing Test

The purpose of this test is to check that there are no non-characteristic harmonics present in the network with the SVC in operation. Given balanced system voltages, presence of non-characteristic harmonics is usually indicative of asymmetries in SVC components such as transformers, reactors, etc. or unequal firing of SVC thyristor valves by the control system. The test is carried out with the SVC operating at various levels of current up to full load current, each phase voltage and current together with the harmonic content is measured at both the primary and secondary side of the SVC transformer. Using the data obtained, together with known or measured asymmetries of SVC components, tolerances on firing angles can be determined.

6.3.1.3 Reactive Power Rating Tests

The line-to-line voltage U and phase current I_{SVC} at the point of common coupling of the SVC (or at the point where the SVC rating is specified) are measured with the SVC operating at full continuous inductive power current ($I_{SVC} = I_L$) :

$$Q_L = \sqrt{3} \cdot U \cdot I_L \qquad \text{(absorption)}$$

and then at full continuous capacitive current ($I_{SVC} = I_C$)

$$Q_C = \sqrt{3} \cdot U \cdot I_C \qquad \text{(generation)}$$

The rating of the SVC in the reactive power absorption and generation operating range is given by :

$$Q_{Lrated} = \left(\frac{U_{rated}}{U}\right)^2 \cdot Q_L$$

$$Q_{Crated} = \left(\frac{U_{rated}}{U}\right)^2 \cdot Q_C$$

6.3.1.4 Energisation Tests

The purpose of these tests is to verify that there are no undamped oscillations following the connection of the SVC to the system, i.e., no resonances occur between the network and the SVC.

Voltages in all phases and a phase current on both the primary and secondary side of the SVC transformer are recorded as the SVC is connected to the network. The tests are repeated a few times with the valves blocked and deblocked, i.e., with the automatic voltage regulator of the SVC free-running.

These tests must be carried out under as many different power system operating conditions as possible (e.g., peak load, off-peak load, light load) and for all different values of fixed capacitors/filters and/or mechanically switched capacitors associated with the SVC to ensure adequate coverage of all possible resonances.

6.3.1.5 Harmonic Performance Tests

These tests are carried out to verify that the harmonic currents of the SVC comply with the specified performance. Prior to connecting the SVC to the network, measurements are performed at the point of connection to obtain a measure of existing harmonic voltages in the network.

Following the connection of the SVC to the network, the current is adjusted between zero and full TCR rating to find the value of compensator current yielding the maximum value of a particular harmonic (e.g., 5th, 7th, etc.). At this conducting angle, a frequency analysis is carried out usually analysing harmonics up to the 30th harmonic. The harmonic analysis is performed on both the voltage and current on the primary as well as the secondary side of the SVC transformer.

Following the analysis, appropriate harmonic performance parameters (e.g., D, TIF, IT) are calculated and compared with specified values. For combined TCR/TSR/TSC type compensators, harmonic performance tests and analysis should be carried out with and without the TSC branch in service. Harmonic performance tests should be conducted under various network demand conditions (i.e., peak load, off-peak load, light load, etc.) to ensure compliance with the specified performance under as many operational conditions as possible.

In a similar manner to the combined TCR/TSR/TSC case, when TCRs are combined with fixed capacitors/filters and/or with mechanically switched capacitors, harmonic performance tests and analysis should be carried out for all different values of such components as they can significantly influence harmonic resonances and voltage distortion levels. The specified harmonic performance levels should be complied with for all specified combinations of shunt capacitive elements.

6.3.1.6 Operating Characteristics and Slope Setting

Power system voltage variations at the busbar to which the SVC is connected is a function of the SVC reactive power output and equivalent system impedance at that busbar. These tests can therefore be carried out only to the extent that the resulting voltage variations are within limits acceptable to the utility. The system equivalent for these tests is illustrated in fig. 6.3.

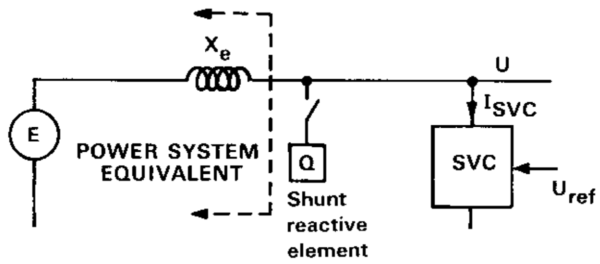


Fig. 6.3 Circuit for determining the SVC operating characteristics

Given the above conditions are satisfied, the SVC operating characteristics can be determined by one of the following alternative methods :

(a) with the SVC reference voltage Uref and slope setting fixed, the power system characteristics as seen from the SVC busbar are modified by switching shunt reactive elements, changing system voltage, switching transmission lines, etc. For each variation introduced, the SVC busbar voltage U and current I are measured and plotted as shown in fig. 6.4a.

(b) with the SVC slope setting fixed the SVC reference voltage Uref is varied. At each value of U_{ref}, the SVC busbar voltage U and current I are measured. Then $\Delta U = U - U_{ref}$ is plotted as a function of current I_{SVC} as shown in fig. 6.4b.

From a plot of the $\Delta U = U - U_{ref}$ as a function of SVC current, per unit value of the slope setting (or slope reactance) can be calculated from

$$SL = X_{SL} \text{ (pu)} = \frac{\Delta U(I_{rated}) - \Delta U(I = 0)}{U_{rated}}$$

as shown in fig. 6.5.

The measurements described can be repeated at various values of SVC slope settings and/or under varying system equivalent impedance conditions to verify the steady-state operating characteristic of the SVC within its design range.

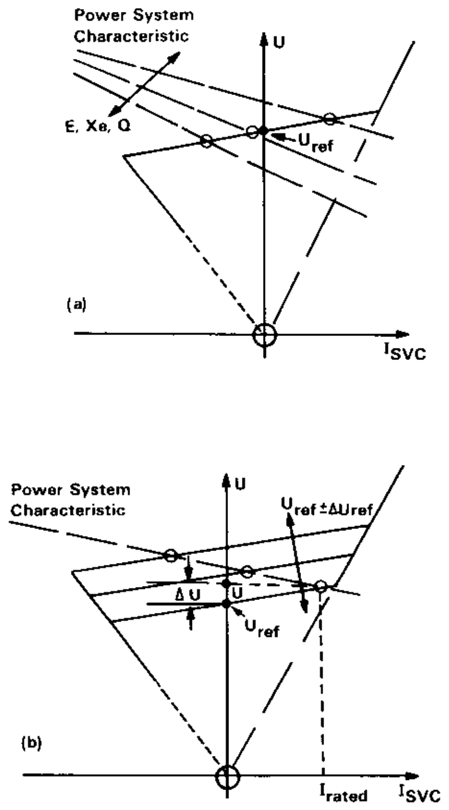


Fig. 6.4 Alternative methods of determining the SVC operating characteristics and slope setting

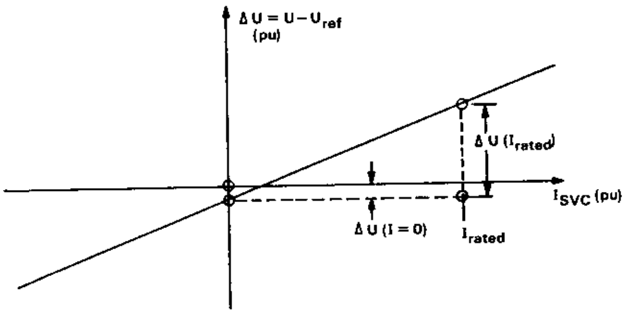


Fig. 6.5 Determination of SVC slope reactance

Depending upon the properties of the SVC control system the $\Delta U = f(I)$ characteristic shown in fig.6.5 may not always pass through the origin, i.e., $\Delta U\ (I = 0) \neq 0$. Prior to carrying out these tests, additional control signals (other than the voltage signal) which may modify U_{ref} during the test, need to be disconnected to ensure correct determination of the control characteristics.

6.3.1.7 Static Characteristic of the Uncontrolled SVC

The purpose of this test is to check the linearity of the reactive power output (Q) of the SVC as a function of the SVC control system output signal B_{SVC}. The SVC and its control system are illustrated in fig. 6.6. The test is important in establishing that the control system produces firing signals such that the SVC output can be varied linearly within a given tolerance, over the design range.

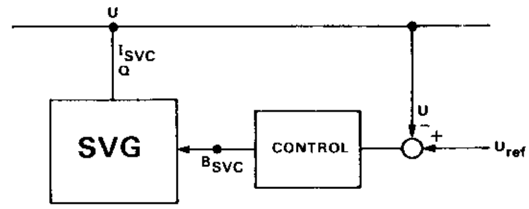


Fig. 6.6 The SVC and its control system

The test is performed by varying the reactive power output of the SVC over the design capability range taking readings of

- SVC reactive power output Q
- busbar voltage U
- control output signal B_{SVC}

Each one of the measured values of reactive power output Q are corrected to the SVC rated output by

$$Q_{corr} = Q_{meas} \left(\frac{U_{rated}}{U} \right)^2$$

The measured reactive power output values, corrected to the SVC rated value (Q_{corr}), are then plotted against the corresponding control signal B_{SVC} measured, as shown in fig. 6.7.

The $Q = f(B_{SVC})$ characteristic thus obtained should be substantially linear within acceptable limits. Some SVC control systems may not produce an explicit B_{SVC} control output signal. In such cases, the procedure should be suitably modified to monitor and interpret the available control signals to ensure that the control system produces firing signals such that the SVC output can be varied linearly over the design range.

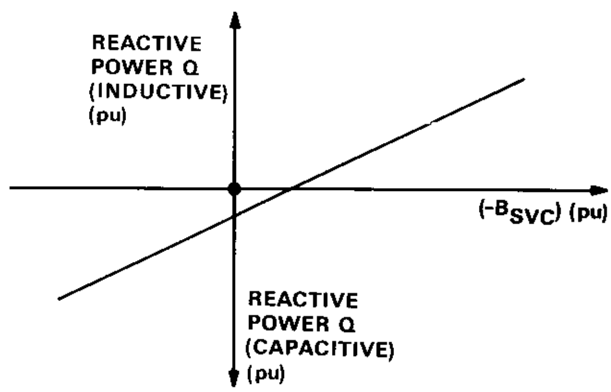


Fig. 6.7 Linearity of SVC reactive power output with control output signal

6.3.1.8 SVC Small Signal Response Tests

In order to determine the step response of the SVC to small signals, recordings are taken of the voltage U, the SVC current I and the control signal B_{SVC}

(if available), when a step change ΔU_{ref} is applied at the reference summing junction of the SVC control system, as shown in fig. 6.8.

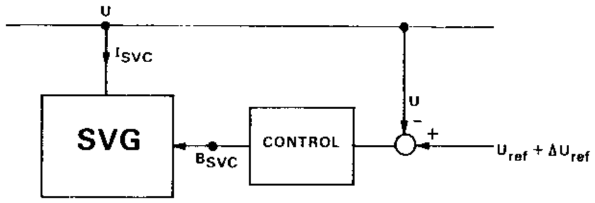


Fig. 6.8 SVC small signal response test arrangement

From the recordings of SVC voltage (U), current (I), (I/U), and B_{SVC} versus time, the control characteristics of the control loop and the SVC can be identified as described in Section 5.3.2 of Chapter 5 and shown in fig. 6.9.

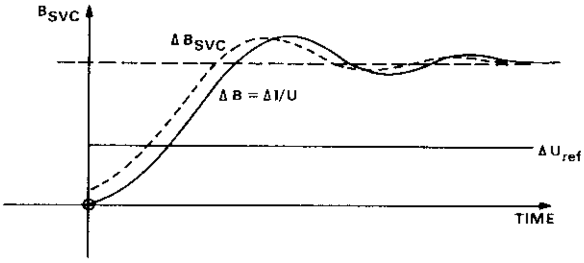


Fig. 6.9 SVC small signal response

It should be noted that the response time is strongly affected by the power system equivalent impedance X_e at the point of the SVC connection. Any change in the system due to switching or control may modify the response. When carrying out these tests the signal ΔU_{ref} should be chosen such that the SVC is operating within its capability limits.

6.3.1.9 SVC Control System Tests

The objective of these tests is the verification of best gain and time constant settings for the SVC control system, ensuring damped response over varying system operational conditions. The tests are usually initiated under minimum system fault level (i.e., maximum system equivalent impedance) operating conditions at the SVC point of connection. Small signal response tests as described in the previous section are repeated at various control system settings and system equivalent impedances (i.e., system fault levels) which are modified by switching shunt reactive elements, changing system voltage, switching transmission lines, etc. The tests are analysed to establish the settings ensuring damped SVC output response over the widest range of system operating conditions.

6.3.1.10 Large Disturbance Tests

In order to determine the large disturbance performance of the SVC, it is usual to carry out a single phase to earth fault test in the vicinity of the SVC. The SVC busbar voltage, SVC phase current, SVC transformer neutral current and SVC control system input and output are typically recorded for subsequent analysis.

An alternative or additional test could be the switching of an appropriate capacitor, reactor, transmission line or transformer in the vicinity of the SVC to produce a disturbance of the desired magnitude. Such tests are particularly relevant when the purpose of the SVC is the control of temporary overvoltages using its short-term overload reactive absorption capability.

Tests to verify the run-through capability of the SVC are necessary for SVCs connected to power systems with single- or three-phase autoreclose facilities. The tests should verify that the SVC will not be disconnected following power system faults or large disturbances initiating the autoreclosure sequences and, will be available for system support following completion of such sequences when its presence may be most needed. The test verifying the run-through capability can be carried out at site, by removing the controlled busbar voltage signal from the SVC regulator summing junction and measuring the time taken for the SVC control/protection system to trip the SVC circuit breaker.

6.3.1.11 Heat Run

For this test, the compensator is operated at rated reactive output in both the inductive and capacitive range, until stable operating temperature is reached. The absolute temperature and temperature rise above cooling medium are noted for the various SVC components.

Recommended time for the heat run is typically 8-10 hours if the system conditions make it possible.

6.3.1.12 Current Limiter Tests

To ensure that the compensator will not be overloaded or tripped from the system when the voltage rises beyond rated value, the current regulator/limiter must be checked for correct performance. One method for checking the limiter without going beyond rated values is to lower the set points, say from 1.0 p.u. to 0.8.p.u., and then control the current limiter at the lower set point.

6.3.1.13 Noise Control

The acoustic noise measurements on transformers and reactors are recommended to be carried out according to NEMA standard. Since there are no similar strictly applicable standards for thyristor valves, pump motors, cooling fans, etc., values of 60-65 dbA at a distance of 10 metres from the component (ISO R507, IEC R179) are suggested for manned substations and for substations in built-up areas containing SVCs.

6.3.1.14 Radio Interference

The radio interference level measurements should be carried out according to standards set in IEC-CISPR Publication 1.

6.3.1.15 Cooling System Test

Following completion of equipment erection at site, the cooling system integrity, especially for liquid cooling systems, should be tested in a similar manner to the tests in Section 6.2.1.4.9.

6.3.2 Site Tests for Saturated Reactor (SR) type SVCs

The site tests for these types of SVCs are, in general very similar to those for other types of SVC. Thus the tests summarised under Section 6.3.1 will generally apply, with the exception of tests concerning thyristor valves and firing control systems.

6.3.3. Site Tests for Self-Commutated Converter and Line-Commutated Converter Type SVCs

The site tests for these types of SVCs are also in general very similar to those for other types of SVC. Thus the tests summarised under Section 6.3.1 will generally apply. Site tests may also include some tests establishing correct interactions between SVC subassemblies.

CHAPTER 7

CONTROL OF STATIC VAR COMPENSATORS FOR SPECIFIC APPLICATIONS AND FUTURE TRENDS

7.1 INTRODUCTION

In transmission system applications, static var compensators are utilised where fast control of reactive power is of particular benefit in maintaining and/or improving the system overall performance. The design and flexibility of the compensator control system is therefore particularly important if the benefits of the SVCs are to be fully realised over a wide range of power system design and operational conditions. Changes in power system conditions such as modified generation patterns due to fuel cost differentials, extensive utilisation of existing generation sites/transmission routes due to difficulties in obtaining new sites/routes, etc., can introduce both steady-state and dynamic problems as described in Chapter 1.

In order to realise the full benefits of a particular SVC installation the SVC control system needs to be designed such that a robust, flexible and consistent performance is obtained under a wide range of system operational conditions and structural changes. Furthermore the SVC control system should be capable of co-ordinating the SVC response with other nearby reactive compensation sources while minimising the operating losses.

It is clear that the control system design is a compromise among the abovementioned considerations. There are inherent dangers in choosing inflexible SVC control characteristics especially in circumstances where changes in the power system structure results in much reduced system fault levels, severely degrading the SVC performance and causing loss of control action. In these circumstances it is necessary to ensure continuous adjustement of SVC control settings in line with changes in power system characteristics. Recent advances in control system design and microprocessor control systems allow a more consistent speed of response to be obtained over a wide range of operating conditions. Furthermore, through the inclusion of additional control signals, it is possible to obtain better dynamic performance and secondary control/co-ordination with other reactive compensation devices in the transmission system.

In this Chapter, the SVC control system will be examined in terms of specific applications and future trends.

7.2 PRINCIPLES OF VOLTAGE CONTROL AND GAIN SUPERVISION

The principal objective of an SVC in a transmission system is to control voltage at the point of connection. Since an open-loop control strategy is not suitable for achieving such an objective within the required accuracy, (ref. 289), a closed-loop, i.e., feedback control system, is used. The voltage to be controlled is continually measured and compared with a reference value according to a voltage control characteristic :

$$U = U_{ref} + (SL) \cdot I_{SVC}$$

where SL is the slope of the control characteristic

I_{SVC} is the SVC current (+) for inductive and (-) for capacitive current

and U is the controlled busbar voltage to which the SVC is connected.

The controlled voltage (U) is continually influenced by the changes in the operational patterns of the transmission system to which it is connected. The transmission system at the controlled voltage busbar can be characterised by the equivalent system reactance (X_e) corresponding to a short circuit fault MVA infeed (S_c) as shown in fig. 7.1a. Thus in terms of systems quantities the control voltage (U) can be expressed by :

$$U = \frac{X_{SVC}}{X_e + X_{SVC}} \cdot E \quad \text{with} \quad Q_{SVC} = \frac{U^2}{X_{SVC}} \quad \text{and} \quad S_c = \frac{U^2}{X_e}$$

for $X_{SVC} >> X_e$ usually obtained in power systems :

$$U = E - X_e \cdot I_{SVC} \approx E\left(1 - \frac{X_e}{X_{SVC}}\right)$$

or alternatively in terms of reactive power for $Q_{SVC} << S_C$

$$U = \frac{E}{1 + \frac{Q_{SVC}}{S_C}} \approx E\left(1 - \frac{Q_{SVC}}{S_C}\right)$$

In the above equations the equivalent system reactance (X_e) continually varies according to the changes in the generation, load and transmission configuration. The voltage at the controlled busbar is also influenced by these changes. A simplified block diagram of the SVC voltage control characteristic including the transmission system effects is shown in fig. 7.1b (ref. 148, 223, 267, 321).

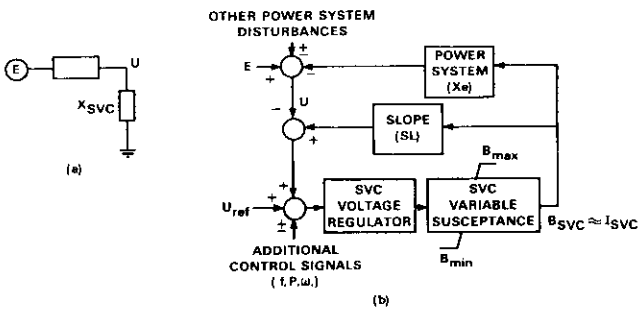


Fig. 7.1 Simplified transfer function diagram of the SVC voltage control system including transmission system effects for $U \approx U_{rated}$

Assuming the adoption of SVC voltage control system settings corresponding to the minimum system short-circuit fault MVA infeed conditions ($S_{c\,min}$), the variations in the response time of such a control system as a function of system fault MVA infeed and SVC reactive power output is illustrated in fig. 7.2 (ref. 223, 267). The figure indicates that the response time of an SVC control system set in the above manner will become larger, i.e., the response will become slower as the system fault MVA infeed increases. Inconsistency of response over varying system conditions is undesirable as it prevents the advantages of installing the SVC to be consistently realised and in some cases may lead to control system instability.

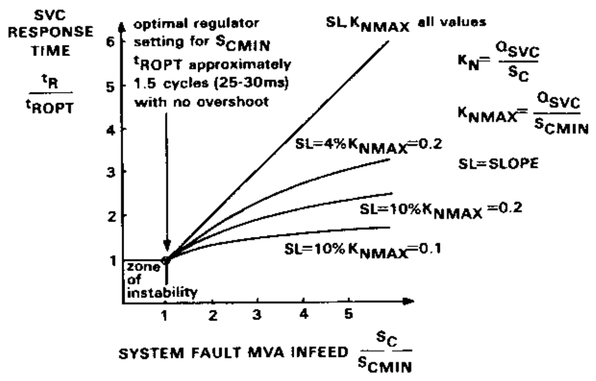


Fig.7.2 Influence of system short-circuit fault MVA infeed and SVC output on voltage control loop response

One example of solving the widely varying SVC response problem is the provision of pre-set gain values within the SVC voltage regulator which can be selected manually to match the system operating conditions. Assuming such gain values can be established, the manual selection of the appropriate gain cannot be considered sufficiently fast to ensure adequate adjustment especially under rapidly varying system conditions. To avoid SVC control system instability and the consequent system voltage control problems, an automatic gain supervision control can be included within the SVC voltage regulator. The role of this control feature is the continuous adjustment of SVC voltage regulator gain over a wide range of power system operating conditions such that uniform, near-optimum response can be obtained consistently (ref. 321). The practical advantage of such control over a wide range of system operating conditions is most likely to ensure their adoption as a standard control feature in future applications.

In its simplest form, the automatic gain control can take the form of gain switching control, switching a number of pre-set gain values. The control action could be based on interpretation of external signals such as transmission line circuit breaker positions at the substation connecting the SVC to the system (ref. 328). Alternatively, an automatic device capable of detecting control system instability can be installed to adjust the SVC voltage regulator gain continuously (ref. 321). This method may be adequate if the control system instability is in a frequency range widely separated from the electromechanical oscillation frequences of the power system. The connection of gain supervision control to the SVC voltage regulator is illustrated in fig. 7.3.

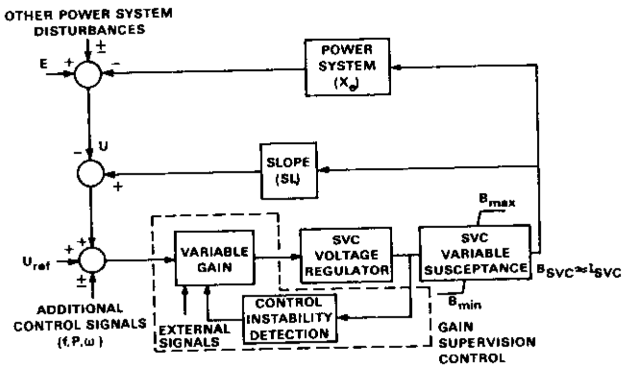


Fig. 7.3 Connection of gain supervision control to the SVC voltage control system ($U \approx U_{rated}$)

An illustration of results of a study of a SVC being subjected to operating conditions which have led to its voltage control system becoming dynamically unstable is given in fig. 7.4. A further illustration is given in the manner in which the studies have shown how stability of the control system can be regained by the introduction of an automatic gain supervisor type of controller (ref. 321).

Due to the adaptive nature of gain supervision control, addition of such facilities can prove valuable if the power system is subject to frequent wide variations of equivalent system impedance at the SVC point of connection.

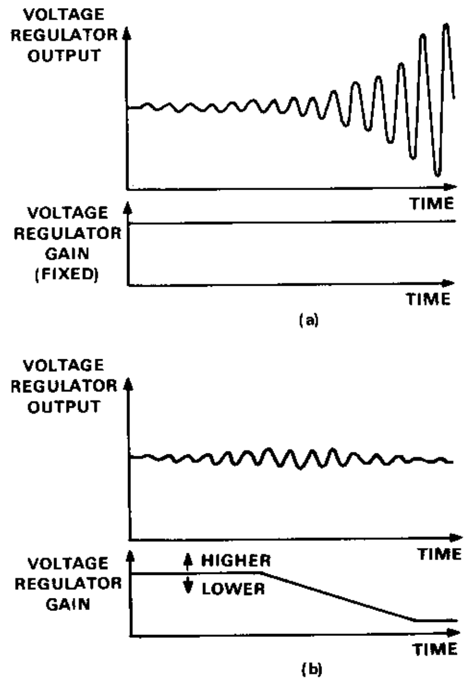


Fig. 7.4 Illustration of SVC voltage control system behaviour; (a) without and (b) with gain supervision control

The accuracy of the SVC voltage regulator can be improved by using two feedback control loops, with the outer loop based on the slope of the voltage control characteristics and the inner loop on current feedback. This allows for much more accurate tracking of the SVC current in the control range. The structure of such an SVC voltage regulator control system is shown in fig. 7.5 (ref. 289).

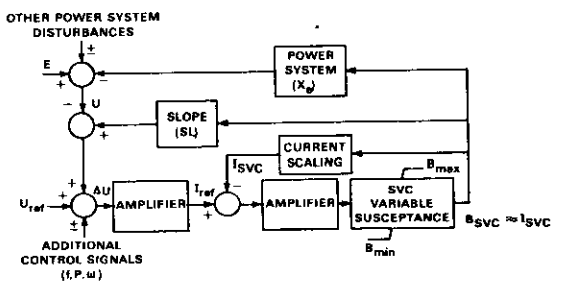


Fig. 7.5 Simplified block transfer function diagram of SVC voltage and current control system including transmission system effects ($U \approx U_{rated}$)

The provision of a load dependent signal enables a TC, TSC, TSR, SCC and LCC type SVCs to exhibit a voltage/load droop characteristic within its rated MVar operating range. In the case of SR type SVCs, however, the slope of the voltage control characteristic is fixed by the slope correcting capacitor and saturated reactor design. The control action of such a compensator, to minimise voltage variations, is entirely due to its inherent response characteristics. External voltage regulator loops are therefore not required. However, the design of the SR type SVC permits the use of slow acting voltage control loop, based upon SVC current measurement, to adjust the tap-changer of the SVC transformer.

Due to the fast response of their inherent or control system characteristics SVCs are capable of exerting accurate control on the busbar voltages so long as the reactive power demanded by the voltage variations remains within the SVC control range. For system voltage variations beyond its control range the SVC will continue to function as a fixed shunt reactor for system overvoltages and as a fixed shunt capacitor for system undervoltages. The SVC can be operated continuously in the undervoltage range. However, in the overvoltage range, continuous operation may be limited by the overload rating of the SVC inductive elements. For TCR, TSR, SCC and LCC type SVCs, continuous or sustained periods of operation in the overvoltage range may entail a substantial increase in capital expenditure because both the inductive elements and the thyristor valves will have to be rated for such duty. The inherent overload capability and fast response of the SR type SVCs make them more suitable for such applications.

7.3 PRINCIPLES OF REACTIVE POWER CONTROL AND CO-ORDINATION

Static var compensators with their capability for continuous fast variation of their output, are most suitable for meeting the dynamic response requirements of the power system. The operating regime of the SVCs requires co-ordination with other reactive power sources in order to obtain desired overall response, matching system requirements. If this co-ordination is not provided the SVCs will tend to operate often at the extremes of their capability range due to their fast response while other reactive power sources will remain relatively quiescent. Thus, the SVCs will be responding to normal network operational changes leaving little or no reserve for counteracting large and small system disturbances. The addition of a reactive power control loop into an individual SVC or a group of SVCs in a substation, together with co-ordinated control and switching logic for controlling other reactive power sources in the vicinity of the SVCs, would achieve the desired effects of co-ordination between individual SVCs and other slower acting reactive compensation devices. A possible configuration of such a control system is shown in fig. 7.6.

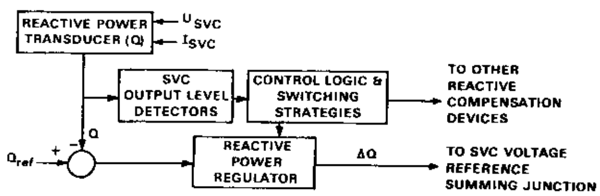


Fig. 7.6 General configuration for reactive power control

The reactive power control loop is a slower acting loop than the voltage control loop and/or inherent response characteristics of the SVC. In its simplest form, the reactive power control loop brings the SVC back to a predetermined operating point within its control range following each system change. This action is illustrated in fig. 7.7. The figure assumes that under power system operating conditions characterised by Curve (1), the compensator operates at point A of its control characteristic at reactive output Q_{ref}. For a change in power system operating conditions, characterised by Curve (2), and corresponding to a voltage change U, the SVC operating point will rapidly move and settle at B. The reactive power control will now slowly bring the SVC output back to its original value Q_{ref} at point C. At the same time the resulting voltage rise in the network can be compensated with slower mechanically-switched devices (refs. 148, 223 and 267).

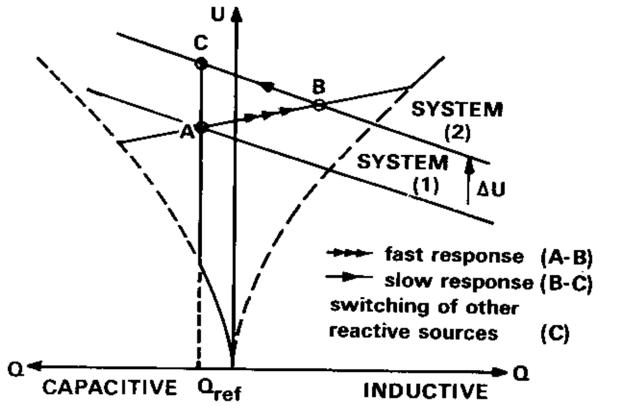


Fig. 7.7 Principle of reactive power control with an SVC

The principle of co-ordinating the SVC output with mechanically switched shunt reactors (MSR) and capacitors (MSC) is illustrated in fig. 7.8. The switching of MSR and MSC devices is usually carried out in relation to SVC output, busbar voltage and/or SVC current. This type of co-ordinating control can be applied to operate in conjunction with all types of SVCs including TCR, TSR, TSC, SCC and LCC, and SR types. Care needs to be taken to ensure appropriate hysteresis characteristics for switching MSR and MSC devices to avoid hunting and possible damage to mechanical switching devices due to frequent operation.

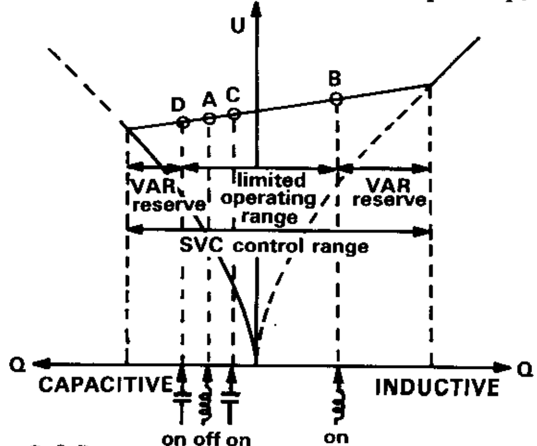


Fig. 7.8 Principle of switching mechanically switched shunt reactors and capacitors in conjunction with the SVC

Many practical examples of reactive power control and co-ordination process can be found in ref. 140, 223, 267, 326, 328, 329. Co-ordination has in many cases been extended to include SVC component switching and control strategies to deal with both system disturbance and energisation conditions. Use of such strategies enables control in anticipation of a particular power system event ensuring fast response and appropriate control action. Examples of such strategies can be summarised as follows :

- keeping a TCR in a continuous state of readiness to ensure availability of maximum reactive power absorption when a cable section to which the TCR is connected is energised (ref. 284).

- initiation of continuous conduction of TCRs upon detection of system faults in the vicinity of the installation such that voltage rises on the associated cables can be limited upon fault clearance (ref. 284).

- dropping the TCR loading quickly to zero as well as rapid switching of TSC and MSC to assist voltage recovery following a fault in the vicinity of the SVC (refs. 328, 329).

Further examples of such strategies which have been used in practical schemes can be found in Chapter 8.

7.4 PRINCIPLES OF CONTROL FOR SYSTEM TRANSIENT STABILITY AND POWER OSCILLATION DAMPING PERFORMANCE ENHANCEMENT

The transient stability and power oscillation damping performance of a power system can be improved through quency deviation
Studies have confirmed the beneficial effects of strategies based upon fast insertion of thyristor switched capacitor (TSC) and mechanically switched capacitor (MSC) type devices for system transient stability, and additional feedback loops based upon (ΔP/Δt) of (Δf) for power oscillation damping (refs. 89, 140, 148, 263 and 335). The results of a study illustrating the transient stability enhancement obtainable through the use of a 100 MVar TSC are given in fig. 7.9 (ref. 89). The figure illustrates that, following a three-phase fault causing the outage of one of the two parallel tie-lines between two power systems, stability can be maintained for power transfers up to the thermal rating of the tie-line remaining in service.

In order to enhance the power oscillation damping performance of power systems, additional power oscillation damping loops are installed in generator excitation control systems. However, under certain system operating conditions, further damping of power oscillations may be required, as conventional voltage control via reactive compensation devices at busbars away from generation sources, can actually reduce systems damping (refs. 172, 302).

Possible configurations of power oscillation damping controls are shown in fig. 7.10. Such controls are required to track power oscillations in the 0.1 - 2 Hz range with sufficient accuracy to introduce the required additional damping by changing the output of TCR, TSR, TSC, SCC and LCC type SVCs. Due to their inherent control characteristics, based upon voltage variations, it is not readily possible to apply such additional control signals to SR type SVCs. Although not included in fig. 7.10, control strategies for switching of MSR and MSC devices can of course be added as described in the previous section.

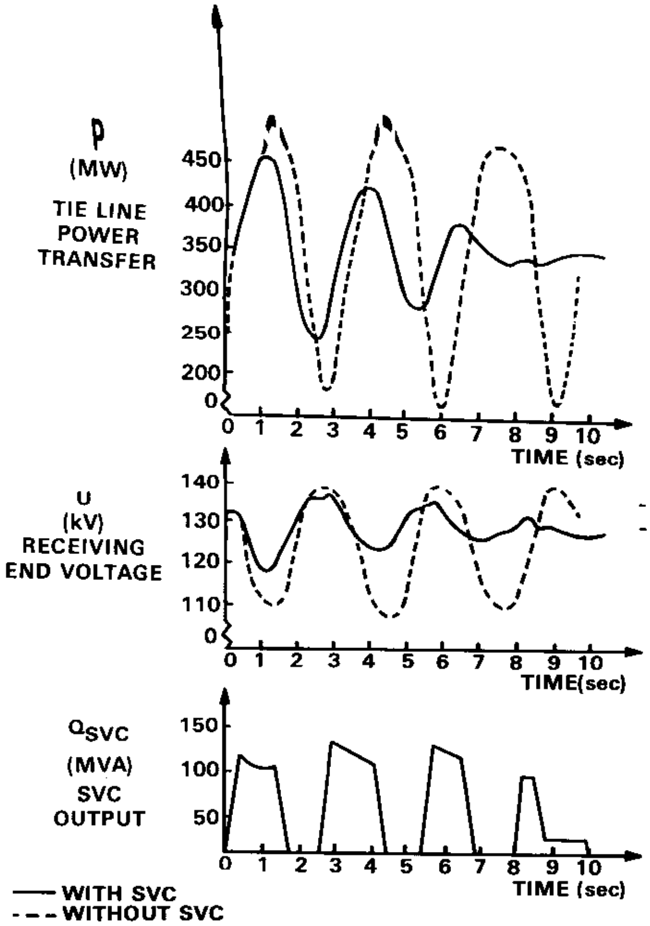


Fig. 7.9 Effect of a 100 MVar TSC comprising 10 steps
phase fault

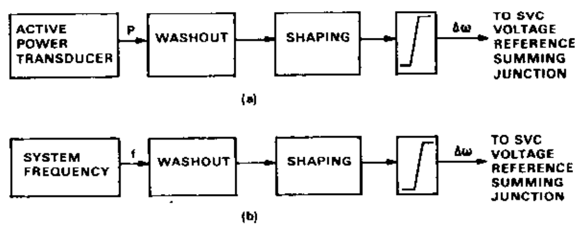


Fig. 7.10 Possible configuration for power oscillation damping controls based upon (a) system acceleration (ΔP/Δt) and (b) system frequency deviation (Δt)

Additional control loops for power oscillation damping purposes have been installed as part of practical SVC control schemes (refs. 302, 332, 342, 353 and 358), further details of which can be found in Chapter 8. The principle of improving power oscillation damping using (ΔP/Δt) as an additional control signal in conjunction with a TSC type SVC is illustrated in fig. 7.11(a). The onset of power oscillation is detected via continuous monitoring of power changes on a transmission line in the vicinity of the SVC, and the TSC steps are switched in or out depending upon the sign of rate of power change. The switching process continues until the power changes fall below a predetermined level. Site test results obtained from a recent application using additional damping signal based upon (ΔP/Δt) on a TCR are given in fig. 7.11(b) (ref. 358). The test was carried out to determine, system damping performance following loss of generation in a power system exporting power to another system over a tie-line.

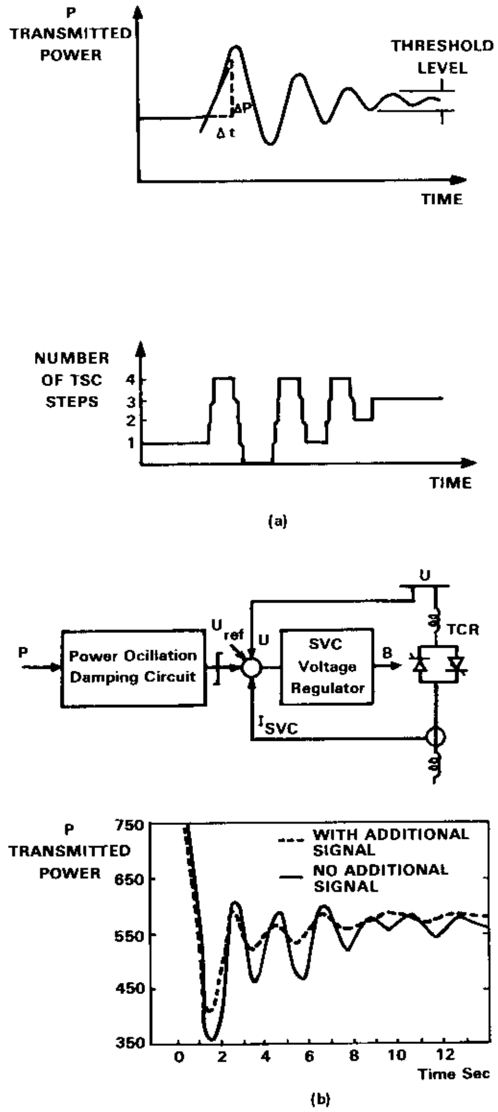


Fig. 7.11 Principle of power oscillation damping performance enhancement utilising ($\Delta P/\Delta t$) as an additional signal (a) in a TSC control system and (b) in the TCR control system in a practical case

7.5 CONTROL FOR SUBSYNCHRONOUS RESONANCE DAMPING APPLICATIONS

Subsynchronous oscillations which can occur due to the interaction between the electrical power systems containing series capacitor compensation of transmission lines and turbo generator mechanical systems can be damped by installing an SVC in the vicinity of the particular generator (refs. 185, 330). Effective damping of subsynchronous resonance(s) can be achieved by utilising an additional control loop based upon the generator rotor speed deviation signal ($\Delta\omega$) (refs. 265, 330).

Thyristor controlled reactor (TCR) type SVCs are most commonly used for subsynchronous oscillation damping purposes. It is not possible to use saturated reactor (SR) type SVCs for such applications due to their inherent control characteristics.

7.6 PRINCIPLES OF INDEPENDENT PHASE CONTROL

Individual control of each SVC phase susceptance is required for load balancing applications in order to achieve the continuous adjustment needed to reduce the magnitude of the varying voltage unbalance in a power system. The SVC voltage control loop for such applications is arranged such that each individual phase of the SVC is controlled through its own independent controller while operating within the SVC control range. An example of such a voltage control loop structure is given in fig. 7.12.

While the system voltage unbalance is within the SVC control range, individual phase voltage control can be used to maintain a pre-set reference voltage. However, when one of the individual phase controls demands an SVC output at or beyond the control range, then two different slow acting control strategies can be applied depending upon the requirements. The "balanced voltage control" strategy ensures that preference is given to negative phase sequence (NPS) voltage control by adjusting the reference set point of all three individual controllers such that a pre-set control error is achieved. This is of interest when network voltage changes of high magnitude tend to force the SVC to operate outside its control range. On the other hand "average voltage control" strategy ensures preference is given to positive phase sequence (PPS) voltage control by adjusting the reference set point of all three individual controllers such that the average of three phase voltages is kept equal to the set reference voltage.

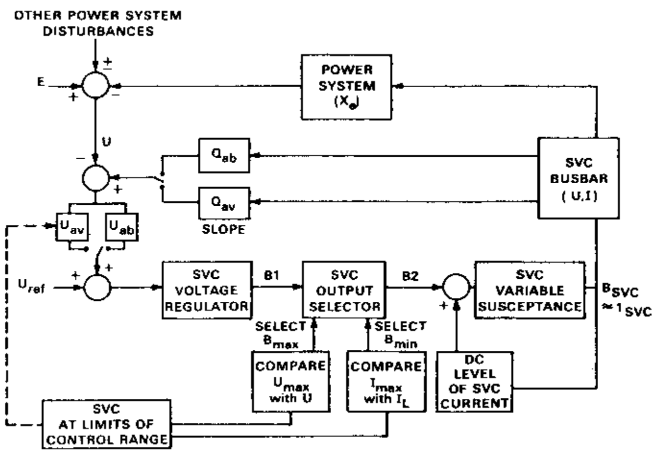


Fig. 7.12 Illustration of individual phase control with an SVC

In order to achieve the desired voltage control characteristic the "individual" or "average" droop can be calculated. Use of average droop ensures the aiming of all three individual controllers to the same effective set point and effective elimination of NPS voltage component. In addition to the above, facilities such as slow acting SVC limit controls to prevent the operation of the SVC outside its control range, and dc current level control to prevent a build-up of dc currents which cause saturation of the SVC transformer, are required. The latter control acts to reduce the asymmetry of thyristor firing by adjusting half-wave firing instants.

Continuous individual phase control can only be achieved by thyristor controlled reactor (TCR) type SVCs. The plain thyristor switched capacitor (TSC) and thyristor switched reactor (TSR) type SVCs are only capable of exercising individual phase control in discrete steps, which generally means that to achieve the same quality of control as the TCR many discrete switching steps need to be employed. SVCs consisting of mechanically switched reactor (MSR), mechanically switched (MSC) or fixed capacitor (FC) units in combination with thyristor controlled reactors (TCR) have an enhanced control range and individual phase control characteristics similar to those of the TCR type SVCs. Converter (SCC and LCC) type SVCs with common passive DC storage component (C or L) may not be suitable for load balancing applications due to the greatly increased ripple content in the DC quantities. The saturated reactor (SR) type SVCs are capable of reducing NPS voltages due to system unbalance. The magnitude of the finite reduction depends upon power system and SVC characteristics. Use of three single-phase saturated reactors instead of a single three-phase unit can yield further finite reduction of NPS voltages. The increased harmonic filtering requirements for a single three-phase unit and the finite nature of the NPS performance improvement, dependent upon system and SVC characteristics, needs to be borne in mind when considering these types of SVCs for load balancing applications.

7.7 FUTURE TRENDS

Due to recent advances in microprocessors and information processing technology many of the control and protection functions associated with SVCs can now be combined within one controller.

Such a microprocessor based controller can be equipped through suitable software to co-ordinate the SVC output in accordance with :

- voltage control requirements during normal system operation
- voltage control requirements during large system disturbances
- gain control adjustment according to system configuration to achieve optimum SVC response
- hierarchical control requirements according to predetermined strategies
- system transient stability performance requirements
- system damping performance requirements
- system subsynchronous damping requirements
- system individual phase balance requirements

The microprocessor based control systems are also ideally suited for overall system control applications, such as secondary voltage control, which coordinate overall system reactive power needs through dispatching the output of each available reactive compensation element for a particular system configuration.

CHAPTER 8

A SURVEY OF OPERATIONAL EXPERIENCE WITH STATIC VAR COMPENSATORS

8.1 INTRODUCTION

In recognition of the need to demonstrate the successful application of static var compensators to transmission systems, a survey on the SVC operational experience has been conducted by CIGRE WG 38-01 Task Force No.2. To accomplish this task, a survey questionnaire seeking information both on the nature of the particular SVC application and the year-by-year operational experience was prepared. This questionnaire was circulated worldwide to the utilities with SVC installations on order and/or in service.

Replies were received from 25 utilities on 73 individual SVC installations. This chapter includes the analysis of the replies in terms of detailed SVC technical data related to each application and operational experience.

Together with the SVC functional specification discussed in Chapter 5, the provision of technical and performance data on current SVC installations forms useful background information to assist power system engineers in the specification and design of new SVC projects. The operational data is expected to benefit those concerned with both design of future and operation of existing schemes.

The value of such survey data has been amply demonstrated through CIGRE Study Committee 14 survey data on HVDC links. Similar benefits are obtainable by extending this current survey to periodically obtain information on new SVC schemes and further operating experience of existing schemes. The necessary protocols for the reporting procedures are well established and can be modified by regular review to suit developing needs.

8.2 DESCRIPTION OF THE SURVEY QUESTIONNAIRE

The survey questionnaire was arranged in two parts, the first seeking "application and design" and the second seeking "reliability and performance" data. Adequate notes and definitions were provided to assist the contributing utilities in completing the questionnaire. The contributors were also reminded that only SVC installations commissioned, on order or in the planning stage for application to their HV/EHV network would be included in this survey. SVC installations for industrial applications, such as flicker reduction, have been excluded from this survey.

Part I of the questionnaire on "application and design" data sought information mainly on the following technical characteristics of the SVCs, namely :

(i) present status, type and cooling method

(ii) continuous and overload rating, the means of varying the SVC output

(iii) purpose(s) of installing the SVC (in order of importance)

(iv) control strategies applied for operation under system undervoltage and overvoltage conditions

(v) main (M1, M2...) and supplementary (S1, S2...) control signals used in controlling the SVC output and the means of obtaining these signals

(vi) slope of the control characteristic, reference voltage setting and range

(vii) maximum and minimum system fault levels at the point of connection of the SVC

(viii) specified and measured harmonic levels for the SVC, provisions made for harmonic filter(s)

In addition to the above information, the contributors were asked to include :

(ix) a single line diagram of the SVC indicating rating of major SVC components, connection arrangements and other significant equipment in the vicinity of the SVC

(x) pertinent comments on the application and design of the SVC

(xi) details of field tests carried out to confirm the performance of the SVC.

These last three items of information were considered of special importance in terms of conveying information on both the design and successful operation of the SVC installations.

The contributors were requested to quote nominal rating in MVar at the appropriate winding side of the SVC transformer to which this rating is applicable. For the overload rating, the appropriate current rating with the corresponding duration at that rating was requested.

Part 2 of the questionnaire on "reliability and performance" data sought information mainly on the following operational characteristics of the SVC :

(i) overall availability
(ii) planned outage rate
(iii) forced outage rate
(iv) mean time between planned outages
(v) mean time between forced outages
(vi) mean time per planned outage
(vii) mean time per forced outage
(viii) number of main SVC component failures causing forced outages
(ix) other causes leading to forced outages

The main components of the SVC this purpose were designated as :

(a) transformers
(b) capacitors
(c) reactors
(d) filters
(e) circuit breakers and isolators
(f) thyristor valves
(g) SVC control and internal protection equipment
(h) auxiliaries
(i) other specific components.

The contributors were requested to quote the above "reliability and performance" data for annual periods of operation. In cases where this period was shorter, the actual period of operation in hours was requested. The terms and definitions used in obtaining the "application and design" as well as "reliability and performance" data are included in Chapter 9.

8.3 RESULTS OF THE SURVEY

The results of the survey are presented in the form of four tables according to the particular SVC types or combinations of SVC types :

Table I - Thyristor Controlled Reactors (TCR)

Table II - Thyristor Controlled Reactors and Mechanically Switched and/or Fixed Capacitors (TCR + MSC + FC)

Table III - Thyristor Controlled Reactors and Thyristor Switched Capacitors (TCR + TSC)

Table IV - Other Types of SVC including individual application or combinations of :

(a) Thyristor Controlled Reactor, Thyristor Switched Capacitor and Fixed Capacitor (TCR + TSC + FC)

(b) Thyristor Controlled Reactor, Thyristor Switched Capacitor, Thyristor Switched Reactor and Mechanically Switched Reactor (TCR + TSC + TSR + MSR)

(c) Thyristor Switched Capacitor and Thyristor Switched Reactor (TSC + TSR)

(d) Self-Commutated Converter (SCC)

(e) Thyristor Controlled Transformer and Fixed Capacitor (TCT + FC)

(f) Saturated Reactor (SR)

(g) Saturated Reactor and Mechanically Switched and/or Fixed Capacitor (SR + MSC + FC)

In each table, the "application and design" data is included in Part 1 while the "reliability and performance" data is included in Part 2 of the table. The "application and design" data is given on an "individual" unit basis in almost all cases, except where total ratings for the particular static var system (SVS) are given. The "reliability and performance" data is given on an "individual" unit basis without exception, and operational experience for each operational year is detailed.

In terms of the total installed SVC capacity on a year by year basis the replies received from 25 utilities can be summarised as follows :

YEAR	N° of SVC UNITS	TOTAL INSTALLED SVC CAPACITY Capacitive MVar	Inductive MVar
1969	1	20	15
1975	1	80	8
1977	1	30	18
1978	7	1112	353
1979	4	230	57
1980	2	345	145
1981	5	67	450
1982	6	825	591
1983	6	590	672
1984	17	2747	1131
1985	11	1650	1300
1986	11	1100	600
1987	1	70	50
TOTAL	73	8866	5390

The SVC capacity quoted in the above summary take account of harmonic filters associated with the SVC installations. This means that the actual MVar rating of inductive SVC components installed is larger than that shown. The reader is requested to refer to single line diagrams indicating individual component ratings to obtain a better appreciation of the actual amounts of inductive plant installed.

In the following sections, salient points from the analysed results of the survey are presented for each type of SVC on which information has been received. Observations on the additional comments received, and field tests conducted, is presented in separate sections for all SVC types.

8.4 SVCs CONSISTING OF THYRISTOR CONTROLLED REACTORS (TCR)

The experience with this type of SVC dates back to 1977. Although continuous ratings vary, the largest individual rating quoted is for 180 MVar SVCs in Norway. Preference appears to be for combining the TCRs with mechanically switched or fixed capacitor banks acting as harmonic filters, with the exception of three Norwegian installations. The output of the TCRs is varied continuously in all quoted applications. Combinations of TCRs with larger sizes of mechanically switched or fixed capacitors over and above the harmonic filtering requirements, are covered in Section 8.5.

Although the HV voltage of the SVC varies from system to system, the voltages at the LV side of the SVC transformer appear to be in the range of 8 to 14 kV. All applications, except Norway, use six pulse thyristor configuration. Air, water or glycol is used for cooling of thyristors.

The TCR type of SVC is most commonly installed for voltage control, reactive power compensation and subsynchronous resonance damping purposes. As a result of closer control of voltage and reactive power by the SVC, improvement of power transfer capability is quoted as a further benefit.

The control strategies adopted for operation under transient undervoltage and overvoltage conditions vary between applications and are quoted in Table I.

The preferred main control signal appears to be three-phase voltage measured at the HV side of the SVC transformer, with the current measured at the LV side of the SVC transformer being the preferred supplementary control signal. The preferred method of measuring the HV side voltage is wound voltage transformers.

The preferred slope of the SVC control characteristic is around 5%, with the voltage reference setting of 0.95 p.u. to 1.02 p.u. of nominal voltage. The reference setting is variable at around ± 5% to ± 10 % of the nominal voltage.

Preference appears to be given to specifying acceptable limits for harmonic voltages, currents and voltage distortion at the HV side of the SVC transformer and carrying out the measurements at that point. Harmonic filters appear to be usually provided for the 5th and 7th harmonics, although in certain cases filters for 2nd and 3rd harmonics are also provided.

From Table I (Part 2) the following general conclusions can be derived in terms of the performance of TCR type SVCs :

(a) Overall availability averages around 98% or better

(b) Average planned outage rate is around 1% per annum while the average forced outage rate is observed to be about 0.5%, or lower

(c) Mean time between planned outages appears to improve with increasing years in operation. The figures appear to settle out to an average of 1.5 months of mean time between planned outages with 6 hours as the mean outage duration in the Chilean experience, to an average of six months and 24 hours, respectively, in the Norwegian experience

(d) In the Norwegian experience the mean time between planned and forced outages and the corresponding time per planned or forced outages are somewhat similar. In the Chilean experience, forced outages are observed to be approximately twice as rare as planned outages with considerably less average time spent to correct the causes for the forced outages

(e) Very few failures of transformers, capacitors, reactors, filters, circuit breakers and isolators causing forced outage of the TCR type SVCs are reported by all contributors. Norway reports some failures of thyristor valves causing forced outages, but these appear to decrease with accumulated periods of experience. Similarly, Chile reports some SVC control and internal protection failures causing forced outages, which are also observed to decrease with experience.

Among other causes of forced outages, Chile reports refrigeration system failures and Norway reports a surge arrester failure due to an earth fault as well as some auxiliary equipment faults.

The above conclusions generally indicate that TCR type SVCs have performed reliably and satisfactorily as components of the power systems to which they have been applied. The number of forced outages due to failures of major TCR components is observed to be relatively low, as well as the period of disruption due to such failures.

8.5. SVCs CONSISTING OF THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

The technical characteristics of TCR type SVCs have been included together with their operation performance in the previous section. Some of these units include capacitive filter elements tuned to particular harmonics. These filter elements provide some MVAr generation range to the TCRs. In this section combinations of TCR and mechanically switched and/or fixed capacitor devices will be examined where the capacitive elements included are well above the rating required for harmonic filtering purposes.

The experience with the (TCR+MSC+FC) type of SVCs dates back to 1978 as shown in Table II. By far, the largest number of such SVCs are expected to be in operation on the ESCOM (South Africa), and the CHESF (Brazil) transmission systems by mid 1985 to 1987, and five such SVCs are already in service in the Hydro-Quebec (Canada) system. The largest installations are on the Hydro-Quebec and ESCOM systems.

Although the HV voltage of the SVC varies from system to system in the 132 kV to 735 kV range, the preferred LV voltages are in the range of 22 to 30 kV for the larger, and 5 to 24 kV for the smaller SVCs. The majority of the SVCs appear to be twelve pulse configuration while CHESF reports six pulse operation as optional. Air or water cooling is utilised for cooling the thyristors.

Hydro-Quebec reports that four large identical SVCs are installed mainly for improving system transient capability and system damping, with added benefits of voltage control as well as limitation of temporary overvoltages. The larger SVCs on the ESCOM system are installed mainly for improving power transfer and system transient capability. However, the main purpose of the smaller SVCs on the ESCOM system is to minimise the voltage unbalance on the network due to single phase AC traction loads.

Apart from Texas Utilities which reports automatic switching of capacitor banks under lower than nominal voltage conditions, no other specific undervoltage strategies have been reported. Hydro-Quebec reports a series of time duration ratings for up to 2 p.u. overvoltage.

The preferred main control signal is three-phase voltage for the North American SVCs, while individual phase voltages and three-phase voltage, based upon positive and negative sequence only, are preferred by ESCOM and CHESF, respectively. ESCOM reports the use of reactive power as a supplementary signal for switching other means of reactive compensation at the same busbar as the SVC. No clear preference for the method of deriving the main control signal emerged from the replies received.

Preferred slope of the control characteristic is around 3%. While Hydro-Quebec reports a voltage reference setting at nominal system voltage with a ± 5 %, ESCOM reports a voltage reference setting varying in the + 10 % to - 5 % range according to system conditions.

Specification of harmonic performance at the HV busbar is preferred by all the contributors, with Hydro-Quebec and CHESF specifying total and individual harmonic voltage distortion as well as telephone influence factor (TIF) and total harmonic current factor (IT). Individual harmonic current levels are specified by ESCOM. Fixed capacitor banks are utilised as necessary to provide harmonic filtering.

Hydro-Quebec reports a number of additional protection and control features associated with the (TCR + FC) type SVCs on their system. As fuller definition of these features can be found in Chapter 9. A description of the single-phase control applied by ESCOM is given in Table II.

The operational experience so far relates mainly to the Rimouski and Nemiskau SVCs on the Hydro-Quebec system. From the performance data supplied, satisfactory performance of the Rimouski unit with an average of 97 % overall availability is noted. Reactor failures in the early years, and capacitor as well as external equipment failures in the later years of operation, are reported as the main causes of forced outages for this SVC. The poor overall availability of the first Nemiskau SVC in the first two years of operation appears to be mainly due to the failure of the SVC transformer lasting 91 days. In addition, capacitor, SVC control and protection, external equipment failures and human error have contributed adversely to the overall availability. The experience with the second Nemiskau SVC shows a marked improvement over the first unit.

Information on the reliability of the ESCOM compensators is not available. However, no major component failures have been reported in the first year of operation other than a human error causing damage to two thyristors.

8.6 SVCs CONSISTING OF THYRISTOR CONTROLLED REACTORS AND THYRISTOR SWITCHED CAPACITORS (TCR + TSC)

Although the experience with the (TCR + TSC) type of SVCs is confined to the last five years, the majority of the SVCs described in Table III were commissioned between mid 1983 and mid 1985. The majority of the SVCs are rated in the 100 MVar to 300 MVar range, both in MVar generation and absorption range. The SVC output is varied continuously in all applications.

The HV voltage of the SVC varies from system to system in the range of 120 kV to 765 kV, the LV voltages are in the 2.36 kV to 18.7 kV range. Preference appears to be for water cooled thyristors of six pulse configuration, with the exception of air cooling in the ESCOM as well as twelve pulse configuration in the Hydro-Quebec and Norwegian SVCs.

Hydro-Quebec reports that two SVCs at Chateauguay are installed mainly for limiting temporary overvoltages associated with the HVDC link at the same location. The other four identical SVCs are installed mainly for improvement of system transient capability and system damping. ESCOM reports voltage balancing as the main duty of their SVC. Voltage control is cited as the main duty for the SVCs in the SECV (Australia), NVE (Norway) and EDELCA (Venezuela) systems.

Hydro-Quebec reports fixed and/or selectable strategies for SVC operation under transient undervoltage conditions, while under transient overvoltage conditions the SVCs are pushed to their inductive ceiling. Norway reports that, upon fault clearance, the TSC is blocked and TCR is pushed to the inductive ceiling.

The preferred main control signals for the Hydro-Quebec SVCs is three-phase voltage and current, with the voltage measured by a wound VT on the HV side of the SVC transformer. The ESCOM compensator utilises individual phase voltages as the main control signal for voltage balancing duty. SECV and NVE report three-phase voltage as the main signal. SECV utilises frequency and HV current(s) as supplementary signals for enhancing system damping performance, while NVE uses B_{ref} (susceptance) and LV currents as supplementary signals for voltage control purposes.

Preferred slope of the control characteristic is 3 %, except for 5 % used in the Norwegian and 1 % in the ESCOM compensators. Reference voltage settings are generally applied at nominal voltage with a ± 5 % range. Norways reports voltage reference setting corresponding to 0.95 p.u. of nominal and ESCOM reports that the voltage reference setting is varied according to system conditions.

Specification of harmonic performance at the HV busbar is preferred by all utilities participating in the survey. Total as well as individual harmonic voltage distortion, telephone influence factor and total harmonic current factor are specified by Hydro-Quebec and EDELCA. ESCOM reports specification of harmonic currents at the HV busbar while SECV also includes harmonic voltage levels in their specification. Norway specifies total and individual harmonic voltage levels.

EDELCA and Hydro-Quebec report tuning of TSC capacitor bank and series reactor to the 4.5th harmonic (270 Hz) and 5th harmonic, respectively. Separate filters for the 5th and 7th harmonic are included in the SECV compensator, while in the ESCOM compensator filters for the 3rd and 4.5th harmonic (225Hz) are provided.

Detailed definitions of a number of the additional protection and control features associated with the (TCR + TSC) type SVCs on the Hydro-Quebec system are included in Chapter 9. Among the control features used, SVC control system gain supervision is one of the most interesting. Hydro-Quebec and EDELCA indicate use of filtering techniques to protect the SVC controller against second harmonic instability and to improve dynamic response.

The operational experience relating to ESCOM and SECV SVCs is given in Table III. ESCOM reports that the data needed to calculate SVC reliability, is not available. In the five year operational period (1979-1984), ESCOM reports three capacitor failures as causes of SVC forced outages. The thyristor failures reported by ESCOM appear to be mainly due to problems in monitoring the standing voltage on capacitor cans, and saturation of auxiliary supply transformers causing wrong firing, in a design including no redundancy. SECV reports very few failures of the main SVC components in their first year of operation, leading to availability figures of 97.8 % to 99.3 % fot the two SVCs.

8.7 OTHER TYPES OF SVC

Table IV includes the details of SVCs of miscellaneous types, including :

- combination of thyristor controlled reactors, thyristor switched and mechanically switched and/or fixed capacitors (TCR + TSC + MSC + FC)
- combination of thyristor controlled and mechanically switched reactors together with thyristor switched capacitors (TCR + TSC + MSR)
- thyristor switched capacitors and thyristor switched reactors (TSC + TSR)
- self-commutated converters (SCC)
- combination of thyristor controlled transformer and fixed capacitors (TCT + FC)
- saturated reactors (SR)
- combination of saturated reactors and mechanically switched and/or fixed capacitors (SR + MSC + FC).

Among the various types of SVCs shown in Table IV, the experience with the thyristor controlled types dates back to 1978, while the experience with the saturated reactor type SVCs to 1969. Although ratings for individual SVCs span a wide range, the highest ratings observed are 450 MVar for TCT on the Hydro-Quebec (Canada) and 150 MVar for SR on the CEGB (UK) systems.

Six or twelve pulse arrangement is utilised by all thyristor controlled SVCs in Table IV, except for the SCC installation which utilises a 36-pulse arrangement to minimise harmonic generation. Water cooling appears to be used most frequently for cooling of thyristors.

The main purpose of installing the SVC is declared as :

- limitation of temporary overvoltages by Eletronorte (Brazil) and CEGB
- voltage control by SEGBA (Argentina), CAPC (Zambia), NEPA (Nigeria), CELB and SECWA (Australia) and CFE (Mexico)
- system damping enhancement by Vattenfall (Sweden) and Hydro-Quebec (Canada)
- reactive power compensation by Kansai Electric (Japan) and CERN (France)

In the case of thyristor controlled SVCs, except for SCC types, preference appears to be for the use of three-phase voltage measured at HV as the main control signal with the HV current as the supplementary control signal. In the case of the SCC installation, DC voltage, reactive and active power as a main control signal in addition to three phase voltage. The saturated reactor (SR) compensators tend to utilise the SR current for controlling the SVC transformer tapchanger and for switching other reactive compensation devices in the vicinity. The control of the (SR) type of SVC is inherent in its design characteristics.

Practices for controlling harmonics are observed to vary widely, as shown in Table IV. Hydro-Quebec reports tuning of the fixed capacitor bank on the (TCT + FC) type SVC to the 5th and 7th harmonics. CERN reports extensive filter arrangements on the (SR) type SVC due to the pulsed nature of the load on the same busbars as the SVC. CEGB indicates installation of filters on the (SR + MSC) type SVC mainly to improve the harmonic performance of the HVDC installation on the same busbars.

SEGBA mentions remote control and Vattenfall microcomputer control their SVC units. Kansai Electric indicates that the (SCC) type SVC on their system was constructed as a pilot plant for field testing. CERN mentions the use of three regulators on the (SR) type of SVC for accurate voltage control purposes. Detailed definitions for the additional protection and control features of Hydro-Quebec (TCT + FC) type SVCs are included in Chapter 9.

In terms of operational experience, the following are observed from Table IV :

- CERN report very few problems (mainly due to capacitors) with their installation over the past nine years.
- Few major component failures are reported by SEGBA over the first five months of operation of the two SVCs at Rodriguez.
- Despite a number of major component failures and problems initiated by extremely high ambient temperature, Sweden report 97.7 % availability for the two SVCs at Hagby in the first year of operation.
- The availability of the Hydro-Quebec (TCT + FC) type SVC has been adversely affected by a number of major component failures causing forced outages.
- CELB (Australia) reports improved availabilities in the 87 - 100 % range for the Blackwater (SR) type SVCs with accumulated periods of experience, while SECWA (Australia) report 98.3 % availability of the (SR) type SVCs in the first 8 months of operation. Few of the forced outages appear to be related to major components (e.g., capacitors) although some control and protection failures are reported as the main cause of forced outages. The number of forced outages is observed to decrease with accumulated operating experience.

8.8 ADDITIONAL COMMENTS

The additional comments received from the utilities bring into light interesting features of the SVCs and future trends. One of the main features is the changing role of SVCs in certain systems, and successful adaptation of the existing SVCs through control structure and/or major component changes to the new requirements of the system. EdeF (France) indicates a recent utilisation of an SVC for voltage control which was originally installed for flicker compensation. Vattenfall (Sweden) reports the extension of the two TSCs in a programmed manner by installation of additional TCRs to suit the planned system requirements (ref. 332).

Many of the contributors indicate the use of signals related to the SVC output to control other reactive compensation devices at the same busbar or in the vicinity of the SVC. SEGBA (Argentina) and Vattenfall (Sweden) report remote control of the SVCs.

Interesting trends appear to be evolving in the control and co-ordination of the SVCs with other reactive power compensation devices. Vattenfall reports use of microprocessor control and supervision of the TSCs at three different hierarchical levels. Due to the exacting requirements of controls to compensate a pulsed load, CERN reports the use of three regulators to control and maintain the SVC characteristics best suited to the requirements. Extensive use of band reject filters to improve the dynamic response of the SVC and to protect the controls against harmonic instability is becoming a common practice. Hydro-Quebec reports the use of a gain supervisor and optimiser as an aid in continually tuning the SVC controls to achieve the desired SVC performance under changing network conditions (ref. 321). The use of system frequency as a supplementary signal to the SVC control for system damping enhancement is a development which is likely to be more frequently applied intransmission networks operated closer to stability performance limits.

8.9 SVC FIELD TESTING TRENDS

All utilities participating in the survey expressed preference for field tests in addition to the normal SVC equipment commissioning tests. The field tests, especially for the larger size of SVCs, represent the first opportunity to test the performance of all the SVC components at the same time. From the comments received on field testing, one or more of the following tests were carried out by each utility to confirm the SVC performance against the specification :

1. SVC control system tests
2. Voltage regulating performance tests
3. Small disturbance dynamic performance tests
4. Large disturbance dynamic performance tests
5. Overload capability tests
6. Harmonic performance tests

The control system tests include testing of switching sequences, start up sequences,synchronising/firing pulse generation and distribution, control limit signals, override signals and the response of the control system.

The voltage regulating performance tests are carried out mainly to establish the SVC rating and the slope of the control characteristic. These tests are usually carried out by inducing reactive power changes in the network under otherwise steady-state system conditions. The reactive power changes are usually induced by switching other reactive compensation equipment in the vicinity of the SVC or by switching unloaded transmission lines.

The small disturbance dynamic performance characteristics are tested to establish the dynamic response for small voltage/reactive power changes within the SVC control range. Injection of small step voltage changes to the SVC voltage regulator is a classical way of establishing small disturbance dynamic performance.

The large disturbance dynamic performance of the SVC is tested by means of a system fault (usually single line to ground) or by large reactive power changes outside the SVC range. These tests also verify correct functioning of the SVC control sequences under disturbances likely to cause erroneous operation.

Where overload ratings are specified, system fault and/or large reactive power change tests are used to establish the specified ratings.

Finally, harmonic performance tests are carried out to confirm the specified performance and to examine the need for any additional filtering, considered only marginally beneficial based on analytical studies in the design stage.

The above tests are usually repeated under a variety of network conditions to establish performance under as wide system strength conditions as possible. These repeat tests also enable checking of the SVC performance over the specified operating voltage range.

In some cases where network resonances at certain harmonic frequencies are expected, extensive measurements of the system harmonic impedance are undertaken. Wherever necessary, monitoring of SVC interactions with equipment is also undertaken.

In cases where the SVC is mainly used for improving system transient and/or damping performance, other system tests to examine such performance may be necessary.

8.10 CONCLUSIONS

The survey of SVC installations has provided valuable insight to both technical design, testing and operational experience of such installations throughout the world. Continued monitoring of this experience is most likely to be of continued benefit to utilities who are in the process of planning SVC installations. The sharing of experience is of benefit to all in assuring more reliable service from both existing and planned SVC equipment. With the commissioning of a large number of SVCs in the near future more operational experience will become available.

The general experience with SVC installations underlines the need for very close co-operation between the manufacturers and utilities in both establishing the SVC technical characteristics, matching these characteristics to short and long term power system needs, and bringing the devices into service. Careful and detailed definition of the SVC characteristics, taking account of the future system needs, ensures manufacture of equipment that will meet the requirements in the most effective way. The operational experience to date indicates whilst the experience obtained is more than satisfactory improvements in certain areas will yield better experience in the future.

TABLE I

PART 1 - APPLICATION AND DESIGN DATA FOR THYRISTOR CONTROLLED REACTORS (TCR)

REF. NO.	1, 2 & 3	4	5	6	7 & 8	9
1. UTILITY	Endesa, Chile	Basin Electric Bismarck, USA	El Paso Electric, Texas, USA	Norwegian Water Resources & Electricity Board, Norway	Norwegian Water Resources & Electricity Board, Norway	Electricite de France
SVC Location	Maintecillo (1 Unit) Pan de Azucar (2 Units) Substations	Victory Hill Substation		Kvandal Substation	Hasle (2 Units) Substation	Les Ancizes Substation
2. STATUS	In Service	In Service	In Service	In Service	In Service	In Service
3. COMMISSIONING DATE	January 1981	November 1977	March 1984	June 1982	March 1981	June 1982
4. TYPE OF SVC	TCR	TCR	TCR	TCR	TCR	TCR
Thyristor Configuration	Six Pulse	Six Pulse	Six Pulse	Twelve Pulse	Twelve Pulse	Six Pulse
Thyristor Cooling Method	Air	Air	Air	Glycol	Glycol	Air
5. SVC RATING						
Continuous Rating MVAr (Capacitive)	22.4 MVAr @ 13.8 kV	30 MVAr @ 13.8 kV	25 MVAr @ 13 kV	-	-	24.64 MVAr @ 63 kV
Continuous Rating MVAr (Inductive)	30.0 MVAr (*) @ 13.8 kV	10.0 MVAr (*) @ 13.8 kV	50 MVAr (**) @ 13 kV	160 MVAr @ 420 kV	180 MVAr @ 420 kV	21 MVAr (**) @ 63 kV
Overload Rating (Capacitive)	-	-	-	-	-	-
Overload Rating (Inductive)	1.233 pu I - 15 min. 1.333 pu I - 10 min. 1.5 pu I - 5 min. @ 13.8 kV		3 pu I - 10 sec. @ 13 kV	1.3 pu I - 1 sec. @ 420 kV	1.1 pu I - cont. 1.5 pu I - 1 sec. @ 420 kV	1.9 pu I - 600 sec. 3 pu I - 0.5 sec.
Rated Voltage of the SVC Transformer	230/13.8 kV	230/115/13.8 kV	345/115/13 kV	420/8.33/8.24 kV	420/11.78/11.8 kV	63/9 kV
Rated Frequency	50 Hz	60 Hz	60 Hz	50 Hz	50 Hz	50 Hz
6. TOTAL OUTPUT OF SVC VARIED	Continuously	Continuously	Continuously	Continuously	Continuously	Continuously
Step Size MVAr (Capacitive)	-	-	-	-	-	-
Step Size MVAr (Inductive)	-	-	-	-	-	-

(*) including filters (**) not including filters

TABLE I

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS (TCR)

REF. NO.	1, 2 & 3	4	5	6	7 & 8	9
7. PURPOSE OF INSTALLING SVC						
Voltage Control	1	1	1	1	-	2
Voltage/Load Balancing	-	-	5	-	1	-
Reactive Power Compensation	2	-	3	2	2	-
Limiting of Temp. Overvoltages	-	-	4	-	-	-
Improving Power Tr. Capability	3	2	2	3	3	-
Improving System Transient Cap.	-	-	6	-	-	-
System Damping Enhancement	-	-	-	-	4	-
Subsynchronous Resonance Damping	-	-	-	-	-	-
Others	-	-	-	-	-	1-flicker comp. (see additional comments)
Control Strategy Under Transient Undervoltage	Temporary firing pulse interruption 0.7 puU - 0.2 sec. <0.5 puU - SVC disconnection	None	None	MVAr absorption reduced till 0.75 puU when thyristors fire for max. absorption 0.75 puU - 1 sec.	MVAr absorption reduced till 0.75 puU when thyristors fire for max. absorption 0.75 puU - 1 sec.	0.7 puU - cont. 0.15 puU - 0.3 sec.
Transient Overvoltage Magnitude and Duration	-	1.05 puU - 60 sec.	1.6 puU - 10 sec.	1.3 puU - 1 sec.	1.3 puU - 1 sec.	1.7 puU - 0.5 sec. without SVC
8. MAIN(M) & SUPPLEMENTARY(S) CONTROL SIGNALS						
Three Phase Voltage	M at HV	M at HV	M at HV	M at HV	M at HV	M2 at HV
Individual Phase Voltage	-	-	M at HV	-	-	-
Current (s)	-	-	S at LV	S at LV	S at LV	S2 at LV
Active Power	-	-	-	-	-	M1 at HV
Reactive Power	-	-	-	-	-	M1 at HV
Speed	-	-	-	-	-	-
Frequency	-	-	-	-	-	-
Others	-	-	-	-	-	-
9. CONTROL SIGNAL SENSORS	Wound VT	Wound VT	Wound VT	Wound VT	Wound VT	Wound VT

TABLE I

PART 1 - APPLICATION AND DESIGN DATA FOR THYRISTOR CONTROLLED REACTORS (TCR)

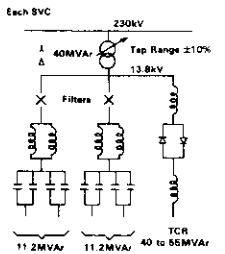
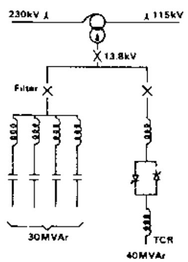
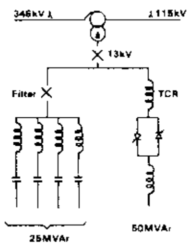
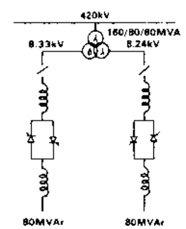
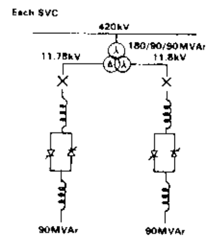
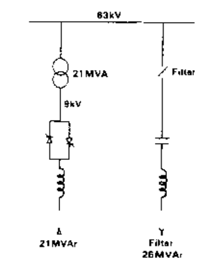
REF. NO.	1, 2 & 3	4	5	6	7 & 8	9
10. SLOPE OF THE CONTROL CHARACTERISTIC	4%	0.5%	5%	5%	5%	6.3%
11. REFERENCE VOLTAGE SETTING AND ± RANGE %	1.02 pu nom. ±10%	1.0 pu nom. ±5%	1.0 pu nom. ±5%	0.95 pu nom. ±5%	0.95 pu nom. ±5%	1.0 pu nom. ±5%
12. FAULT LEVEL AT HV						
Maximum	900 MVA	450 MVA	7.5 kA	22000 MVA	30000 MVA	630 MVA
Minimum	300 MVA	250 MVA	-	1000 MVA	3000 MVA	200 MVA
13. HARMONICS Specified at . . . Busbar	Currents 20% total at HV bus	-	Harmonic Currents 2nd 100A 5th 420A 7th 300A 11th 140A all measured at the 13kV tertiary of transformer to which SVC is connected	For all harmonics above fundamental at HV $D_n \leqslant 0.7\%$ $D_{rss} \leqslant 1\%$	-	D_n (odd) $\leqslant 0.6\%$ D_n (even) $\leqslant 1\%$ $D_{rss} \leqslant 1.6\%$
Measured at . . . Busbar	Currents 2.77% total at HV bus	-	-	@ transformer HV U_5 = 0.1% U_7 = 0.04% U_{11} = 0.08% U_{13} = 0.06% I_5 = 0.31% I_7 = 0.1% I_{11} = 0.44% I_{13} = 0.33%	@ transformer HV U_5 = 0.11% U_7 = 0.06% U_{11} = 0.43% U_{13} = 0.31% I_5 = 0.15% I_7 = 0.07% I_{11} = 1.0% I_{13} = 0.753%	-
15. SINGLE LINE DIAGRAM						
16. HARMONIC FILTERS	5th 13.8 kV (LV) connected with rating of 11.2 MVAr	2nd, 3rd, 5th and 7th total rating @ 13.8 kV (LV) 30 MVAr	2nd, 5th, 7th and 11th total rating @ 13 kV (LV) 25 MVAr	None	None	@ 63 kV (HV) 3rd filter rated 12.8 MVAr 5th filter rated 11.9 MVAr

TABLE I

PART 1 - APPLICATION AND DESIGN DATA FOR THYRISTOR CONTROLLED REACTORS (TCR)

REF. NO.	1, 2 & 3	4	5	6	7 & 8	9
17. ADDITIONAL COMMENTS	None	None See References 122, 134 & 217	-	None	None See References 246, 284 & 358	Initially this SVC was built for flicker compensation purposes. However, subsequently it has been utilised as a means of voltage control. See Reference 344
18. FIELD TESTS	1. SVC starting test to prove the control sequence and its influence on the rest of the system both in manual and automatic modes. 2. SVC voltage regulating performance test to verify SVC response to changes in voltage. 3. SVC performance tests under 220kV transmission line charging conditions to verify SVC response at manual and automatic operating modes under various system line charging conditions. 4. Tests to check the SVC response at various levels of system voltage. 5. Tests to check SVC response during transformer energising to analyse resulting disturbance.	1. SVC Start-up 2. SVC response to low voltages 3. SVC response to fast MW load changes 4. SVC response to an unbalanced fault See Reference 217			1. SVC response to single phase to ground fault 28 km away from the station. 2. SVC response to energisation of cables in the vicinity of the SVC under different system fault level conditions (varying from 14000 MVA to 9000 MVA) See References 246, 284, 358	1. Tests on SVC response at various system fault levels. 2. SVC response tests utilising a nearby hydro-generator plant.

TABLE I

PART 2 : RELIABILITY AND PERFORMANCE DATA FOR THYRISTOR CONTROLLED REACTORS (TCR)

RELIABILITY AND PERFORMANCE DATA / SVC REF. NO.	1			2			3			6		7			8			9	
LOCATION	Endesa, Chile Maintecillo			Endesa, Chile Pan de Azucar (1)			Endesa, Chile Pan de Azucar (2)			NVE Norway Kvandal		NVE, Norway Hasle (1)			NVE, Norway Hasle (2)			EdeF, France Les Ancizes	
YEAR	1981	1982	1983	1981	1982	1983	1981	1982	1983	6/82 - 6/83	6/83 - 3/84	3/81 - 3/82	3/82 - 3/83	3/83 - 3/84	3/81 - 3/82	3/82 - 3/83	3/83 - 3/84	1983	1984
1. Overall Availability of the SVC %	99.27	99.15	98.03	97.9	98.34	98.82	98.57	99.12	98.87	98.2	98.6	97.3	98.0	98.5	97.3	98.6	99.2	95	100
2. Planned Outage Rate (P.O.R.) %	0.57	0.7	1.1	2.0	0.97	1.05	1.38	0.87	0.96	1.4	1.2	0.96	0.96	0.68	0.96	0.68	0.27	0	-
3. Forced Outage Rate (F.O.R.) %	0.16	0.15	0.87	0.1	0.69	0.13	0.05	0.01	0.17	0.5	0.2	1.8	1.1	0.82	1.8	0.68	0.54	5	-
4. Mean Time Between Planned Outages (Hours)	796.4	548	973	398.2	584	730	584	626	626	1752	2190	2190	2190	4380	2190	2920	8760	-	-
5. Mean Time Between Forced Outages (Hours)	1251	1752	1095	584	1095	2920	973	973	1251	1460	3285	1752	2190	4380	1752	2920	2920	-	-
6. Mean Time Per Planned Outage (Hours)	4.55	3.8	11.0	7.98	7.7	6.0	8.07	5.4	6.0	24.4	27.3	21	21	30	21	20	24	-	-
7. Mean Time Per Forced Outage (Hours)	2.0	2.7	9.5	0.4	0.75	3.7	0.44	0.06	2.1	7.7	6.5	31.2	24	36	31.2	20	16	-	-
8. Number of Failures Causing Forced Outage(s) of the SVC. Please Specify for:																			
8.1 Transformers	-	-	-	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
8.2 Capacitors	2	-	-	-	-	-	-	-	-	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-	-
8.3 Reactors	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8.4 Filters	-	-	-	-	-	-	-	-	-	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-	-
8.5 Circuit Breakers and Isolators	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8.6 Thyristor Valves	-	-	-	-	-	-	-	-	-	4	-	3	2	1	3	3	2	-	-
8.7 SVC Control & Internal Protection Equipment	1	2	4	2	2	2	1	5	1	-	-	-	-	-	-	-	1	1	-
8.8 Auxiliaries	-	-	-	1	1	-	-	-	1	2	2	2	2	1	2	-	-	-	-
8.9 Others (Please Specify):	Refrigeration System 4 (2)	3(2)	4(2)	Refrigeration System 10 (2)	5 (2)	1(2)	Refrigeration System 7(2)	5(2) 3(1)	1 (2)	-	-	-	-	1(3)	-	-	-	-	-
9. If the above quantities apply to a period of less than one year please indicate the period in hours.	-	-	-	-	-	-	-	-	-	-	6570	-	-	-	-	-	-	100 (4)	2190

(1) Fittings (2) Refrigeration system (3) Primary side surge arrester (4) Testing in 1983

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

	1	2 & 3	4 & 5	6	7, 8, 9, 10, 11 & 12	13, 14, 15, 16 & 17	18
1. UTILITY	Hydro-Quebec, Canada			Texas Utilities, USA	ESCOM, South Africa	ESCOM, South Africa	Ande, Paraguay
SVC Location	Rimouski Substation (CLC31)	Nemiskau (2 Units) (CLC11 and CLC12) Substation	Albanel (2 Units) Substation			Perseus (2 Units) Hydra (2 Units) Poseidon Substations	San Lorenzo Substation
2. STATUS	In Service	In Service	In Service	In Service	In Service	In Service	In Service
3. COMMISSIONING DATE	February 1978	Autumn 1978	Autumn 1982	August 1984	April 1983–June 1984	February 1984	1985
4. TYPE OF SVC	TCR + MSC	TCR + MSC	TCR + MSC	TCR + FC + MSC	TCR + FC	TCR + FC	TCR + FC + MSC
Thyristor Configuration	Six Pulse	Twelve Pulse	Twelve Pulse	Six Pulse	Six Pulse		12 Pulse
Thyristor Cooling Method	Air	Air	Air	Air	Water		Deionised Water
5. SVC RATING							
Continuous Rating MVAr (Capacitive)	84 MVAr @ U = 0.97 pu	300 MVAr @ U = 0.97 pu	300 MVAr @ U = 0.97 pu	150 MVAr @ 138 kV	35 MVAr @ U = 0.9 pu @ 132 kV	250 MVAr @ 400 kV (also 150 or 50 MVAr)	100 MVAr @ 66 kV
Continuous Rating MVAr (Inductive)	0 MVAr(*) @ U = 1.0 pu (with slope @ 3%)	105 MVAr @ U = 1.01 pu (with slope @ 3%)	105 MVAr @ U = 1.01pu (with slope @ 3%)	55 MVAr @ 13.8 kV	10 MVAr(*) @ U = 1.1pu @ 132 kV	50 MVAr @ 400 kV (also 150 or 250 MVAr)	80 MVAr @ 66 kV
Overload Rating (Capacitive)	-	-	-	-	-	-	-
Overload Rating (Inductive)	120 MVAr - 5 min. @ U = 1.04 pu 200 MVAr - 1 sec. @ U = 1.065 pu	1719 MVAr - 0.033 sec. @ U = 2 pu 1400 MVAr - 0.033 sec. @ U = 1.8 pu 1100 MVAr - 1 sec. @ U = 1.6 pu	1719 MVAr - 0.033sec. @ U = 2 pu 1400 MVAr - 0.033sec. @ U = 1.8 pu 1100 MVAr - 1 sec. @ U = 1.6 pu	2.3 puI - 10 sec. (125 MVAr)	1.4 puI - 0.05 sec. 1.1 puI - 15 sec.	1.4 puI - 0.05 sec. 1.1 puI - 15 sec.	
Rated Voltage of the SVC Transformer	230/24 kV	735/22/22 kV	735/22/22 kV	230/138/13.8 kV	132/5.1 kV	400/30 kV	66 kV
Rated Frequency	60 Hz	60 Hz	60 Hz	60 Hz	50 Hz	50 HZ	50 Hz
6. TOTAL OUTPUT OF SVC VARIED	Continuously	Continuously	Continuously	Continuously in the 55 MVAr absorption to 25 MVAr generation range. Capacitor step size 62.5 MVAr in generation range.	Continuously	Continuously	Continuously
Step Size MVAr (Capacitive)	-	-	-		-	-	-
Step Size MVAr (Inductive)	-	-	-		-	-	-

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

	1	2 & 3	4 & 5	6	7, 8, 9, 10, 11 & 12	13, 14, 15, 16 & 17	18
7. PURPOSE OF INSTALLING SVC							
Voltage Control	1	2	2	1	2	3	1
Voltage/Load Balancing	-	-	-	-	1(*)	-	-
Reactive Power Compensation	-	-	-	-	-	-	-
Limiting of Temp. Overvoltages	2	3	3	-	-	-	-
Improving Power Tr. Capability	-	-	-	2	-	1	2
Improving System Transient Cap.	-	1	1	-	-	2	-
System Damping Enhancement	-	1	1	-	-	-	-
Subsynchronous Resonance Damping	-	-	-	-	-	-	-
Others	-	-	-	-	-	-	-
Control Strategy Under Transient Undervoltage	None	None	None	Fixed capacitor banks switched in @ U = 0.95 to 0.97 pu instantaneously	None	None	MSC are switched in and MSR is switched out
Transient Overvoltage Magnitude and Duration	See Overload Rating	See Overload Rating For 3 phase overvoltages over 1.5 pu for 0.033 sec. the voltage regulator is pushed to inductive ceiling	See Overload Rating	None	-	-	1.5 pu - 0.1 sec. 1.2 pu - 5 sec.
8. MAIN(M) & SUPPLEMENTARY(S) CONTROL SIGNALS							
Three Phase Voltage	M at HV	M at HV	M at HV	M at LV	-	-	M1 @ HV
Individual Phase Voltage	-	-	-	S at LV	M at LV	M at LV	M2 @ HV & LV
Current(s)	-	-	-	-	-	-	S1 @ HV & LV
Active Power	-	-	-	-	-	-	S2 @ LV
Reactive Power	-	-	-	-	S1(**) at HV	S1 at LV	-
Speed	-	-	-	-	-	-	-
Frequency	-	-	-	-	-	-	-
Others	Provision for implementation of supplementary signals has been made if such signals are desired in future			-	-	-	-
. . . .				-	-	-	-
9. CONTROL SIGNAL SENSORS	Wound VT	Transformer Bushing Capacitor	Transformer Bushing Capacitor	Wound VT	Wound VT	Capacitor Voltage Divider	Wound VT

(*) Voltage balancing: Reduction of negative-phase sequence voltage produced by single phase AC traction loads.
(**) For droop control and switching of other "external" shunt reactors and capacitors at the same substation.

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

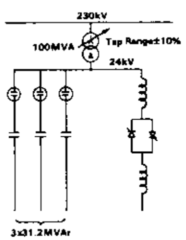
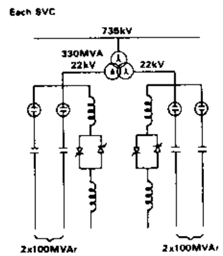
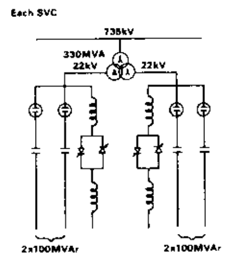
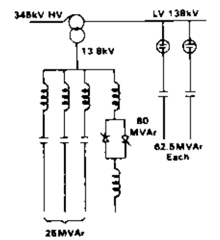
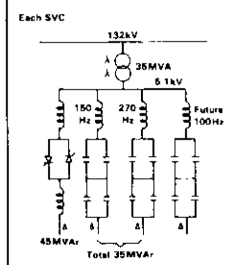
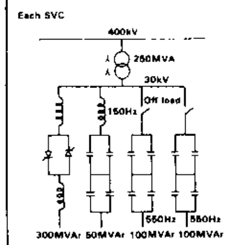
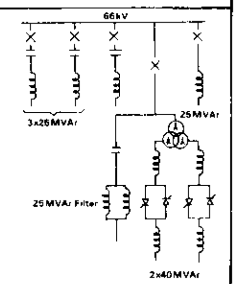
	1	2 & 3	4 & 5	6	7, 8, 9, 10, 11 & 12	13, 14, 15, 16 & 17	18
10. SLOPE OF THE CONTROL CHARACTERISTIC	3% (Adjustable 3-10%)	3% (Adjustable 3-10%)	3% (Adjustable 3-10%)	3.3%	Close to 0% (Adjustable 0-10%)	3%	3% (Adjustable 0-10%)
11. REFERENCE VOLTAGE SETTING AND ± RANGE %	1.0 pu nom. ±5%	1.0 pu nom. ±5%	1.0 pu nom. ±5%	1.02 pu nom. @ 138 kV ±5%	Ref. V setting according to system conditions +10 to -5% range	Ref. V setting according to system conditions +10 to -5% range	1.0 pu nom. ±10%
12. FAULT LEVEL AT HV Maximum Minimum	5000 MVA 2000 MVA	50 kA 5.5 kA (could be 0.5 kA under abnormal conditions)	50 kA 5.5 kA (could be 0.5 kA under abnormal conditions)	Max. 24.5kA @ 13.8 kV 19.5kA @ 138 kV 8.7 kA @ 345 kV Min. 23.9kA @ 13.8 kV 14.5kA @ 138 kV 2.9 kA @ 345 kV	16 kA or 3660 MVA 0.45 kA or 103 MVA	21800 MVA 2800 MVA	@ 66 kV bus 1000 MVA 300 MVA
13. HARMONICS Specified at . . . Busbar	@ HV bus $D_n \leqslant 1\%$ $D_{arith} \leqslant 4\%$ Max. TIF - 20 Max. IT - 25000	@ HV bus $D_n \leqslant 1\%$ $D_{arith} \leqslant 4\%$ Max. TIF - 20 Max. IT - 10000	@ HV bus $D_n \leqslant 1\%$ $D_{arith} \leqslant 4\%$ Max. TIF - 20 Max. IT - 10000	Specified at 138 kV bus $D_n \leqslant 1\%$ for harmonics $n \leqslant 25$	Specified at HV (132 kV) bus $D_n \leqslant 1\%$ $D_{rss} \leqslant 3\%$ Individual Harmonic Currents $< \frac{4.5}{n}$ where n is the harmonic number	Specified at HV (400 kV) bus $D_n \leqslant 1\%$ $D_{rss} \leqslant 3\%$ Individual Harmonic Currents $< \frac{40}{n}$ where n is the harmonic number	D_n (odd) < 0.5% D_n (even) < 0.25% I_5 < 3.5A I_{11} < 1.5A @ 66 kV
Measured at . . . Busbar	@ HV bus Max. total voltage distortion 2.3% max. voltage distance @ 5th harmonic - 0.97% Max. TIF - 9.26 Max. IT - 4840	Measured @ HV bus with all Nemiskau & Albanel units in service Max. total voltage distortion 0.82% Max. volt. dist. @ 3rd harmonic - 0.23% Max. TIF - 3.25 Max. IT - 1145	Max. total voltage distortion -1.367% Max. voltage dist. @ 3rd harmonic - 0.45% Max. TIF - 4.63 Max. IT - 1160		Measured at HV bus $D_n < 1\%$ including the SVC influence	Measurements in progress	
15. SINGLE LINE DIAGRAM							
16. HARMONIC FILTERS	None	None	None	@ 13.8 kV tertiary 2nd - 5 MVAr 5th - 10 MVAr 7th - 13.3 MVAr	@ 5.1 kV LV 3rd - 12 MVAr 5th & 7th - 23 MVAr See note on field tests	@ 30 kV LV 3rd - 50 MVAr 11th - 100 MVAr 11th - 100 MVAr	25 MVAr High damped filter @ 66 kV

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR

THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

	1	2 & 3	4 & 5	6	7, 8, 9, 10, 11 & 12	13, 14, 15, 16 & 17	18
17. ADDITIONAL COMMENTS	TCR are at maximum conduction angle at U = 1.065 pu for 1 sec. (with U_{ref} = 1.0 pu) Max. U_{ref} = 1.05 pu Protection features: - Voltage breakover - Overcurrent limit - Thyristor over-temperature protection See References 175, 183, 184, 204	TCR are at max. condition angle at U = 1.046 pu for 2.5 sec. (with U_{ref} = 1.0 pu) Max. U_{ref} = 1.05 pu Protection control features: - Voltage breakover protection - Overcurrent limit - Thyristor overtemperature protection - Joint control - Var limiter - Voltage control current limit - Overvoltage regulator override - Non-linear gain - Emergency response time setting (manual) - Time constant supervisor (understudy) - TCR A.s balance (to minimise dc current) - AC filter in the control system to prevent control system instability due to network resonance See References 190, 160, 211		None	Compensator operates on a single phase basis control options are: (a) Voltage control (b) Current control (3-phase only) Compensator slope is dependent either on: (i) average output of all 3 phases (equal slope on each phase) (ii) the output of each phase determining the slope of that phase. When one phase reaches its capacitive or inductive limit preference is given either to: (a) maintaining the average voltage control (positive sequence only) (b) maintaining the negative phase sequence control	All comments on SVCs 7-12 apply with the following additional comments: - First two compensators commissioned will also control up to 4 x 100 MVAr shunt reactors situated in the same substation. - Compensators applied to long distance transmission scheme of 1600 km @ 400 kV	SVC layout designed to permit future installation of three further MSCs. SVC designed for six pulse operation when one TCR is out of service.
18. FIELD TESTS	Field tests carried out for each installation in service. Tests carried out to verify: 1) Steady-state characteristics; rating, slope, harmonic production, control system transfer functions. 2) Network impedance as a function of frequency has been measured at Nemiskau and Albanel. 3) Dynamic characteristics; by step injection to voltage regulator, inductor and transformer switching, single line to ground fault application. Dynamic characteristic tests also verified control settings. Comments: - Large perturbation tests considered necessary to verify compensator performance under conditions of need and to verify firing pulse synchronisation. - Model testing on TNA permits identification of possible harmonic instability problems. - Event recorders are very useful to observe control system stability during compensator operation.			None	Field tests on first two units carried out as part of commissioning to prove: - individual response of units to faults and load switching in the system under various system configurations - interaction between these two units which are approx. 40 km's apart on the 132 kV network - interaction with other pieces of equipment e.g. transformer automatic tapchangers and shunt capacitor banks See References 218, 327, 337	Commissioned in Feb. 1984. Due to urgency of commissioning other SVCs only monitoring of SVC behaviour has been undertaken.	Tests on SVC steady-state and dynamic response and harmonics under different SVC and system operating conditions. See References 326 and 348

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

	19	20 & 21	22	23	24	25, 26 & 27	28, 29 & 30
1. UTILITY	CHESF, Brazil	CHESF, Brazil	CHESF, Brazil	CHESF, Brazil	CHESF, Brazil	CHESF, Brazil	CHESF, Brazil
SVC Location	Fortaleza Substation	Banabuiu and Milagres Substations	Rio Largo Substation	S. Luis Substation	Teresina Substation	Natal, Funil and Irece Substations	Sobral, Piripiri and Bom Jesus de Lapa Substations
2. STATUS	On Order	On Order	On Order	On Order	On Order	On Order	On Order
3. COMMISSIONING DATE	1984/5	1985	June 1986	December 1986	November 1986	January 1986	1986/7
4. TYPE OF SVC	TCR + FC	TCR + FC	TCR + FC	TCR + FC	TCR + FC	TCR + FC	TCR + FC
Thyristor Configuration	12 pulse (6 pulse optional)	12 pulse (6 pulse optional)	12 pulse (6 pulse optional)	12 pulse (6 pulse optional)	12 pulse (6 pulse optional)	12 pulse (6 pulse optional)	12 pulse (6 pulse optional)
Thyristor Cooling Method							
5. SVC RATING							
Continuous Rating MVAr (Capacitive)	2 x 100 MVAr @ 26 kV	100 MVAr @ 12.3 kV	200 MVAr @ 26 kV	200 MVAr @ 16.7 kV	100 MVAr @ 8.35 kV	50 MVAr @ 8.35 kV	50 MVAr @ 8.35 kV
Continuous Rating MVAr (Inductive)	2 x 70 MVAr @ 26 kV	70 MVAr @ 12.3 kV	0 MVAr @ 26 kV	140 MVAr @ 16.7 kV	70 MVAr @ 8.35 kV	30 MVAr @ 8.35 kV	0 MVAr @ 8.35 kV
Overload Rating (Capacitive)	-	-	-	-	-	-	-
Overload Rating (Inductive)	2 x 77 MVAr - cont. 2 x 168 MVAr - 10 sec 2 x 357 MVAr - 150 msec.	100.8 MVAr - 10 sec. 137.2 - 150 msec. 226.8 - 33 msec.	-	168 MVAr - 10 sec. 274.4 MVAr - 100 msec 453.6 MVAr - 33 msec.	100.8 MVAr - 10 sec. 137.2 MVAr - 150 msec. 226.8 MVAr - 33 msec	43.2 MVAr - 10 sec. 58.8 MVAr - 150 msec. 97.2 MVAr - 33 msec.	-
Rated Voltage of the SVC Transformer	230/26/26 kV	230/12.3/12.3 kV	230/26/26 kV	230/16.7/16.7 kV	230/8.35/8.35 kV	230/8.35 kV	230/8.35 kV
Rated Frequency	60 Hz	60 Hz	60 Hz	60 Hz	60 Hz	60 Hz	60 Hz
6. TOTAL OUTPUT OF SVC VARIED	Continuously	Continuously	Continuously	Continuously	Continuously	Continuously	Continuously
Step Size MVAr (Capacitive)	-	-	-	-	-	-	-
Step Size MVAr (Inductive)	-	-	-	-	-	-	-

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR
* THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED (TCR + MSC + FC)

	19	20 & 21	22	23	24	25, 26 & 27	28, 29 & 30
7. PURPOSE OF INSTALLING SVC							
Voltage Control	1	1*	1	1*	1	1	1
Voltage/Load Balancing	-	-	-	-	-	-	-
Reactive Power Compensation	-	-	-	-	-	-	-
Limiting of Temp. Overvoltages	2	-	-	-	-	-	-
Improving Power Tr. Capability	-	-	2	2	2	2	2
Improving System Transient Cap.	-	-	-	2	3	-	-
System Damping Enhancement	-	-	-	-	-	-	-
Subsynchronous Resonance Damping	-	-	-	-	-	-	-
Others	-	-	-	-	-	-	-
Control Strategy Under Transient Undervoltage							
Transient Overvoltage Magnitude and Duration							
8. MAIN (M) & SUPPLEMENTARY (S) CONTROL SIGNALS							
Three Phase Voltage	M** @ HV	M** @ HV	M @ HV	M** @ HV	M @ HV	M** @ HV	M** @ HV
Individual Phase Voltage	-	-	-	-	-	-	-
Current (s)	M @ HV	M @ HV	M @ HV	M @ HV	M @ HV	M @ HV	M @ HV
Active Power	-	-	-	-	-	-	-
Reactive Power	-	-	-	-	-	-	-
Speed	-	-	-	-	-	-	-
Frequency	-	-	-	-	-	-	-
Others	-	-	-	-	-	-	-
. . . .							-
9. CONTROL SIGNAL SENSORS							

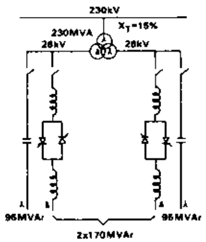
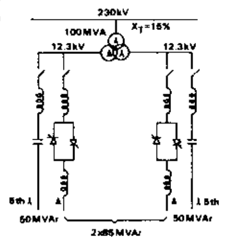
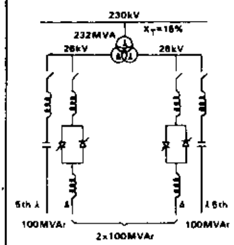
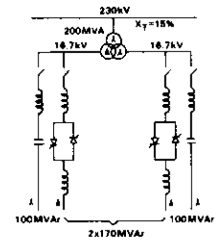
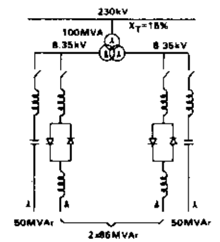
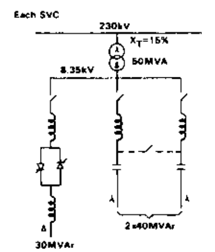
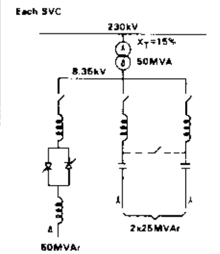
* Voltage control in the nominal 0.95 pu to 1.05 pu range and to limit voltage change due to a single outage within 5% (steady-state) at Milagres and St. Luis.

** Positive and negative sequence

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR

THYRISTOR CONTROLLED REACTORS AND MECHANICALLY SWITCHED AND/OR FIXED (TCR + MSC + FC)

	19	20 & 21	22	23	24	25, 26 & 27	28, 29 & 30
10. SLOPE OF THE CONTROL CHARACTERISTIC	Adjustable 0-10%	Adjustable 0-10%	Adjustable 0-10%	Adjustable 0-10%	Adjustable 0-10%	Adjustable 0-10%	Adjustable 0-10%
11. REFERENCE VOLTAGE SETTING AND ± RANGE %	-	-	-	-	-	-	-
12. FAULT LEVEL AT HV Maximum Minimum	1600 MVA 350 MVA	2500 MVA* 1600 MVA** 310 MVA* 960 MVA**	3890 MVA 1560 MVA	2800 MVA 730 MVA	1250 MVA 1000 MVA	1320/800/1250 MVA 600/680/300 MVA	595/650/280 MVA 475/550/165 MVA
13. HARMONICS Specified at . . . Busbar	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000	@ HV D_n (odd) $\leqslant$ 1% D_n (even) $\leqslant$ 0.6% D_{rss} $\leqslant$ 1.5% TIF < 25 IT > 10000
Measured at . . . Busbar	-	-	-	-	-	-	-
15. SINGLE LINE DIAGRAM							
16. HARMONIC FILTERS	None	Fixed capacitor arms tuned to 5th harmonic total rating 2 x 84.3 MVAr @ 16.29 kV	Fixed capacitor arms tuned to 5th harmonic total rating 2 x 199.7 MVAr @ 37.34 kV	Fixed capacitor arms tuned to 5th harmonic total rating 2 x 114.37 MVAr @ 18.9 kV	Fixed capacitor arms tuned to 5th harmonic total rating 2 x 70.89 MVAr @ 10.1 kV	Fixed capacitor arms tuned to 5th harmonic total rating 2 x 35.45 MVAr @ 10.1 kV	Fixed capacitor arms tuned to 5th harmonic total rating 2 x 35.45 MVAr @ 10.1 kV

* at Banabuiu Substation   ** at Milagres Substation

TABLE II

PART 1 - APPLICATION AND DESIGN DATA FOR

THYRISTOR CONTROLLED REACTOR AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

	19	20 & 21	22	23	24	25, 26 & 27	28', 29 & 30
17. ADDITIONAL COMMENTS	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ± 0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are three phase iron cored.	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ± 0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are three phase iron cored.	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ± 0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are threee phase iron cored.	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ± 0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are three phase iron cored.	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ± 0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are three phase iron cored.	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ± 0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are three phase iron cored.	Continuous output @ 230 kV must be possible without any component exceeding maximum rated temperature with all reserve equipment out of service under the following conditions: T_{amb} = 40°C freq. = 60Hz ±0.1Hz U = 230 kV ±5% SVC transformer at nominal tap. TCR reactors are three phase iron cored.
18. FIELD TESTS	-	-	-	-	-	-	-

TABLE II

PART 2 - RELIABILITY AND PERFORMANCE DATA FOR THYRISTOR CONTROLLED REACTOR AND MECHANICALLY SWITCHED AND/OR FIXED CAPACITORS (TCR + MSC + FC)

RELIABILITY AND PERFORMANCE DATA / SVC REF. NO.	1					2			3			4 & 5	6	7 - 12
LOCATION	Hydro-Quebec, Canada Rimouski (CLC31)					Hydro-Quebec, Canada Nemiskau (CLC11)			Hydro-Quebec, Canada Nemiskau (CLC12)			Hy-Qu Albanel	Texas Util.	Escom S.Africa
YEAR	1979	1980	1981	1982	1983	1981	1982	1983	1981	1982	1983			
1. Overall Availability of the SVC %	96	97	97.74	97.7	96.7	54.69	57.4	74.4	74.75	88.2	63.5			
2. Planned Outage Rate (P.O.R.) %	2.32	1.32	0.18	1.93	3.0	5.41	2.28	21.0	14.29	9.14	27.4			
3. Forced Outage Rate (F.O.R.) %	1.3	1.7	2.09	0.38	0.3	39.9	40.33	4.6	10.96	2.65	9.1			
4. Mean Time Between Planned Outages (Hours)	486.66	461	1251.42	2190		241.8	486.66		197.86	380.86		DATA NOT AVAILABLE	DATA NOT AVAILABLE	
5. Mean Time Between Forced Outages (Hours)	973.33	1460	796.36	1095		120.9	398.18		290.2	273.75				
6. Mean Time Per Planned Outage (Hours)	11.3	6.13	2.2	42.41	29.0	13.07	11.13	80.0	28.26	34.82	240.0			
7. Mean Time Per Forced Outage (Hours)	12.6	24.68	16.61	4.2	3.0	48.25	160.58	40.0	31.79	7.26	57.0			
8. Number of Failures Causing Forced Outage(s) of the SVC. Please Specify for:														
8.1 Transformers	-	-	-	-	(1)	(2)	(2)	(1)			(1)			(3)
8.2 Capacitors	1(0.1)	1(1.3)	3(55.3)	3(8.2)		6(177.7)	4(570.4)		4(96.3)	9(14.8)				
8.3 Reactors	5(21.4)	4(36.6)	-	-										
8.4 Filters	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			
8.5 Circuit Breakers and Isolators	-	-	-	-		-	-		-	-				
8.6 Thyristor Valves	-	-	-	-		-	-		-	-				
8.7 SVC Control & Internal Protection Equipment	-	-	-	-		5(103.8)	6(8.2)		1(80.2)	8(11.0)				
8.8 Auxiliaries	-	-	-	-		-	-		-	-				
8.9 Others (Please Specify):	External Equipment & Human Error					External Equipment & Human Error			External Equipment & Human Error					Human Error
....	3(2.1)	1(0.3	7(2.3) 1(0.5)	2(2.1)		24(6.3) 1(0.8)	7(3.1) 5(236.1)		9(1.3) 1(0.2)	10(0.8) 5(0.9)				1
9. If the above quantities apply to a period of less than one year please indicate the period in hours.	-	-	-	-	-	4353	-		4353	-				

NOTES:

(1) Information incomplete for Rimouski and Nemiskau SVC units for the year 1983. Number in brackets give average duration in hours for corresponding cause.

(2) Figures include coupling transformer failure lasting 91 days from 21 November 1981.

(3) Early experience in SVC units Ref. No. 7 & 8. Oversight in protection (not design) allowing operation of thyristors after switching off of cooling system. Two thyristors damaged as a result.

(4) Operating experience data as yet unavailable on SVCs Ref. Nos. 13 to 30 as they are at early commissioning stage or on order.

TABLE III

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS & THYRISTOR SWITCHED CAPACITORS (TCR + TSC)

	1 & 2	3, 4, 5 & 6	7	8 & 9	10	11 & 12	13
1. UTILITY SVC Location	Hydro-Quebec, Canada Chateauguay (2 units) Substation	La Verendrye (2 units) Chibougamau (2 units) Substations	ESCOM, South Africa Sishen Substation	State Electricity Commission of Victoria, Australia 2 units	Norwegian Water Resources and Electricity Board, Norway Rod Substation	CVG Electrificacion del Caxoni Ca (EDELCA) Venezuela La Horqueta and San Geronimo S/Stns.	American Electric Power, USA Beaver Creek S/Stn.
2. STATUS 3. COMMISSIONING DATE	In Service Spring 1984	In Service Aut. 1984-Aut. 1985	In Service February 1979	In Service June 1983	In Service February 1984	In Service March 1985	In Service November 1980
4. TYPE OF SVC Thyristor Configuration Thyristor Cooling Method	TCR + TSC Twelve Pulse Water	TCR + TSC Six Pulse Water	TCR + TSC Six Pulse Air	TCR + TSC Six Pulse Water	TCR + TSC Twelve Pulse Water	TCR + TSC Six Pulse Water	TCR + TSC Six Pulse Water
5. SVC RATING Continuous Rating MVAr (Capacitive) Continuous Rating MVAr (Inductive)	166 MVAr @ U = 1 pu 93 MVAr @ U = 1 pu slope adjustable 0-10%	300 MVAr @ U = 0.97 pu 105 MVAr @ U = 1.01 pu slope adjusted to 3%	20 MVAr @ 132 kV 10 MVAr @ 132 kV	100 MVAr @ 220 kV 60 MVAr @ 220 kV	250 MVAr @ 420 kV 250 MVAr @ 420 kV	300 MVAr @ 765 kV 280 MVAr @ 765 kV	125 MVAr @ 138 kV (extended to 325 MVAr by using 4 x 50 MVAr mechanically switched capacitors controlled from SVC) 125 MVAr @ 138 kV
Overload Rating (Capacitive)	-	-	-	-	-	-	1.3 puI - 10 sec. 1 < 1.3 pu - cont. (based on TSC)
Overload Rating (Inductive)	479 MVAr - 0.066 sec. @ U = 2.2 pu: 288 MVAr - 0.183 sec. @ U = 1.71 pu: 189 MVAr - 0.75 sec. @ U = 1.38 pu: 120 MVAr - cont. @ U = 1.1 pu	400 MVAr - 0.25 sec. @ U = 2 pu: 144 MVAr - 1.5 sec. @ U = 1.2 pu: 132 MVAr - 3.0 sec. @ U = 1.15 pu: 121 MVAr - 1 hour @ U = 1.1 pu	-	1.1 puI - cont.	1.3 puI - 1 sec.	1.0 puI - cont. 1.18 puI - 30 min. 2.54 puI - 0.25 sec.	Trip at 1.1 pu over-voltage after 2 seconds (based on TCR)
Rated Voltage of the SVC Transformer	120 kV	735 kV	132/2.36 kV	220/10.5 kV	420/16.3/16.3 kV	765/18.7 kV	138/8.3 kV
Rated Frequency	60 Hz	60 Hz	50 Hz	50 Hz	50 Hz	60 Hz	60 Hz
6. TOTAL OUTPUT OF SVC VARIED Step Size MVAr (Capacitive) Step Size MVAr (Inductive)	Continuously - -	Continuously - -	Continuously - -	Continuously - -	Continuously - -	Continuously - -	Continuously - -

TABLE III

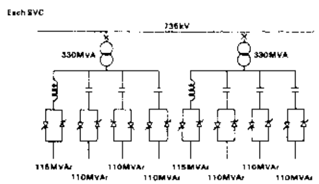
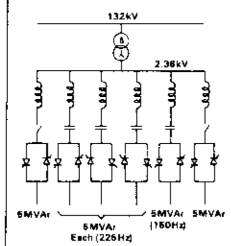
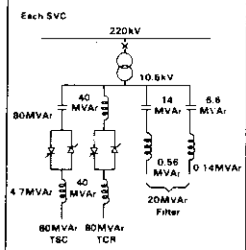
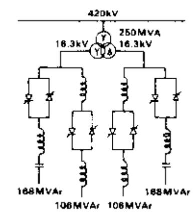
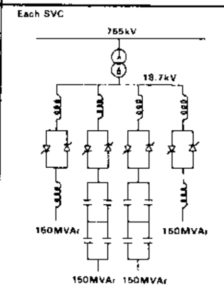
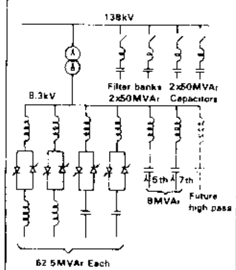
PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS & THYRISTOR SWITCHED CAPACITORS (TCR + TSC)

	1 & 2	3, 4, 5 & 6	7	8 & 9	10	11 & 12	13
7. PURPOSE OF INSTALLING SVC							
Voltage Control	2	2(*)	-	1	1	1	1
Voltage/Load Balancing	-	-	1(**)	-	-	-	-
Reactive Power Compensation	3(*)	-	-	-	-	-	-
Limiting of Temp. Overvoltages	1(*)	3(*)	-	-	-	-	-
Improving Power Tr. Capability	-	-	-	-	2	2	-
Improving System Transient Cap.	-	1	-	3	-	-	-
System Damping Enhancement	-	1	-	2	-	-	-
Subsynchronous Resonance Damping	-	-	-	-	-	-	-
Others	-	-	-	-	-	-	-
Control Strategy Under Transient Undervoltage	Used for reactive compensation of HVDC terminal. For any single phase voltage below 0.7 pu and above 1.3 pu as well as loss of DC link power flow the SVC will go to the inductive ceiling.	(1) For U below 0.7 pu for more than 200 msec. either: (i) no special action (ii) TSC out, normal voltage control (iii) TSC out, TCR in, voltage regulator at inductive ceiling can be selected (2) For U above 1.5 pu TSC out, TCR in and regulator at inductive ceiling	None	None	Upon fault clearance TSC is blocked and TCR is pushed to max. MVAr absorption 0.75 pu - 1 sec.	Strategy under study	-
Transient Overvoltage Magnitude and Duration			-	-	1.3 puU - 1 sec.	-	-
8. MAIN(M) & SUPPLEMENTARY(S) CONTROL SIGNALS							
Three Phase Voltage	M1 at HV	M1 at HV	-	M at HV	M at HV	-	M at HV
Individual Phase Voltage	-	-	M at HV	-	-	M1 at HV	-
Current(s)	M2 at HV	M2 at HV	-	S2 at HV	S at LV	M2 at HV	-
Active Power	-	-	-	-	-	-	-
Reactive Power	-	-	-	-	-	-	-
Speed	-	-	-	-	-	-	-
Frequency	-	-	-	S1 at HV	-	-	-
Others	Provision for implementation of supplementary signals has been made if such signals are desired in future		-	-	S at LV B_{ref} (susceptance)	-	-
9. CONTROL SIGNAL SENSORS	Wound VT	Wound VT	Wound VT	CVT	Wound VT	CVT	Wound VT

(*) See additional comments for control strategy (**) Reduction of negative phase sequence voltages produced by single phase AC traction loads

TABLE III

PART 1 - APPLICATION AND DESIGN DATA FOR
THYRISTOR CONTROLLED REACTORS & THYRISTOR SWITCHED CAPACITORS (TCR + TSC)

	1 & 2	3, 4, 5 & 6	7	8 & 9	10	11 & 12	13
10. SLOPE OF THE CONTROL CHARACTERISTIC	Probably 3% Adjustable 0-10%	3% Adjustable 3-10%	1%	3%	5%	3%	1%
11. REFERENCE VOLTAGE SETTING AND ± RANGE %	1.0 pu nom. ±10% range	1.0 pu nom. ±5% range	U_{ref} varies according to system conditions ±5% range	1.0 pu nom. ±10% range	0.95 pu nom. ±5% range	1.0 pu nom. ±5% range	1.0 pu nom. ±5.6% range
12. FAULT LEVEL AT HV							
Maximum	8300 MVA	50 kA	1000 MVA	14300 MVA	15000-30000 MVA	30 kA	2240 MVA
Minimum	2700 MVA	5.5 kA (Abnormal conditions 0.5kA)	300 MVA	500 MVA or 2200 MVA	3000 MVA	5 kA	980 MVA
13. HARMONICS Specified at . . . Busbar	@ HV bus $D_n \leqslant 1\%$(*) $D_{rss} \leqslant 4\%$(*) Max. TIF = 20(*)	$D_n \leqslant 1\%$ $D_{rss} \leqslant 4\%$ Max. TIF = 20 Max. IT = 10000	@ HV bus $D_n \leqslant 1\%$ $D_{rss} \leqslant 3\%$ Individual harmonic currents < $\frac{18}{n}$ where n is the harmonic number	@ HV bus D_n(odd) $\leqslant 1\%$ D_n(even) $\leqslant 0.5\%$ $D_{rss} \leqslant 1.5\%$ Harmonic currents	$D_n \leqslant 0.7\%$ $D_{rss} \leqslant 1\%$	@ HV bus $D_n \leqslant 1\%$ $D_{rss} \leqslant 4\%$ for harmonics up to 50th TIF < 20 IT < 10000	@ HV bus $D_n \leqslant 1\%$ $D_{rss} \leqslant 4\%$
Measured at . . . Busbar	-	-	@ HV bus D_n max. $\leqslant 1\%$ for each harmonic	@ HV bus Harmonic voltages and currents from 2nd to 35th harmonic and total harmonic distortion measured to prove compliance with above criteria	-	-	@ HV bus $D_n \leqslant 0.5\%$ $D_{rss} \leqslant 1\%$ measured with filters in service
15. SINGLE LINE DIAGRAM							
16. HARMONIC FILTERS	- SVC; TSC branches tuned to 5th harmonic - Filters on HV bus common to HVDC terminal and SVC	SVC; TSC branches tuned to 270 Hz. No filtering effect intended	3rd - 5 MVAr 225 Hz - 3 x 5 MVAr	5th - 13 MVAr 7th - 7 MVAr	None	TSC capacitor bank and series reactor tuned to the 4.5th (270 Hz) harmonic.	5th and 7th harmonic filters of 8 MVAr total connected at LV. 4.5th harmonic filter 2 banks of 50 MVAr each connected at HV

(*) Harmonic limits defined for the overall installation including HVDC terminal, SVCs and filters

TABLE III

PART 1 - APPLICATION AND DESIGN DATA FOR THYRISTOR CONTROLLED REACTORS & THYRISTOR SWITCHED CAPACITORS (TCR + TSC)

	1 & 2	3, 4, 5 & 6	7	8 & 9	10	11 & 12	13
17. ADDITIONAL COMMENTS	- Max. voltage reference 1.1 pu. This is the max. voltage at which phase angle control may be used in steady-state. - Protection features; breakover diode protection, TCR current limiter, overload control, TSC overcurrent protection. - Control features; joint control, Var regulator, HVDC terminal compensation, priority action, non-linear gain, discontinuous operating range.	- Max. voltage reference 1.05 pu with voltage ref. @ 1 pu the TCR are controlled at their max. conduction angle @ V = 1.01 pu cont. - Protection features; TCR valve overvolt. prot. firing, TCR valve overload prot., TSC valve overvolt. prot., TSC overcurrent protection, TSC capacitor, overcharge. - Control features; joint control, Var limiter, overvolt. regulator override, undervolt. strategies, emergency response time setting (manual) gain supervisor and optimiser, control AC filter for network resonance. See Refs. 160, 190, 211	- Phases are individually controlled to achieve neg. phase sequence voltage reduction. - The compensator is not large enough to control system volt. (pos. phase sequence). In order to maintain dynamic freedom for compensator (to allow it to balance phase voltages) a varying (floating) reference voltage was introduced. The reference voltage level is now determined by the mean system voltage.	None See Reference 302	None	(1) Low pass filters installed in the voltage measuring circuit to prevent harmonic impedance resonances around 90 Hz under load rejection conditions. (2) 60 Hz band reject filter on voltage signal to prevent second harmonic instability (3) ZnO arrestors installed for overvoltage protection of TSC valves (4) Min. loss control at low MVAr output (5) Automatic switching of MSRs at the same substation through the SVC control	Extensive TNA studies to verify results obtained from digital computer studies. These studies have checked the SVC characteristics, control system design and settings, harmonic performance and performance under system disturbance conditions. Study of harmonic performance indicated that at higher system loading levels resonance at 11th harmonic could occur thus provision for a high pass filter has been made. See References 161, 328, 329.
18. FIELD TESTS	For general philosophy followed in field tests, see comments expressed on TCR and TCR + FC equipment installations of the same utility.		Correlation between train movements and compensator output proved extremely difficult. Once the compensator was allowed freedom (as indicated above) it maintained the level of the negative phase sequence voltage to below 0.5%.	None See Reference 302	None	Detailed test programme under consideration including: (1) Short circuit tests at SVC terminals (2) Load rejection (3) Harmonic measurement (4) Single-pole switching	Field tests to verify: (1) SVC voltage regulation and control characteristics (2) Joint control of SVC together with four MSC banks (3) SVC response to single phase to earth fault on 138 kV busbars and to line outage conditions (4) SVC response to small disturbances (5) SVC harmonic performance. No problems experienced following some 50 system faults in the vicinity of the SVC over the years

TABLE III

PART 2 - RELIABILITY AND PERFORMANCE DATA FOR
THYRISTOR CONTROLLED REACTORS AND THYRISTOR SWITCHED CAPACITORS (TCR + TSC)

RELIABILITY AND PERFORMANCE DATA / SVC REF. NO.	7	8	9	13				
LOCATION	ESCOM SISHEN	SECV SVC1	SECV SVC2	American Electric Power, USA Beaver Creek				
YEAR	1979 to 1984	1983	1983	From Nov'80	1981	1982	1983	To Sept'84
1. Overall Availability of the SVC %	Data sufficiently accurate	97.8	99.3	93.2	91.1	95.6	96.2	94.3
2. Planned Outage Rate (P.O.R.) %	to comply with the given formula is	1.2	0.6	-	7.7	3.6	3.3	5.2
3. Forced Outage Rate (F.O.R.) %	not available. The compensator layout is such	1.0	0.1	6.8	1.2	0.8	0.5	0.5
4. Mean Time Between Planned Outages (Hours)	that it can operate with reduced out-	735	1540	-	4380	4380	8760	3216
5. Mean Time Between Forced Outages (Hours)	put following a thyristor failure by	1029	1540	528	2920	8760	8760	2144
6. Mean Time Per Planned Outage (Hours)	opening a branch isolating switch	9.0	9.0	-	336	156	288	168
7. Mean Time Per Forced Outage (Hours)		10.0	2.0	36	37	72	48	10
8. Number of Failures Causing Forced Outage(s) of the SVC. Please Specify for:								
8.1 Transformers	-	-	-					
8.2 Capacitors	3	-	-					
8.3 Reactors	-	1	-					
8.4 Filters	-	-	-					
8.5 Circuit Breakers and Isolators	-	-	-					
8.6 Thyristor Valves	Many (1)	-	-					2
8.7 SVC Control & Internal Protection Equipment	-	2	1	-	1	1	1	1
8.8 Auxiliaries	-	-	1					
8.9 Others (Please Specify):	-	1 (2) 1 (3)	-	2 (4)	1 (5) 1 (6)			
9. If the above quantities apply to a period of less than one year please indicate the period in hours.	-	5144	3080	1056	8760	8760	8760	6432

NOTES:

(1) All thyristors replaced due to corrosion between thyristors and heatsink (nickel to aluminium). Thyristors also failed (in groups of 3 because of no redundancy) due to problems in the capacitor switching circuit monitoring standing voltage on capacitor cans. Saturated auxiliary supply transformers led to failure of fuses supplying the circuits monitoring standing voltage on capacitor can. This led to the TSC thyristors firing in the wrong instant and their subsequent failure.

(2) Loose CVT secondary wiring.

(3) Control wiring damaged by contractor.

(4) Secondary cooling system failure.

(5) Cooling tower failure.

(6) Accidental tripping of fire fighting system.

(7) Operating experience data as yet unavailable on SVCs Ref. Nos. 1, 2, 3, 4, 5, 6, 10, 11 and 12 as they are at the early commissioning stage.

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

	1	2 & 3	4 & 5	6	7	8
1. UTILITY	Eletronorte, Brazil	Segba, Argentina	Swedish State Power Board, Sweden	The Kansai Electric Power Co. Japan	Hydro-Quebec, Canada	Central African Power Corp.
SVC Location		Rodriguez Substation SVC1 and 2	Hagby Substation (2 units)		Laurentides (1 unit)	Kitwe Substation (2 units)
2. STATUS	Being Planned	In Service	In Service	For testing between Jan. 1980 - Sept. 1981	In Service	In Service
3. COMMISSIONING DATE	August 1987	August 1983	December 1982	January 1980	Autumn 1978	1969
4. TYPE OF SVC	TCR + TSC + FC	TCR + TSC + TSR + MVAR	TSC + TSR	SCC	TCT + FC	SR (Twin Tripler)
Thyristor Configuration	Six Pulse	Twelve Pulse	Six Pulse	36 Pulse	Six Pulse	-
Thyristor Cooling Method	Air	Water	Water	Water	Water	-
5. SVC RATING						
Continuous Rating MVAr (Capacitive)	70 MVAr @ 230 kV	320 MVAr (total) @ 1.1 puU of 500 kV nom.	200 MVAr (total) @ 11.5 kV	20 MVAr @ 77 kV	330 MVAr @ U = 0.97 pu	20 MVAr
Continuous Rating MVAr (Inductive)	50 MVAr @ 230 kV	532 MVAr (total) @ 1.1 puU of 500 kV nom.	200 MVAr (total) @ 11.5 kV	20 MVAr @ 77 kV	100 MVAr @ U = 1.01 pu @ slope = 3%	15 MVAr
Overload Rating (Capacitive)	1.15 puI - 30 min. 1.1 puI - cont.	1.1 puI - cont. 1.0 puI - cont.	-	1.2 puI - 60 sec.	-	-
Overload Rating (Inductive)	1.8 puI - 0.1 sec. 1.4 puI - 0.5 sec. 1.15 puI - 30 min. 1.1 puI - cont.	1.37 puI - 1 min. 1.1 puI - cont. 1.0 puI - cont.	-	1.2 puI - 60 sec.	With capacitor bank switched out: 1400 MVAr - 0.083 sec. @ U = 1.7 pu 1100 MVAr - 1 sec. @ U = 1.5 pu: 119 MVAr - cont. @ U = 1.1 pu	80 MVAr for 2 minutes
Rated Voltage of the SVC Transformer	230/? kV	500/220/132 kV 132/11.5/11.5 kV	220/11.5 kV	77/0.715 kV	735/39 kV	330/220/11 kV
Rated Frequency	60 Hz	50 Hz	50 Hz	60 Hz	60 Hz	50 Hz
6. TOTAL OUTPUT OF SVC VARIED	Continuously	Continuously	In Steps	Continuously	Continuously	Continuously
Step Size MVAr (Capacitive)	-	-	50 MVAr/step	-	-	-
Step Size MVAr (Inductive)	-	-	100 MVAr/step	-	-	-

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

	1	2 & 3	4 & 5	6	7	8
7. PURPOSE OF INSTALLING SVC						
Voltage Control	2	1	2	-	2	1
Voltage/Load Balancing	-	-	-	-	-	-
Reactive Power Compensation	5	-	-	1	-	-
Limiting of Temp. Overvoltages	1	-	-	-	3	2
Improving Power Tr. Capability	-	-	-	2	-	-
Improving System Transient Cap.	3	2	-	3	1	-
System Damping Enhancement	4	3	1	4	1	-
Subsynchronous Resonance Damping	-	-	-	-	-	-
Others	-	-	-	-	-	-
Control Strategy Under Transient Undervoltage	For 20% voltage drop SVC should reach max. MVAr generation in less than 2 cycles. For voltage drops higher than 20% SVC output should be 240 in less than 1.5 cycles. SVC should be restored 0.5 sec. after removal of disturbance	None	None	None	None	None
Transient Overvoltage Magnitude and Duration	1.0-0.8 puU < 0.033 sec. < 0.8 puU < 0.025 sec. V > 1.0 puU < 0.033 sec.	-	-	-	SVC capacitor banks are tripped for voltages above 1.25 pu persisting over 25 msec. Also see rating of SVC.	1.2 pu - 2 minutes
8. MAIN(M) & SUPPLEMENTARY(S) CONTROL SIGNALS						
Three Phase Voltage	M1 at HV	M at HV	M at HV	-	M1 at HV	-
Individual Phase Voltage	S2 at HV	-	-	-	-	-
Current (s)	M2 at HV	S at HV	S at HV	-	M2 at HV	M (SR current)
Active Power	-	-	M at HV	S at HV	-	-
Reactive Power	S1 at HV	-	-	M2 at HV	-	-
Speed	-	-	-	-	-	-
Frequency	-	-	-	-	-	-
Others	-	-	-	DC voltage M1 at LV	Provision for implementation of supp. signal exists if these are needed.	-
. . . .	-	-	-	-		-
9. CONTROL SIGNAL SENSORS	CVT	CVT	Wound VT		Wound VT	SR current from reactor also used for SVC transformer tapchanger control

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

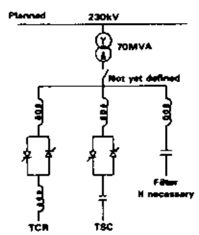
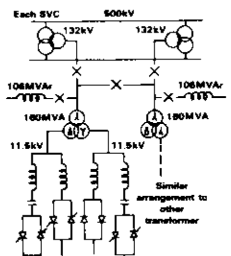
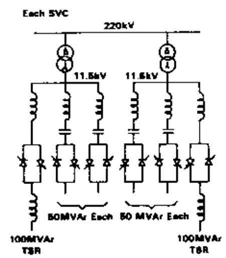
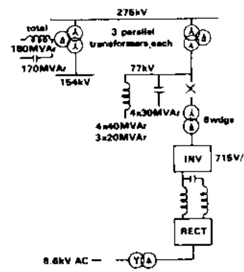
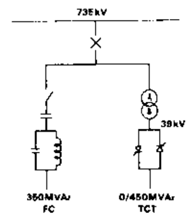
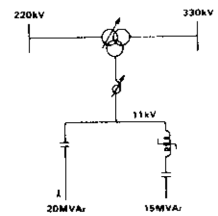
	1	2 & 3	4 & 5	6	7	8
10. SLOPE OF THE CONTROL CHARACTERISTIC	Adjustable 0.1 to 8%	0% at 500 kV HV bus	2%	Not specified. No voltage control was installed	3% adjustable 3 to 10%	0%
11. REFERENCE VOLTAGE SETTING AND ± RANGE %	1.0 pu nom. +5 to -10% range	1.0 pu nom. ±10% range	1.0 pu nom. ±2% range	N/A	1.0 pu nom. ±5% range	1.0 pu nom. ±10% range
12. FAULT LEVEL AT HV						
Maximum	-	9000 MVA @ HV bus	24.4 kA	22 kA at the 275 kV Substation	50 kA	1500 MVA
Minimum	-	7000 MVA @ HV bus	-	10 kA	5.5 kA	400 MVA
13. HARMONICS Specified at . . . Busbar	@ HV bus D_n(odd) $\leqslant$ 1% D_n(even) $\leqslant$ 0.5% D_{rss} $\leqslant$ 1.5% TIF < 25 IT < 25000	D_{arith} $\leqslant$ 3% Guaranteed values requested from manufacturer are incremental values taking into account SVC contribution alone	-	-	D_n $\leqslant$ 1% D_{arith} $\leqslant$ 4% Max. TIF 20 Max. IT 22800	@ 220 kV busbar D_n $\leqslant$ 1%
Measured at . . . Busbar	-	Measurements currently being processed	-	ΣU_n = 0.79% (at 20 MVAr capacitive) ΣI_n = 2.94% (at 20 MVAr capacitive) ΣU_n = 0.63% without SVC	D_n(max) = 0.65% (3rd harmonic) D_{arith}(max) = 1.57% TIF 6.13 IT 23900 Noise on PLC has increased for some lines so micro-wave telecomm. installed	-
15. SINGLE LINE DIAGRAM						
16. HARMONIC FILTERS	-	None	None	None	SVC capacitor bank tuned to 5th and 7th harmonics	None

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

	1	2 & 3	4 & 5	6	7	8
17. ADDITIONAL COMMENTS	None	The installation is remotely controlled from the control center at Costanera located 60 km away from the SVC. The control of the SVC is totally independent of the six synchronous compensators of ±125 MVAr rating located at Ezeiza Substation which is linked with Rodriguez Substation via 60 km long 500 kV lines.	SVC is controlled in any one of 3 following modes: 1. Auto mode by micro-computer 2. Manual mode with micro-computer supervision 3. Manual mode control is common to both SVC units Computer control is in three different levels: 1. Voltage control (220 kV) 2. Extreme voltage control (220 kV) 3. Damping of oscillations in the 400 kV system Level 3 has the highest priority, Level 1 the lowest. See Reference 332	This SVC was constructed as pilot plant for field testing. Its features are as follows: 1. Compact structure 2. No filters 3. Quick response 4. Although voltage control was not installed it was made available See References 245, 269	Protection features: - Breakover diode prot. - TCT current limiter - Overload control Control features: - MVAr limiter - Overvoltage regulator override - SVC capacitor bank tripping on over-voltage - TCT DC flux control See Reference 188	Without the SVC loss of load would cause a voltage rise of 70 kV or more on the 330 kV system containing a 430 km long line. The SR is loaded to 2.5 times its nominal rating for 2 minutes to allow operator action.
18. FIELD TESTS	None	The following field tests were carried out: 1. Harmonic measurements with and without SVC 2. Investigation of low frequency network voltage resonance by changing network configuration and applying step changes into the SVC control 3. Max. MVA excursion tests 4. Line tripping tests on lines from Rodriguez Substation and elsewhere in the network (tripping loaded and unloaded lines) 5. Tripping of shunt reactors at Rodriguez and at other locations up to 500 kms away 6. Tripping of synchronous compensators at Ezeiza Substation	To verify SVC behaviour full scale tests have been carried out in December 1982. 1. General commissioning tests 2. Tests to verify regulating properties of the SVC and to establish voltage regulator parameters 3. Tests to verify SVC and voltage regulator performance - mainly line switching tests - to check damping of power oscillations See Reference 332	The following tests were carried out: 1. Static characteristic tests (a) MVAr/DC voltage (b) MVAr/phase difference between SVC and line voltage 2. Dynamic characteristic tests (a) Step response (b) Switching of nearby capacitor banks (c) Overcurrent protection test (d) Harmonic meas. (e) Audible noise measurements (f) Radio noise meas. (g) Temperature meas. (h) SVC performance during system faults See References 245, 269	For field tests see comments on other Hydro-Quebec SVC installations. See Reference 188	Slope, harmonic, voltage regulation and overload measurements and tests. See References 236, 249

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

	9 & 10	11 & 12	13 & 14	15	16, 17 & 18	19, 20 & 21
1. UTILITY	CERN, France	National Electric Power Authority, Nigeria	Capricornia Electricity Board, Queensland, Australia	C.F.E., Mexico	State Electricity Commission of Western Australia	Central Electricity Generating Board, UK
SVC Location	CERN (2 units)	Gombe (1 unit) and Maiduguri (1 unit) S/Stn.	Blackwater (2 units) Substation	Cuidad Juarez Station	Merredin (1 unit) and Kalgoorlie (2 units) S/Stn.	Sellindge (2 units) Ninfield (1 unit) S/Stns.
2. STATUS	In Service	In Service	In Service	In Service	In Service	On Order
3. COMMISSIONING DATE	November 1975 (unit 1) May 1978 (Unit 2)	1978	1979	1979/1980	1984	1985/6
4. TYPE OF SVC	SR (Treble Tripler)	SR (Treble Tripler)	SR (Treble Tripler)	SR (Treble Tripler)	SR (Twin Tripler)	SR (Treble Tripler)
Thyristor Configuration	-	-	-	-	-	-
Thyristor Cooling Method	-	-	-	-	-	-
5. SVC RATING						
Continuous Rating MVAr (Capacitive)	80 MVAr* @ 18 kV	-	60 MVAr @ 66 kV	90 MVAr @ 69 kV	40 MVAr @ 30.5 kV	150 MVAr @ 400 kV
Continuous Rating MVAr (Inductive)	9 MVAr* @ 18 kV	8 MVAr (SR only) 27 MVAr (including 3 x 6.3 MVAr MSR)	0 MVAr @ 66 kV	47 MVAr @ 69 kV	32 MVAr @ 30.5 kV	150 MVAr @ 400 kV
Overload Rating (Capacitive)	1.0 puI - cont.	-	-	-	-	-
Overload Rating (Inductive)	3.33 puI - 900 sec.	-	-	Inherent	-	2.83 puI - 0.5 sec. 1.5 puI - 60 min.
Rated Voltage of the SVC Transformer	400/18 kV	132/33 kV	132/66 kV	230/69 kV	220/132/30.5 kV	400/56.5 kV
Rated Frequency	50 Hz	50 Hz	50 Hz	60 Hz	50 Hz	50 Hz
6. TOTAL OUTPUT OF SVC VARIED	Continuously	Continuously	Continuously	Continuously	Continuously	Continuously
Step Size MVAr (Capacitive)	-	-	24 MVAr steps for MSC	30 MVAr steps for MSC	21 MVAr steps for MSC	50 MVAr steps for MSC
Step Size MVAr (Inductive)	-	5 or 6.3 MVAr steps for MSR	-	-	-	-

* each individual unit including filters

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR
OTHER TYPES OF STATIC VAR COMPENSATORS

	9 & 10	11 & 12	13 & 14	15	16, 17 & 18	19, 20 & 21
7. PURPOSE OF INSTALLING SVC						
Voltage Control	2	1	1	1	1	-
Voltage/Load Balancing	-	-	-	-	-	-
Reactive Power Compensation	1	2	2	2	5	2
Limiting of Temp. Overvoltages	-	-	-	3	4	1
Improving Power Tr. Capability	-	-	-	4	2	-
Improving System Transient Cap.	-	-	-	-	3	-
System Damping Enhancement	-	-	-	-	-	-
Subsynchronous Resonance Damping	-	-	-	-	-	-
Others	Reduce effects of pulsing CERN accelerator load on 400 kV network	-	-	-	-	
Control Strategy Under Transient Undervoltage	None	None	None	None	Maintain SR currents normally at high levels to ensure a dynamic capacitive swing range of 44 MVAr.	
Transient Overvoltage Magnitude and Duration	-	SR and MSRs rated at 3 x 6.3 and 2 x 5 MVAr are switched on if SR overloads due to overvoltage.	-	Not a utility requirement.	2.7 puI - 0.5 sec.	1.16 puU - 0.5 sec.
8. MAIN(M) & SUPPLEMENTARY(S) CONTROL SIGNALS						
Three Phase Voltage	-	S at HV	-	-	S at HV	-
Individual Phase Voltage	-	-	-	-	-	-
Current(s)	M1 (peak current of reactor)	M (SR current)	M (SR current)	M (SR current)	M (SR current)	M (SR current)
Active Power	-	-	-	-	-	-
Reactive Power	-	-	-	-	-	-
Speed	-	-	-	-	-	-
Frequency	-	-	-	-	-	-
Others	S1 (slope correcting capacitor impedance)	-	-	-	-	-
. . . .	S2 (reactor temperature)	-	-	-	-	-
9. CONTROL SIGNAL SENSORS	M1 from reactor line bushings. S1 & S2 from VTs across reactor neutral bushings (wound VTs used)	SR current used to control switching of MSRs and SVC transformer tapchanger control	SR current	SR current and wound VT for busbar voltage	SR current used to switch MSCs and control SVC transformer tap-changer	The SR current is used for tapchanger control, switching of MSCs and for protection purposes

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

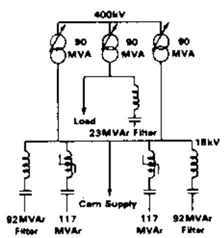
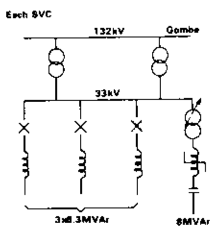
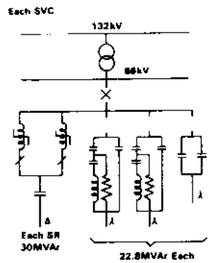
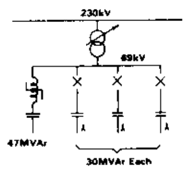
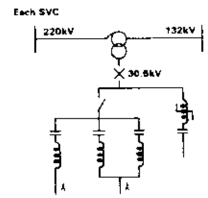
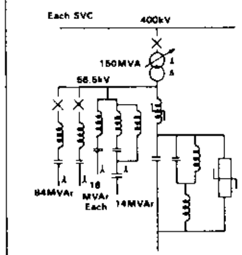
	9 & 10	11 & 12	13 & 14	15	16, 17 & 18	19, 20 & 21
10. SLOPE OF THE CONTROL CHARACTERISTIC	±0.3%	4%	0.5 % at 66 kV	0%	3.5% (on 50 MVA)	5%
11. REFERENCE VOLTAGE SETTING AND ± RANGE %	1.0 pu nom. ±0.3% range	1.0 pu nom. ±10% range	-	1.0 pu nom. at 69 kV	1.03 pu at 132 kV +12, -8% at 220 kV	1.0 pu nom. ±5% range
12. FAULT LEVEL AT HV Maximum Minimum	 17 kA or 530 MVA 16 kA or 500 MVA	Gombe Maiduguri 125 MVA 95 MVA 100 MVA 80 MVA	 - 310 MVA at 132 kV	 2500 MVA 1000 MVA	 400 MVA 200 MVA	 35000 MVA 4000 MVA
13. HARMONICS Specified at . . . Busbar	$I_{17}/I_{fund} < 1.5\%$ $I_{19}/I_{fund} < 2\%$ $I_{n>19}/I_{fund} < 1\%$	at 132 kV busbar $D_n < 1\%$	at 132 kV busbar $D_n < 1\%$	at 230 and 69 kV busbar $D_n < 1\%$	at 132 kV busbar D_n (odd) < 1% D_n (even) < 0.5% $D_{rss} < 1.5\%$ TIF 20 max. IT 20000	$D_n \ll 1\%$ $D_{rss} \ll 1.5\%$ Specified in conjunction with the HVDC link in the vicinity
Measured at . . . Busbar	-	-	-	-	Measured harmonic voltages 3rd < 0.36% 5th < 0.57% 7th < 0.1% 11th < 0.1% 25th < 0.1%	-
15. SINGLE LINE DIAGRAM						
16. HARMONIC FILTERS	18 kV filters for: 2nd-11.6 MVAr 11th-10.1 MVAr 3rd-11 MVAr 13th-7.2 MVAr 5th- 9 MVAr 17th-19.3 MVAr 7th-4.5 MVAr HF - 19.3 MVAr Total 92 MVAr	None	2nd - 2 x 11.4 MVAr Plain - 4 x 11.4 MVAr connected at 66 kV	None	2nd - 5.3 MVAr 3rd - 5.3 MVAr 5th, 11th to 25th - 12 MVAr all connected at 30.5 kV	3rd harmonic - 84 MVAr x 2 + 16 MVAr 2nd harmonic - 14 MVAr Main duty of filters is to improve harmonic perf. of HVDC instal. in the vicinity

TABLE IV

PART 1 - APPLICATION AND DESIGN DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

	9 & 10	11 & 12	13 & 14	15	16, 17 & 18	19, 20 & 21
17. ADDITIONAL COMMENTS	Three regulators complete this SVC. The most important one maintains the pulsed reactive power (90 MVAr) of the reactor within a preset band. The second maintains zero slope characteristic by compensating for temperature drift of series capacitors. The last maintains constant temperature of the reactor to avoid drift of saturation knee point. With these 3 regulators on absolute voltage of 18.1 kV ±0.3% is maintained. The voltage distortion at 18 kV is kept below 0.5% at any harmonic frequency by the filter.	Without the SVCs the loss of load overvoltages at Gombe and Maiduguri would be 1.4 and 1.5 pu respectively. The SVCs contain these voltages to 1.07 pu. See Reference 249	Compensator considered necessary to control voltage fluctuation experienced due to high level of mining load in the vicinity. See References 359, 377	Due to the long length of the 230 kV line (360 km) reactive power control was considered necessary for power transfers up to 150 MW.	The very low fault levels and radial 650 km transmission distance at 220 kV as well as load fluctuations at the receiving end necessitated use of SVCs at mid point and receiving end. Current SVCs rated for up to 70 MW transfers over the 220 kV line. Expansion for up to 100 MW transfers has been allowed for. See References 372, 373	None See References 244, 380
18. FIELD TESTS	The following tests have been performed: - Slope measurement - Harmonic measurement - Voltage regulation - Behaviour in pulsed operation - Unity step response	Slope, harmonic performance and voltage regulation tests.	Slope, harmonic performance and voltage regulation tests. See References 359, 377	Slope, harmonic performance and voltage regulation tests.	System acceptance tests included: - Steady-state voltage regulation tests - System switching tests - Overvoltage tests (energisation and load rejection) - Harmonic tests - Transient stability tests - System fault tests - Energisation tests under abnormal fault levels to verify sub-harmonic resonance studies - SVC component switching tests See References 372, 373	Extensive commissioning and performance tests in preparation. These will include: - Slope measurement and voltage regulation - Harmonic measurement - Overload capability measurements The overload capability tests will be performed by switching appropriate amounts of other reactive compensation plant and/or HVDC link filters in the vicinity of the SVC. See References 244, 380

TABLE IV

PART 2 - RELIABILITY AND PERFORMANCE DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

RELIABILITY AND PERFORMANCE DATA / SVC REF. NO.	1	2 & 3	4 & 5		6		7			
LOCATION	Eletronorte Brazil	Segba Rodriguez	Vattenfall Hagby		Kansai Electric		Hydro-Quebec Laurentides			
YEAR		1983	1983	1984	1980	1981	1979	1980	1981	1982 (5)
1. Overall Availability of the SVC %	DATA NOT AVAILABLE	99.8	97.7	100.0	99.45	99.6	75.78	59.22	87.62	85.56
2. Planned Outage Rate (P.O.R.) %		1.131	1.0	-	0.3	0.4	13	10.6	7.97	1.2
3. Forced Outage Rate (F.O.R.) %		0.476	3.5	-	0.25	0.0	11.2	30.14	4.41	13.24
4. Mean Time Between Planned Outages (Hours)		500.6	1250	-	8640	8640	312.54	380.86	273.75	1092
5. Mean Time Between Forced Outages (Hours)		876	141	-	1580	2880	149.47	208.57	414.14	873.6
6. Mean Time Per Planned Outage (Hours)		5.66	12	-	24	24	40.5	40.47	21.81	13.08
7. Mean Time Per Forced Outage (Hours)		4.17	5 (2)	-	4.0	0.5	16.82	62.87	18.39	115.66
8. Number of Failures Causing Forced Outage(s) of the SVC. Please Specify for:										
8.1 Transformers		-	2	-	-	-	-	-	-	-
8.2 Capacitors		-	-	-	-	-	12(8.4)	5(1.9)	9(36.7)	2(288.1)
8.3 Reactors		-	-	-	-	-	14(41.4)	23(113.4)	-	-
8.4 Filters		-	-	-	-	-	N/A	N/A	N/A	N/A
8.5 Circuit Breakers and Isolators		2	5	-	-	-	-	-	-	-
8.6 Thyristor Valves		-	1	-	-	-	-	-	-	-
8.7 SVC Control & Internal Protection Equipment		-	3	-	4	2	-	-	6(8.3)	1(1.1)
8.8 Auxiliaries		-	24	-	1	-	-	-	-	-
8.9 Others (Please Specify):		2 (1)	18 (3) 9 (4)		-	-	External Equip 19(4.9) Human Error 1(0.5)	14(1.7) -	External Equip 6(1.1) -	2(0.5) -
9. If the above quantities apply to a period of less than one year please indicate the period in hours.		3504	-	1/1/84 to 30/4/84	7920	5760	6876	-	-	4368

NOTES:

(1) Danger of short circuit due to bushes under the busbar system.

(2) The substation is unattended and travel time from supervising center to substation is approximately 1 hour.

(3) The outdoor temperature was extremely high in summer 1983 in the area which caused trippings due to high water temperature.

(4) Unknown causes.

(5) Major failure of TCT transformer causing outage for 10 months excluded from the statistics. Figures in brackets give average duration in hours for the corresponding cause.

TABLE IV

PART 2 - RELIABILITY AND PERFORMANCE DATA FOR OTHER TYPES OF STATIC VAR COMPENSATORS

RELIABILITY AND PERFORMANCE DATA / SVC REF. NO.	8	9 & 10	11 & 12	13 & 14							15	16, 17 & 18	19, 20 & 21
LOCATION	CAPC Kitwe	CERN France	NEPA Nigeria	Capricornia Elec. Board, Australia Blackwater							CFE Mexico	SECWA Aust.	CEGB U.K.
YEAR	To date	To date	To date	1979	1980	1981	1982	1983	1984	1985	To date	1984/5	To date
1. Overall Availability of the SVC %				82	64	90	92	87	95	100		98.3	
2. Planned Outage Rate (P.O.R.) %	Data not available in the required form	Date not available in the required form		0.5	0.1	0.0	0.0	0.0	0.0	0.0		0.82	
3. Forced Outage Rate (F.O.R.) %			Data not available	17.5	36	10	8	13	5	0		0.77	
4. Mean Time Between Planned Outages (Hours)				2208 Tests=2	8760 Tests=1	-	-	-	-	-		2920	
5. Mean Time Between Forced Outages (Hours)				552 FO=8	626 FO=14	1251 FO=7	1095 FO=8	8760 FO=1	8760 FO=1	- -		8760	
6. Mean Time Per Planned Outage (Hours)				12	9	-	-	-	-	-		24	
7. Mean Time Per Forced Outage (Hours)				98	225	109	91	1128	420	-		672	
8. Number of Failures Causing Forced Outage(s) of the SVC. Please Specify for:													
8.1 Transformers			No forced outages reported	-	-	-	-	-	-	-		-	
8.2 Capacitors	5(6)			1	1	2	1	-	-	-		-	
8.3 Reactors				-	-	-	-	-	-	-		-	
8.4 Filters	See Note(1)			-	-	-	-	-	-	-		-	
8.5 Circuit Breakers and Isolators				-	-	-	-	-	-	-		1	
8.6 Thyristor Valves				-	-	-	-	-	-	-		-	
8.7 SVC Control & Internal Protection Equipment				6	12	5	7	1	1	-		1	
8.8 Auxiliaries												1	
8.9 Others (Please Specify):					1 Vermin							-	
9. If the above quantities apply to a period of less than one year please indicate the period in hours.				4416	8760	8760	8760	8760	8760	4344		5800 (2)	

NOTES:

(1) Figures in brackets give average duration in hours for the corresponding cause.

(2) Figures cover all three SVCs installed and include failures of other main transmission plant e.g. 220 kV circuit breakers which result in unavailability of SVCs.

CHAPTER 9

GLOSSARY OF TERMS AND DEFINITIONS

9.1 INTRODUCTION

This chapter contains terms and definitions relating to static var compensators. The definitions have been worded specifically for SVC equipment applicable to high voltage transmission networks. Definitions for industrial applications have not been included as they are beyond the terms of reference of this book. It is nevertheless recognised that with reasonable interpretation, these terms and definitions may be applicable to the SVC equipment in distribution and/ or industrial applications.

An attempt has been made to include those terms and definitions which have been found in current usage. Reference has been made to the British and USA standards, to the work of the Canadian Electrical Association and the International Electrotechnical Commission (IEC). Modifications have been made to some existing terms and definitions for compensator equipment applications where they have been considered ambiguous.

In preparing the general definitions for this section, consideration has been given to those terms in common use, namely, static var compensator, static var generator and static var system. An effort has been made to embody these terms in the document and to indicate how these terms can be used without ambiguity.

For the convenience of the user, this chapter has been divided into seven sections :

- General definitions
- Types of static var compensators (SVCs)
- SVC Components
- Performance characteristics of SVCs and their components
- SVC Modelling techniques
- Terms relating to factory and site tests
- Symbols and acronyms

9.2 GENERAL DEFINITIONS

This section covers the main terms in common use with reference to fig. 1.1 of chapter 1 as follows :

9.2.1 A static var compensator (SVC) is a shunt connected static generator and/or absorber of reactive power (volt ampere reactive or var) whose output is varied so as to maintain or control specific parameters of the electrical power system.

9.2.2 A static var generator (SVG) and or absorber is a static electrical device, equipment, or system that is capable of drawing controlled capacitive and/or inductive current from an electrical power system and thereby generating or absorbing reactive power. SVG is an intergral part of an SVC.

9.2.3 A static var system (SVS) is a combination of different static, and mechanically switched var compensators whose outputs are co-ordinated.

9.2.4 A var compensating system (VCS) is a combination of static var systems and rotating var compensators whose outputs are co-ordinated.

This glossary is confined to different types of static var compensators defined below.

9.3 TYPES OF STATIC VAR COMPENSATORS

This section defines the main types of SVC currently in use :

N°	Term	Definition
9.3.1	Thyristor Controlled Reactor (TCR) Compensator	This compensator consists of bidirectional thyristor valves in series with reactors. The flow of inductive current is controlled by adjusting the conduction angle of the thyristor valves. Fixed capacitors may be added to extend the operating range into the capacitive region
9.3.2	Six-pulse TCR or Twelve-pulse TCR	These are special forms of three-phase thyristor controlled reactors configured to provide harmonic cancellation between individual TCR phases or two groups of TCRs. The six-pulse TCR employs either a delta connection of the TCR phases or a delta winding on the SVC transformer.
9.3.3	Thyristor Controlled Transformer (TCT) Compensator	This compensator consists of bidirectional thyristor valves in series with the secondary windings of a high leakage reactance transformer. The flow of inductive current is controlled by adjusting the conduction angle of the thyristor valves. Fixed capacitors may be added to extend the operating range into the capacitive region.
9.3.4	Saturated Reactor (SR) Compensator	This compensator consists of reactors with iron cores which saturate whenever the applied voltage exceeds a designed saturation level. The inherent non-linear magnetising characteristic of the reactor provides a controlled variation of inductive current proportional to the variation in applied voltage above the saturation level. Fixed capacitors may be added to extend the operating range into the capacitive region.
9.3.5	Thyristor Switched Capacitor (TSC) Compensator	This compensator consists of bidirectional thyristor valves in series with capacitors and a small reactor. The thyristor valves are used to switch the capacitors in or out of service. The capacitive current changes in a step-like manner.

Nº	Term	Definition
		Fixed or thyristor controlled reactors, thyristor controlled transformers, or saturated reactors may be added to provide continuous control of the output current and to extend the operating range into the inductive region and/or to provide continuous control of the output current.
9.3.6	Thyristor Switched Reactor (TSR) Compensator	This compensator consists of bidirectional thyristor valves in series with one or more reactors. The thyristor valves are used to switch the individual reactor banks in or out of service. The inductive current changes in a step-like manner.
9.3.7	Self-commutated Converter (SCC) Compensator	This compensator consists of semiconductor valves arranged to form a multiphase switching convertor circuit on the secondary winding of a transformer. The semi-conductor valves have the capability of being turned on or off by control action which produces self or forced commutation. The switching convertor is controlled to draw variable inductive or capacitive current from the three phases of the power system.
9.3.8	Line-commutated Converter (LCC) Compensator	This compensator consists of thyristor valves arranged to form a multi phase switching convertor circuit on the secondary winding of a transformer. The thyristor valves are commutated by the line voltages at the convertor terminals. The switching convertor circuit is operated to draw variable inductive current from the three phases of the power system. Fixed capacitors may be added to extend the operating range into the capacitive region.

9.4 SVC COMPONENTS

This section identifies the static elements most often employed in static var compensators and outlines the appropriate terms and definitions.

Nº	Term	Definition
9.4.1	Power Components	
9.4.1.1	Inductor (Reactor)	An element which has the capability to store magnetic flux by virtue of its inductance when carrying current.
9.4.1.2	Capacitor	An element which has the capability to store electric energy by virtue of its capacitance when voltage is applied.
9.4.1.3	Saturable Reactor	An iron-cored inductor whose power winding reactance is controlled by changing the magnetic saturation of the core. A unidirectional flux provided by a control winding is the source of saturation.
9.4.1.4	Saturated Reactor	An iron corred inductor designed to saturate and draw high currents when the applied voltage exceeds its nominal saturation level.
9.4.1.5	Treble-Tripler or Twin-Tripler Reactor	Special forms of three-phase saturated reactor having nine or six magnetic cores and power windings arranged to reduce the generation of harmonics and to provide voltage balance between phases.
9.4.1.6	Reactor Transformer	This is a high leakage reactance transformer designed to saturate at high voltage level that behaves like an inductor.
9.4.1.7	Mechanical Switch	An element which is mechanically operated in order to make or break and carry the flow of current in an electric circuit.
9.4.1.8	Thyristor	A bistable semiconductor device including three or more junctions which can be switched from the off-state to an on-state or vice versa.
9.4.1.9	Thyristor Stack	A single structure of one or more thyristors with associated mountings, cooling attachments and electrical and/or mechanical connections, but without trigger (phase) control equipment.
9.4.1.10	Thyristor level	The smallest assembly, consisting of a bidirectional pair of thyristors, their immediate auxiliaries for firing and protection, voltage dividing components and distributed valve reactor.
9.4.1.11	Thyristor Module	The thyristor module is built up from a number of series connected thyristor levels and exhibits the same electrical properties as the completed valve, but only a portion of the full voltage blocking capability of the valve such that it can be used for type tests.
9.4.1.12	Thyristor Valve	An electrically and mechanically combined assembly of thyristor modules, complete

N°	Term	Definition
		with all connections, auxiliary components and mechanical structure which can be connected in series with the reactor or capacitor of each phase of a static var compensator. A combination of two sets (or strings) of thyristors in an antiparallel connection is referred to as a bidirectional valve. The thyristor strings can share the same voltage dividing components, protection and firing components.
9.4.1.13	Valve Structure	The physical (mechanical) structure, holding thyristor modules forming a single-phase valve or individual phase valves forming a three-phase valve which are insulated to the appropriate potential above ground potential. The structure includes thyristor cooling system piping.
9.4.1.14	Valve Base	The platform on which the valve structure and thyristor modules are situated. It may contain electronic circuity for valve firing which are at virtually ground potential.
9.4.1.15	Harmonic Filters	Devices which are designed to suppress undesirable harmonic components of SVC current from being injected into the transmission network. Some or all of the capacitors installed as part of the SVC capacitive rating may be utilised as harmonic filters for suppressing the SVC harmonic currents.
9.4.1.16	Damping Circuits	Devices which are specifically designed to protect the SVC or its major components by suppressing transient over-voltages and currents.
9.4.1.17	Trickle Charge Circuits	A circuit arrangement which provides thyristor switched capacitor banks with a small (trickle) charging current sufficient to maintain a preset d.c. voltage level across a 'switched out' capacitor bank(s). The trickle charge circuits are used mainly for TSC type compensators. Arrangements are made to fire the thyristors for a short period at the appropriate half cycle to maintain the associated capacitor bank at the correct potential. Thus transient disturbances associated with TSC switching are minimised.

In addition to the above SVC components the following components are use in forming a var compensating system (VCS)

9.4.1.18	Mechanically Switched Reactor (MSR)	An assembly of reactor (inductor) elements which can be connected as a group to the power system by means of a mechanical circuit breaker or disconnector switch.
9.4.1.19	Mechanically Switched Capacitor (MSC)	An assembly of capacitor elements which can be connected as a group to the power system by means of a mechanical circuit breaker or a disconnector switch.
9.4.1.20	Fixed Reactor (FR)	An assembly of reactor (inductor) elements which can be connected to the power system either by fixed (unswitched) connections or via off-load mechanical switches.
9.4.1.21	Fixed Capacitor (FC)	An assembly of capacitor elements which can be connected to the power system either by fixed (unswitched) connections or via off-load mechanical switches.

9.4.2 Measurement Components

9.4.2.1	System Connected Measuring Devices	Devices which are connected to the system in order to measure either electrical or physical quantities describing the state of both the network and the SVC (e.g., voltages, currents, temperature).
9.4.2.2	Internal Measuring Devices	Assemblies of analogue/digital devices which accept signals obtained from 'system connected' measuring devices and produce other signals suitable for control and monitoring purposes (e.g., sequence components, average voltage, conduction intervals, etc.).
9.4.2.3	Transducer	An element which accepts a signal in one form and converts it into another form. An example of this is a potentiometer which converts a mechanical position into an electrical voltage signal.

9.4.3 Control Components

9.4.3.1	Control Elements	Components which collectively form a closed or open loop type control systems.
9.4.3.2	Open Loop	An arrangement of components forming a control system in which the "control'action is independent of the output.

9.4.3.3 Closed Loop

An arrangement of components forming a control system in which the 'control' action is dependent upon the output.

The output signal is usually fed back (feedback type control systems) to the input reference element in a manner which minimises the error between the reference and output signals.

9.4.3.4 Regulator

An assembly of electronic devices which performs the comparison of the controlled quantity with the reference value and processes the error signal obtained, in order to provide proper input to the firing dispatching unit of the SVC.

Regulator inputs can also have additional signals for stabilisation and/or protection purposes.

9.4.3.5 Synchronizing and Firing Signal Dispatching Unit

An assembly of devices which provides the valves with firing signals synchronized with respect to the voltage phase and frequency, taking into account the regulator and protection system outputs.

9.4.3.6 Joint Controller

A centralised type of control equipment, the purpose of which is to give a common command to a number of var compensators such that they all share the specified reactive demand on a basis of their ratings.

9.4.3.7 Var Regulator

A particular form of regulator in which the reactive power of the SVC is measured and compared with a reference value, the difference signal being arranged to provide preset level var output.

9.4.3.8 Priority Level Controller

A type of control equipment the purpose of which is to accept several command signals and to decide which signal should have priority of command. An example of this would be an SVC with both a voltage and a reactive load controller. In these circumstances the priority control will allow reactive load control to be operative provided that the controlled terminal voltage did not go beyond preset limits. When terminal voltages is beyond preset limits the controller would revert to voltage control.

9.4.3.9 Var Limit Control

A particular form of 'priority level' control which allows fast acting voltage regulation to be maintained on a SVC provided that the SVC var output does not exceed a preset value. When SVC output exceeds a preset value the controls would revert to var control at the expense of voltage control.

9.4.3.10 Overcurrent Limit Control

A particular form of priority level control which allows fast acting voltage regulation to be maintained on an SVC provided that the output current does not exceed a preset level. Current control would be given priority at the expense of voltage control when SVC current exceeds preset levels.

9.4.3.11 Overvoltage Limit

A particular form of priority level control which allows load type control unless the voltage level exceeds a preset level. In these circumstances priority would be given to voltage control.

9.4.3.12 Adaptive Control

This is a form of control having continuously adjustable dynamic characteristics which are automatically updated to suit the change in dynamic behaviour of the SVC. One of its important performance requirements is to ensure that the SVC does not become unstable (i.e., oscillatory in behaviour).

9.4.4 Protection Components

9.4.4.1 System Protection Element

Components which collectively or individually detect harmful operating conditions and inherently or by automatic procedures act in order to safeguard the overall equipment from consequential damage.

Surge arresters and damping circuits are examples of inherently acting equipment, while overcurrent protection co-ordinated with circuit breaker intervention is an example of an automatic procedure.

9.4.4.2 Protection Elements of Electronic Circuitry

Devices or assemblies of devices which act in order to safeguard from damage or misoperation the electronic equipment of control, measuring and monitoring systems.

9.4.4.3 Voltage Breakover Devices

Devices which act to safeguard thyristors from damage by excessive overvoltages.

The devices are connected across thyristors in such a manner that if overvoltages occur across the device it will initiate a firing of the thyristor, even if no other firing signals are available.

These devices have non-linear characteristics passing current at high voltages.

9.4.4.4 Momentary Overvoltage Protection Elements

Devices which detect excessive overvoltages across the thyristor valve or valves and initiate firing of all three phases for full conduction for a specified short period until the excessive overvoltage has been suppressed. Persistent overvoltages are obtained by other protective devices such as surge arresters.

9.4.4.5 TCR Thermal Overload Protective Devices — Devices which are employed specifically to protect thyristor controlled reactors from excessive thermal overload.

The devices are arranged to detect when the thermal capacity of a TCR has been exceeded and initiate a reduction in current by reducing the thyristor conduction angle to a safe level.

The detection devices can take the form of either summing SVC current or var output (as a function of operating time) or simulating thyristor cell temperature characteristics.

9.4.4.6 AC Voltage Grading Devices — Devices which ensure equal potential across each thyristor pair in a thyristor string in order to provide firing and equal potential at the blocked state of the valve.

9.4.4.7 Snubber Devices — Devices which are arranged to damp high frequency transients occurring during valve operation. These devices contain resistive and capacitive elements and usually form part of the grading devices.

9.4.4.8 DC Voltage Grading Devices for TSC — These devices are fitted across each thyristor or thyristor pair in thyristor switched capacitor valves to ensure equal potential across thyristors, especially when capacitor banks are being discharged (i.e., when disconnected from the system).

9.4.4.9 TSC Capacitor Overcharge Protection Devices — Devices which detect a preset level of overvoltage and initiate a firing pulse to the thyristors to ensure that blocking does not occur until the overvoltage is within safe limits. These devices afford protection for overvoltages with a short duration. Persistent overvoltages are contained by other devices such as surge arresters.

9.4.5 <u>Monitoring Components</u> — Devices providing acoustic and/or optical signals as well as measurements for operator control and alarm purposes. Monitoring can be either local or remote or both.

9.5 PERFORMANCE CHARACTERISTICS OF SVCs AND SVC COMPONENTS

9.5.1 Compensator Equipment

9.5.1.1 Rated Voltage (U_{rated}) — The RMS line-to-line terminal voltage for which the SVC has been designed and rated.

9.5.1.2 Maximum Voltage for Continuous Operation (U_{max}) — The maximum RMS line-to-line terminal voltage at which the SVC can be operated continuously.

9.5.1.3 Minimum Voltage for Continuous Operation (U_{min}) — The minimum RMS line-to-line terminal voltage at which the SVC can be operated continuously.

9.5.1.4 Maximum and Minimum Reference Voltages ($U_{ref\ max}$, $U_{ref\ min}$) — The maximum and minimum RMS values of voltage to be maintained at the busbar, whose voltage is controlled by the compensator, under zero reactive power output from the SVC. These voltages define the range of the voltage control set point.

9.5.1.5 Nominal Rated Current (I_{rated}) — The RMS terminal current in the inductive or capacitive operating range which can flow continuously at rated voltage.

9.5.1.6 Maximum Inductive or Capacitive Current ($I_{L\ max}$, $I_{C\ max}$) — The maximum RMS terminal current in the inductive or capacitive operating range which can flow continuously.

9.5.1.7 Rated Reactive Power (Q_{rated}) $Q_{rated} = \sqrt{3} \cdot U_{rated} \cdot I_{rated}$ — The reactive power which a compensator is capable of absorbing (inductive) or generating (capacitive) in a continuous manner at rated voltage and frequency.

9.5.1.8 Polarity of Reactive Power (Q) — A compensator behaving like an inductance absorbs reactive power and has positive Q. A compensator, behaving like a capacitor generates reactive power and has negative Q. The reader should note that this definition treats the SVC as a reactive load.

9.5.1.9 Susceptance — This is the inverse of the reactance of a shunt connected inductor or capacitor element and is of the form :

$$B_L = \frac{1}{X_L} = \frac{1}{\omega L} \; ; \; B_C = \frac{1}{X_C} = \omega C$$

The polarity of inductive susceptance is negative while the polarity of capacitive susceptance is positive.

9.5.1.10 Maximum Transient Overvoltage ($U_{OV\ max}$) — The highest peak non-repetitive value of 'on-state' terminal voltage for which a compensator has been designed.

9.5.1.11 Maximum Temporary Overvoltage (U_{OV}) — The RMS value of the terminal voltage for which the compensator is designed for a specified time period.

9.5.1.12 Steady State — A discrete relationship which

Voltage/Current Characteristic — exists between the steady-state fundamental frequency positive sequence terminal voltage and the reactive current flowing through the compensator. The relationship is usually plotted with the current on the horizontal axis. The current is assumed to have a positive polarity when the compensator is absorbing reactive power.

9.5.1.13 Slope of the Voltage Control Characteristic (SL_{min}, SL_{max}, SL) — This slope is the ratio of the voltage change over the SVC control range to the rated voltage. It is usually expressed in percent.

9.5.1.14 Response Time — Time to achieve 90 percent of the final value of output after a specified step of change in input, in both the inductive and capacitive linear control range of the SVC.

9.5.1.15 Settling Time — Time to settle within ± 5 percent of the final value of the output after a step change in input.

Response and settling time will change with SVC operating and network conditions.

9.5.1.16 Mode of Control — This is the type of SVC Control to enable the compensator to meet a specified performance objective, e.g. voltage, var control, etc. The control parameter is normally compared with a reference value set for the parameter in the SVC control system.

9.5.1.17 Three Phase Voltage Control — This is a mode of control which employs either average or positive sequence voltage signal to control the voltage level at or near the SVC terminals by varying the SVC output.

9.5.1.18 Individual Phase Voltage Control — This is a mode of control which employs individual phase voltage, both negative and positive sequence or negative sequence only, to control the SVC output.

9.5.1.19 Reactive Power Control — This is a mode of control which can be employed to allow reactive power flow to occur in a preset manner. Normally this would be superimposed on the voltage control mode of an SVC.

9.5.1.20 Supplementary Signal Control — This is a mode of control which enhances the damping of power oscillations and thus enables increased power transfers across a power system.

Supplementary control signals would normally be employed to provide damping of electromechanical oscillations or damping of subsynchronous oscillations. Signals may be derived from active power flow, machine shaft speed, or system frequency; the choice depends upon the specified objective.

9.5.1.21 Individual Voltage Distortion Factor (D_n) — This is the distortion of the voltage waveform caused by an individual harmonic of the order (n). It is expressed as a percentage of the RMS value of the fundamental.

9.5.1.22 Total Voltage Distortion Factor ($D_{r.s.s.}$) — This is the distortion of voltage waveform caused by all the harmonics present.

9.5.1.23 Maximum Voltage Deviation (D_{arith}) — This is the maximum deviation from a relevant sine wave, expressed as a ratio of the sum of the RMS values of all the harmonics, to the RMS value of the fundamental.

9.5.1.24 Total Harmonic Current Factor (IT) — This is a measure of the distortion of the current in a network element e.g., a transmission line. The factor is expressed as the square root of the sum of the weighted squares of the individual current harmonics. The weighting factors for 60 Hz systems are given by Edison Electric Institute and Bell Telephone System (EEI/BTS) guidelines prepared in 1960.

9.5.1.25 Telephone Influence Factor (TIF) — A measure of the interference on a telephone system caused by voltage waveform distortion of a power system in close proximity. The influence factor is derived as a ratio of the square root of the sum of the squares of the weighted RMS values of individual harmonics as a proportion of the fundamental waveform to the RMS unweighted value of the composite waveform. Same EEI/BTS weighting factors are used as those in the (IT) calculation.

9.5.1.26 Telephone Harmonic Form Factor (THF) — This factor is defined in the same way as the telephone influence factor (TIF) except the weighting factors used are given according to guidelines prepared by International Consultative Commission of Telephone and Telegraph Systems (CCITT), mainly for 50 Hz power systems.

9.5.1.27 Equivalent Disturbing Current (EDC) — This is defined in the same way as the total harmonic current factor (IT), except the weighting factors used are according to CCITT guidelines, mainly for 50 Hz power systems.

9.5.1.28 Harmonic Frequencies — Integral multiples of the fundamental frequency of a non-sinusoidal alternating waveform.

9.5.1.29 Minimum Fault Level at point of common Coupling — The minimum fault level (i.e. the system strength) at which a compensator would be expected to operate satisfactorily within its design limits.

The fault level can be expressed either by the three-phase fault current or by the corresponding three-phase short-circuit power.

9.5.1.30 SVC Equipment Power Frequency Operating Range — The power frequency excursion for which a compensator would be expected to operate satisfactorily.

9.5.1.31 Overall Availability — This is defined as the percentage ratio of the actual MVar-hours which a compensator is capable of providing over its controllable inductive and capacitive range, to the maximum continuous controllable MVar-hours for which the equipment has been designed. The period of time over which each of the above MVar-hours is integrated will be one year.The actual MVar-hours reflect the partial MVar capability caused by forced and scheduled outages the SVC elements.

This term describes the operational readiness of a static var compensator in relation to the MVar-hours integrated over a specified period.

9.5.1.32 Outage — The state in which the SVC is unavailable for normal operation due to an event related directly to the equipment itself.

9.5.1.33 Planned (or Scheduled) Outage (PO) — This is an outage which can be deferred for a period of at least one week.

9.5.1.34 Forced Outage (FO) — This is any outage which does not qualify as a scheduled outage.

9.5.1.35 Compensator Mean Time between Failures (MTBF) — This is a measure of the random nature of failure rates of equipment or components expressed in terms of the arithmetic average of interval of time when there are no failures.

9.5.1.36 Compensator Repairability (or Mean Time to Repair) (MTTR) — This is a measure of the time taken to repair or replace failed component parts of a compensator. High availability can be obtained by ensuring that the time to repair any failed device is shorter than the associated mean time between failures of the remaining healthy devices.

9.5.1.37 Three-Phase Reactive Power (Q) — The product of $\sqrt{3}$ times the RMS values of line-to-line voltage and reactive components of current for sinusoïdal waveforms (i.e., total three-phase reactive power).

9.5.1.38 Three-Phase Apparent Power (S) $S = \sqrt{3} . U . I$ — The product of $\sqrt{3}$ times the RMS line-to-line voltage and the RMS current.

9.5.1.39 Redundancy — The existence within a compensator of more than one means of performing a given function where a stated maximum number of the means must fail before the compensator becomes unavailable.

9.5.2 <u>Electrical Network Performance</u>

9.5.2.1 Steady-State Stability — This is the ability of an electrical power system to provide transmission voltage levels which remain steady under conditions in which, the prime mover outputs, the system frequency and the load demands are all assumed to remain constant, i.e., when the system is not subjected to a disturbance.

Power systems are, however, continually in a dynamic state i.e., subjected to small disturbances arising from changing demand and generation output continuously. Thus, the definition includes the ability of an electrical power system to allow adequate damping power or torque to be generated in a manner which cause power oscillations to decay effectively following small disturbances, and also to suppress self excited power oscillations.

9.5.2.2 Transient Stability — This is the ability of an electrical network to survive a sudden large disturbance and settle to a new steady-state condition in a manner which allows interconnected machines to remain in synchronism.

9.5.2.3 Power System Stabilising — The action of an element or group of elements (e.g., SVC, generator excitation control systems, etc.) by which the steady-state, dynamic and/or transient stability of a power system can be secured or enhanced.

9.5.2.4 Synchronising Power — A measure of the ability of one or more synchronous machines on a network to retain synchronism after being subjected to a momentary disturbance. The synchronising component of power or torque is in phase with the equivalent machine rotor angle and can be considered to behave in an analogous manner to the elastic stiffness of a mechanical spring.

9.5.2.5 Damping Power — A measure of the quality of one or more synchronous machines behaving in a coherent manner to suppress i.e., to damp angular oscillations.The damping component of power or torque is in phase with the rate of change of an equivalent machine rotor angle;i.e. angular velocity. It can be considered to behave in an analogous manner to the viscous torque associated with a mechanical type dash pot.

The angular oscillations of a synchronous machine may be either forced by either pulsating torques associated with a prime mower, electrical loads or free oscillations arising from a process of self excitation.

9.5.2.6 Subsynchronous Resonance — An oscillatory condition which occurs at frequencies below rated frequency when there is an inter-change of energy between series capacitors and the inductance of a transmission system. This form of resonance can lead to dangerous consequences if allowed to interact with critical synchronous machine shaft torsional frequencies.

9.5.3 Thyristors

9.5.3.1 Off-state Voltage — The principal voltage when the thyristor is in the off-state.

9.5.3.2 Breakover Voltage — The principal voltage at the breakover point.

9.5.3.3 On-state Voltage — The principal voltage when the thyristor is in the on-state.

9.5.3.4 Crest (peak) Working Off-State Voltage — The highest instantaneous value of the off-state voltage which occurs across the thyristor, excluding all repetitive transient voltages.

9.5.3.5 Repetitive Peak Off-State Voltage — The highest instantaneous value of the off-state voltage which occurs across the thyristor including all repetitive transient voltages, but excluding all non-repetitive transient voltages.

9.5.3.6 Non-repetitive Peak Off-State Voltage — The highest instantaneous value of any non-repetitive transient off-state voltage which occurs across the thyristor.

9.5.3.7 On-state Current — The principal current when the thyristor is in the on-state.

9.5.3.8 Off-state Current — The principal current when the thyristor is in the off-state.

9.5.3.9 RMS On-State Current — The r.m.s. value of the on-state current for full cycle.

9.5.3.10 Repetitive Peak On-On-state Current — The peak value of the on-state current including all repetitive transient currents.

9.5.3.11 Critical Rate of Rise of Off-state Voltage — The lowest value of the rate of rise of voltage which will cause switching from the off-site to the on-state under specified conditions.

9.5.3.12 Critical Rate of Rise of On-state Current — The highest value of the rate of rise of on-state current which a thyristor can withstand without damage.

9.5.3.13 Forward Power Loss — The power loss which occurs within a thyristor cell resulting from the flow of forward current.

9.5.3.14 Reverse Power Loss — The power loss which occurs within a thyristor cell resulting from the flow of reverse current.

9.5.3.15 Total Power Loss — The sum of the forward and reverse power losses of a thyristor cell or cells.

9.5.3.16 Conduction Angle — The angular period of the supply wave during which the thyristor cell conducts.

9.5.3.17 Blocking State — This is the operating condition of one or more thyristors when forward biased but without a firing pulse being applied to their gates. No forward current flows and the thyristors act as a virtual open circuit.

9.6 SVC MODELLING TECHNIQUES

9.6.1 Model — A digital, analogue or reduced scale physical representation of the operating properties of a static var compensator and/or its associated electrical network. A combination of these representation techniques may be used.

9.6.2 Block Diagram — A method by which the physical properties of a system can be represented. The diagram is formed from a number of interconnected discrete blocks each representing an elementary process. Each block is characterized by its transfer function.

9.6.3 Transfer Function — The relationship(s) relating the output(s) to the input(s) of a block describing an elementary process.

According to the type of process and the type of study,the transfer function is defined in frequency (Laplace, Z-transform) or time domain.

9.6.4 Reference Input — This is an external signal applied to a feedback control system as a means of commanding a specified level of output of a compensator.

9.6.5 Bandwidth — A measure of the range of input frequencies over which a control system will respond in an acceptable manner.

In general, bandwidth is taken to be the frequency range between which the amplitude response does not drop 3db below the amplitude of the centre of the passband of the system or filter.

9.6.6 Reference Voltage Gain Term — A term which represents the base gain value for use in converting SVC characteristic and control system quantities to per unit quantities.

9.6.7. Current Compensation Term — A term which represents the current multiplied by suitable reactance value and provides system voltage droop compensation.

9.6.8 Summing Junction Term — A term which represents a device used for adding together several control signals.

9.6.9 Proportional Gain Term — A term which represents the gain of an open loop relationship between output and input.

9.6.10 Additional Stabilizing Function — A control element that modifies the reference voltage depending on control signals such as transmitted power, frequency, etc. in order to enhance system stability.

9.6.11 Power Oscillation Damping — This is a particular application of an additional stabilising function in which a supplementary signal is employed in an SVC to assist in damping active power oscillations on a power system.

9.6.12 Linearization Function — A control block that linearizes the relationship between the output of the controller and the admittance of a controlled TCR.

9.6.13 Limiter Func- — A function that limits the output of a block in its permissible range. A clear distinction should be made between forward and feedback limiters.

9.6.14 Integral Control Element — This a device which is used in closed loop type of control systems as a method of minimizing dynamic lags.

This form of compensation is used to reduce the steady state error of a control system, by providing an infinite open loop gain constant at zero frequency.

In practical terms, an integral type controller will exhibit a finite output level. There are two types of integral control elements :

(a) A device which continues to integrate internally in response to an input signal even though the output signal has reached its set limit level. This can cause a significant time delay to occur in the output signal when responding to the removal of the input signal. This is because of the additional integrating time which occurs before integral signal level has dropped to the output set limit level. This is usually referred to as an integrator with a 'static' or 'wind-up' type limiter in the literature (ref. 333).

(b) A device in which the internal integration action is stopped immediately when the corresponding input signal is removed. In this manner there is no delay time in output signal response. This is usually referred to as an integrator with a 'dynamic' or 'non-wind-up' type limiter in the literature (ref. 333).

9.6.15 Deadband — This is a characteristic of an automatic control system within which a change of value of an input signal (e.g., set value) to an element or system may take place without causing perceptible change to output signal. This is sometimes referred to as the dead zone.

9.6.16 Amplification — This relates to either an element or system and is the ratio of the steady-state amplitude of the output signal from an element or system to the amplitude of a sinusoidal input signal of a given frequency, or the ratio of output and input signal amplitudes when the signal has a constant unidirectional value.

9.6.17 Gain — The amplification of an element or system in which the input and output signals are of the same physical kind.

9.6.18 Dual Gain Characteristics — The characteristic of an element or system in which its gain characteristic has one value for a specified range of voltage control, and another gain characteristic when the voltage is operating beyond the preset range of control.

9.6.19 Adaptive gain control — This is a particular form of adaptive control which continuously adjusts the forward loop gain of the control system to ensure that the SVC does not contribute to the oscillatory behaviour of the power system.

9.7 TERMS RELATING TO FACTORY AND SITE TESTS

9.7.1 Type Test Measurements — Test measurements which are necessary only on a single piece of equipment of a particular type for the purpose of demonstrating that the performance of the equipment complies with the ratings or objectives mutually agreed between the manufacturer and the equipment purchaser.

9.7.2 Temperature Rise Test Measurements — Measurements which are required to demonstrate that the combined equipment will operate continuously under specified load conditions without any component exceeding its rated temperature rise.

9.7.3 Measurement of Reactance of the Phase Reactors — A measurement of the reactance of the load current carrying reactor in each phase of the compensator. In the case of saturated type reactors, this would be a measure of the slope reactance.

9.7.4 Insulation Voltage Withstand Measurements — Measurements which demonstrate the state of the insulation of all components required to operate at high voltage levels.

9.7.4.1 Induced Voltage Measurement — Measurements to be made on assembled equipment to demonstrate the adequacy of the insulation of the transformer, reactors, thyristor stacks and firing circuit barriers for the pulse signals.

9.7.4.2 Measurement of Insulation Resistance — Measurements which quantify the value of resistance of all important insulation components relative to ground and between HV electrical components.

9.7.4.3 RMS Voltage Withstand Measurements — Measurements which are necessary to demonstrate that the high voltage insulation can adequately withstand the specified RMS voltage level at rated supply frequency.

9.7.4.4 Impulse Voltage Withstand Measurements — Measurements which are necessary to demonstrate that a compensator can withstand safely a surge or impulse voltage of known wave shape e.g. 1/50 microsecond wave.

9.7.5 Overall Loss Measurements — Measurements which are necessary to determine electrical losses of a compensator when operating at various specified operating loads.

9.7.6 Routine Test Measurements of Power Components and Auxiliaries — Measurements which are made on component thyristor stacks and assemblies to verify that the components function correctly as individual items. These tests are also important to check for consistency of quality against type test measurements.

9.7.7 Type and Routine Test Measurements of Control Systems — Measurements which are necessary to demonstrate that the compensator control system characteristics are in accordance with the specified performance requirements. These include the linearity of all control elements, the time series (e.g., frequency, step or pulse response) characteristics of feedback circuits, and the range of adjustement of static output/input open loop characteristics.

9.7.8 Protective Systems Measurements — Measurements which are necessary to demonstrate that all protective devices operate in a correct manner including type tests for combined action. These include measurements on components to individually assess their quality of performance.

9.8 SYMBOLS AND ACRONYMS

9.8.1 List of Principal Symbols

A	Additional Control Signal(s)
B	Susceptance
C	Capacitance or Capacitive
E	Generator internal voltage or power system equivalent voltage
e	natural logarithm
f	frequency (Hz) or dependent upon frequency
G1,...	regulator transfer function block(s)
H	measuring and filter circuit transfer function
i	instantaneous value
I	RMS Current
j	$1\angle 90°$ operator
K	Control System gain (output/input) or harmonic weighing factor
L	inductance or inductive
max	maximum
min	minimum
n	harmonic order
N	number of turns
o	at no-load or pre-disturbance value
P	active power
p	harmonic voltage weighting factor
Q	reactive power
R, r	resistance of resistive component
ref	reference value
s	knee-point of saturation characteristic
S	apparent power (P±JQ)
SL	slope
T	control system time constant or time period
t	time
u	instantaneous voltage
U	RMS voltage
W	harmonic current weighting factor
X	reactance
Z	impedance
α	thyristor firing angle

9.8.1 List of Principal Symbols (Cont'd)

ϕ	angular displacement between voltage and current phasors (i.e. power factor) or flux
δ	powersystem load angle or generator load angle
ω	angular frequency (radians/sec)
θ	impedence angle $(=\tan^{-1}\frac{X}{R})$
$\triangle$	incremental quantity operator
Σ	sum

9.8.2 Abbreviations and Acronyms

Term	Meaning
AC	Alternating Current
ASA	American Standards Association
ANSI	American National Standards Institute
BOD	Break-over-diode
BSI	British Standards Institution
CCITT	International Consultative Commission of Telephone and Telegraph Systems
CAS/ACNOR	Canadian Standards Association
CISPR	International Electrotechnical Commission - Special Committee on Radio Interference
DC	Direct Current
EEI/BTS	Edison Electric Institute/Bell Telephone System
EDC	Equivalent Disturbing Current
EMF	Electromotive force
FC	Fixed Capacitor
FO	Forced Outage

9.8.2 Abbreviations and Acronyms (Cont'd)

Term	Meaning
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineers, UK
IEEE	Institut of Electrical and Engineers, USA
IT	Harmonic current factor
KVA	Kilo-volt-amperes
KVar	Kilo-volt-amperes-reactive
LCC	Line-Commutated Convertor
MSC	Mechanically Switched Capacitor
MSR	Mechanically Switched Reactor
MTBF	Mean time between failures
MTTR	Mean time to repair
NEMA	National Electrical Manufacturers Association, USA
PO	Planned Outage
POD	Power Oscillation Damper
PSS	Power System Stabiliser
RMS	Root-Mean-Squared
SCC	Self-Commutated Convertor
SVC	Static Var Compensator
SR	Saturated Reactor
SSR	Subsynchronous Resonance
TCR	Thyristor Controlled Reactor
TSR	Thyristor Switched Reactor
TSC	Thyristor Switched Capacitor
TIF	Telephone Interference Factor
THF	Telephone Harmonic Form Factor

BIBLIOGRAPHY

STATIC VAR COMPENSATORS AND THEIR APPLICATION TO HIGH VOLTAGE ELECTRIC POWER SYSTEMS

This bibliography is based upon the bibliography prepared by IEEE Working Group 79.2 on Static Var Compensators in A.C. Substations and published as paper number 83 WM 105-4 in IEEE Transactions on Power Apparatus and Systems Vol. PAS 102 No.12 in December 1983. The kind permission of IEEE in permitting the incorporation of the bibliography in this report is gratefully acknowledged. The IEEE bibliography has been substantially edited to incorporate both material previously not included and add material published in 1982, 1983, 1984 and 1985, thus bringing it up to date.

1921-1965

1. J.D. Ainsworth, "Filters, Damping Currents and Reactive Volt-Amps in HVDC Converters", Chapter 7 in High Voltage Direct Current Converters and Systems, B.J. Cory (ed.), MacDonald, London 1965.

2. F.G. Baum, "Voltage Regulation and Insulation for Large Power Long Distance Transmission Systems", Journal AIEE, Vol. 40, pp. 1017-1032, 1921.

3. E.Bornitz,M. Hoffman,G. Leiner, "Harmonics in Electrical Systems and their Reduction through Filter Circuits", CIGRE Report 304, 1958.

4. A. Boyajian, "The Physics of Long Transmission Lines", General Electric Review, pp. 15-22, July 1949.

5. CCITT/International Telegraph and Telephone Consultative Committee, "Directives Concerning the Protection to Telecommunication Lines Agains Harmful Effects from Electricity Lines", published by International Communication Union, Geneva, 1963.

6. G.F. Dixon, E. Friedlander, F. Seddon, and D.J. Young, "Static Shunt Compensation for Voltage Flicker Suppression", IEEE Conference Publication No.8, Abnormal Loads on Power Systems, Paper 4144P, 17 p., 1964.

7. EEI-BTS/Joint Committee on Development and Research of Edison Electric Institute and Bell Telephone System, "The Telephone Influence Factor of Supply System Voltages and Currents", Supplement to Engineering Report No. 33, EEI Publication 60-68, Sept. 1960.

8. C.L. Fortescue and C.F. Wagner, "Some Theoretical Considerations of Power Transmission", Journal AIEE, Vol. 43, pp. 106-113, 1924.

9. E. Friedlander, "Long Distance Power Transmission by Alternating Current", Engineering, pp. 1-3, Jan 2, 1942, pp. 21-23, Jan 9, 1942, pp. 41-43, Jan 15, 1942.

10. E. Friedlander, "Fundamentals of the Application of Highly Saturated Iron in Electrical Power Engineering", ETZ-A, Vol. 79, p. 104 (in German), Nov. 4, 1958.

11. E. Friedlander, "Voltage-Flicker Compensation with ac Saturated Reactors". GEC Journal, Vol. 29, No.2, pp. 107-114, 1962.

12. E. Friedlander, A. Telahun and D.J. Young, "Arc-Furnace Flicker Compensation in Ethiopia", GEC Journal of Science and Technology, Vol. 32, No.1 pp. 2-10, 1965.

13. F. Iliceto, J.D. Ainsworth and F.G. Goodrich, "Some Design Aspects of Harmonic Filters for HVDC Transmission Systems", CIGRE, 1964, Vol. 3, Report 405 on Sardinian Link.

14. W. Kramer, "Three-Phase Transformer with Controllable Magnetizing Current", ETZ-A, Vol. 80, pp. 441-445, 1959.

15. A. Kusko, "Polyphase Closed-Core Reactors", IEEE Trans. Power Apparatus and Systems, Vol. PAS-84, pp. 67-74, Jan. 1965.

16. A. Stalewski, "Reactive Power Compensation and Harmonic Filters", Appendix III, CIGRE Report 417, 1960. Also in Direct Current, Vol. 4, pp.130-133.

17. F.M. Stumpf, "Induction Effects of HVDC Transmission on Telephone Communications", IEEE 1965 International Convention Record, Part 9, Abstracts in Direct Current Vol. 10, May 1965.

18. "Survey of Arc Furnace Installations on Power Systems and Resulting Lamp Flicker". (Subcommitte Report), AIEE Trans. Applications and Industry, PIII, pp. 170-183, 1957.

19. C.F. Wagner and R.D. Evans, "Static Stability Limits and the Intermediate Condenser Station", AIEE Trans. pp. 94-123, 1957.

1966-1970

20. D.J. Azar'ev and I.V. Belousov, "Carrying Capacity of Long Distance Transmission Lines with Static Compensators", Elektrichestvo (USSR), No 4-6, 1970.

21. I.V. Belousov, "Automatically Constructed Analysers of Static kvar Compensators", Electrichestvo, No. 5, May 1970.

22. C.D. Clarke, M.J. Johanson-Brown, "The Application of Self-tuned Harmonic Filters to HVDC Converters", IEE Conference Publication No.22, Conference on HVDC Transmission, University of Manchester, Sept. 19-23, 1966, Part 1, pp. 275-276.

23. S.B. Dewan, R.S. Segsworth and M.S. McKinney, "DC Controlled Reactors Using Thyristors", IEE Trans. on Magnetics, Vol. MAG-5, No. 3, Sept. 1969.

24. J.M. Feldman et al, "Shunt Reactor Compensation on Present and Future Transmission Systems", Proc. American Power Conference, pp. 842-853, 1969.

25. E. Friedlander, "Flicker Suppression for Single-phase Resistance Welding Machines", GEC Journal of Science and Technology, Vol. 32, No. 2, pp.79-84, 1965.

26. E. Friedlander, "Static Network Stabilization, Recent Progress in Reactive Power Control", GEC Journal of Science and Technology, Vol.33,No.2,1966

27. E. Friedlander and K.M. Jones, "Saturated Reactors for Long Distance Bulk Power Lines", Electrical Review 184, pp. 940-943, 1969.

28. S.M. Katsnel'son and E.G. Bobrov, "A Thyristor Static Reactive-Power Compensator", Elektrotekhnika (USSR), 41 (12), 1970.

29. E.W. Kimbark, "Improvement of Power System Stability by Changes in the Network", IEEE Trans. PAS, Vol. PAS-88, pp. 773-781, 1969.

30. J. Kauferle, "HVDC Stations Connected to Weak ac Systems", IEEE Trans. Power Apparatus and Systems, Vol. PAS-89, pp. 1610-1619, 1970.

31. W.E. Schwabe, "Ultra-high Power Arc Furnaces", Iron and Steel Engineer, pp. 132-137, Sept. 1969.

32. P.C. Sen, "Smooth Control of Reactive Power Using Static Devices", IEEE Trans. Magn., Vol. MAG-4, No. 3, pp. 325-329, 1968.

1971

33. H. Frank and B. Landstrom, "Power Factor Correction with Thyristor-Controlled Capacitors", ASEA Journal No. 6, 180-184, 1971.

34. E.W. Kimbark, Direct Current Transmission,Vol. 1, Wiley Interscience Division of J. Wiley & Sons, Inc., New York, 1971.

35. V.A. Kulinich, "Compensation Method of Correcting Nonlinear Distortions of the Saturating Reactor Operating Current", Elektrotekhnika (USSR), No. 6, June 1971.

36. L.A. Kuchumov, A.K. Clernovets and Y.Y. Yarvilk, "Effects of Regulation of the Reactor of a Static Compensator on the Regimes of an Electrical System", Elektrichestvo (USSR), No 11, pp. 5-9, Nov. 1971.

37. S.P. Patra, K.P. Basu and S.S. Mukherjee, "Performance of a Static Shunt Compensator for Active and Reactive Powers", J. Inst. of Eng. (India), Electr. Eng. Div. Vol. 51, No. 6, PE-EL 3, Feb. 1971.

1972

38. R. Banks, E. Friedlander and A. Gavrilovic, "Application to EHV Transmission of Static Compensators Using Saturated Reactors", IEEE Canadian Conference on Communication and EHV Transmission, Montreal, pp. 153-154 (72Ch0698-1-Reg 7), November 1972.

39. H. Becker, B. Brandes and K. Gappa, "Three-phase Shunt Reactors with Continuously Controlled Reactive Current", CIGRE Conference, Paris, France, August 1972.

40. H. Becker, "Handling of Reactive Load Impulses in Distribution Networks by Employing Compensation Installations", VDE-Fachbericht, Vol. 27, pp. 92-97 (In German), 1972.

41. E.R. Johnson, P.S. Hasler, R.J. Moran and C.H. Titus, "Static High-speed var Control for Arc Furnace Flicker Reduction", Proc. of the American Power Conference, Vol. 34, pp. 1097-1105, 1972.

42. Y. Ota, Y. Morita, Y. Sakurai, "Flux Diagrams and Operating Behaviour of Three-phase Saturable Reactors", Elec. Eng., Japan, Vol. 92, No. 2, March-April 1972.

43. A Schirman, "Static Reactive Energy Compensators", ACEC Rev., No. 1, pp. 3-11, 1972.

1973

44. J.D. Ainsworth, E. Friedlander and K.J. Ralls, "Recent Development Towards Long Distance ac Transmission Using Saturable Reactors", International Conference on High Voltage DC and/or AC Power Transmission, Nov. 1973, IEE Conference Publication No. 107, pp. 242-247, London.

45. J.D. Ainsworth, E. Friedlander and R. Yacamini, "The Application of Saturated Reactors to AC voltage Stabilization for HVDC Transmission and Other Large Converters", IEEE Conference Paper C73 431-4, July 1973.

46. R.S. Bayless and J.H. Cronin, "New Concepts for Var Compensation in Substations", presented to Pacific Coast Electrical Association, Engineering and Operating Conference, March 23, 1973.

47. Beriger, "Reactive Power in HVDC Transmission", Brown Boveri Review, Vol. 60, pp. 95-99, 1973.

48. C.B. Cooper and D.J. Young, "Saturated Reactor Compensator for Stabilizing Voltage at Load and Generation Points", International Conference on High Voltage DC and/or AC Power Transmission, Nov. 1973, London, IEE Conference Publication No. 107, pp. 87-91.

49. H. Frank and S. Ivner, "TYCAP, Power-factor Correction Equipment Using Thyristor-Controlled Capacitors for Arc Furnaces", ASEA Journal, Vol.46, No. 6, pp. 147-152,1973.

50. L.A. Kuchumov, A.K. Chernovets, V.S. Orlov, M.S. Libkind and Y.Y. Yarvilk, "Voltage Regulation in Networks by a Controlled Static Compensator with Parametric Regulation", Elektrichestvo (USSR), No. 10, pp. 12-17, October 1973.

1974

51. J.D. Ainsworth, C.B. Cooper, E. Friedlander and H.L. Thanawala, "Long Distance ac Transmission Using Static Voltage Stabilizers and Switched Linear Reactors", CIGRE Paper 31-01, September 1974.

52. L.O. Barthold, H. Becker, J. Dalzell, C.B. Cooper H.B. Norman, C.A. Peixoto, K. Reichert, J.C. Roy and B. Thoren, "Static Shunt Devices for Reactive Power Control", CIGRE Paper 31-08, Sept. 1974.

53. E. Clegg, A.J. Heath and D.J. Young, "The Static Compensator for the BSC Anchor Project", IEE Publication No. 110, International Conference on Sources and Effects of Power System Disturbances, London, April 1974.

54. L. Gyugyi and J.W. Motto, "Static Var Control for Voltage Support to Widely Varying Utility Loads", International Conference on Power Semiconductors and Their Applications, IEE, 3-5 December 1974, London.

55. T.E. Harris and R.W. Lye, "A Static Var Compensator for Flicker Control on the Saskatchewan Power Corporation System", Canadian Electrical Association, Montreal, 1974.

56. W. Herbst, J. Kauferle, F. Penedar and K. Reichert

"Controllable Static Reactive Power Compensation of High Voltage Systems", Brown Boveri Review, Vol. 61, pp. 455-459, No. 9/10, September/October 1974.

57. Y.H. George and R. Gosselin, "Static Compensators of Simplified Construction as a Remedy to Power System Disturbances", IEE Publication No. 110, International Conference on Sources and Effects of Power System Disturbances, London, April 1974.

58. M.W. Kennedy, J. Loughran and D.J. Young, "Applications of Static Suppressor to Reduce Voltage Fluctuations caused by a Multiple Arc Furnace Installation", IEE Conference Publication No. 110, Sources and Effects of Power System Disturbances, pp. 130-137, April 1974.

59. D.A. McCallum and C.B. Cooper, "AC System Network Control Methods - Compensation", University of Newcastle-upon-Tyne, Henderson Hall, September 13, 1974.

60. N.N. Nikforovskii and Y.P. Brunov, "Design of an Inductor for a Static Compensator with Optimum Parameters", Izv. Vus. Elektromekh (USSR) No. 10, October 1974.

61. A.R. Oltrogge, "Arc Furnace Voltage Can Be Critical", Electrical World, December 1974.

62. K. Reichert, J. Kauferle and H. Glavitsch, "Controllable Reactor Compensator for More Extensive Utilization of High Voltage Transmission Systems", CIGRE Paper 31-04, September 1974.

63. K. Reichert, J. Kauferle and F. Penedar, "Thyristor-controlled Static Reactor Compensator", International Conference on Power Semiconductors and their Applications, IEE, London, 1974.

64. H.L. Thanawala, W.O. Kelham and W.P. Williams, "The Application of Reactive Compensators in Conjunction with Line Series Capacitors to Increase the Transmission Capabilities of Long ac Lines", CIGRE Paper 32-09, September 1974.

65. L.M. Zisman, A.N. Kurochkin, A.E. Razdin and A.D. Sladkovskii, "Parallel Operation of a Controllable Reactor and a Synchronous Compensator in the Load Node", Izv. Akad. Nauk (USSR) Eneg. Transp., No. 2, March-April 1974.

1975

66. K. Iwamoto and T. Todaka, "Analysis of the Three-phase Series Type Saturable Reactor with Auxiliary Windings. I-Modes and Control Characteristics", Science and Engineering Review, Doshisha Univ. (Japan), 16(2), July 1975.

67. K. Iwamoto and T. Todaka, "Analysis of the Three-phase Series Type Saturable Reactor with Auxiliary Windings. II-Minor-Loop, Response Time and Hunting Phenomenon", Science and Engineering Review, Doshisha Univ. (Japan), 16(2), July 1975.

68. H.H. Jahn, "Fast Compensation of Electric Arc Furnace Disturbance", Elektrotechnische Zeitschrift, Vol. 96, No. 12, p. 564, December 8, 1975 (In German).

69. E. R. Johnson, "Static High Speed Var Control for Light Flicker Reduction", AIME Electric Furnace Proc., Vol. 33, pp. 190-195, 1975.

70. P. Jovanic, "Static Compensators Appl. , High-speed, Automatic Reactive Power Regulation", Elektroprivreda (Yugoslavia), 28, No. 11-12, November-December 1975.

71. J. Karlovits, J. Nagy, F. Rejto, P. Stefan and G. Tevan, "Static Compensators for Supplying Rapidly Variable Reactive Power", Elektrotechnika (Hungary), 68 (4-5), April-May 1975.

72. V.R. Lepp, K.M.Sibgatulin and Yu. N. Cherkasov, "A Saturable Reactor with Separate Operating Windings", Elektrotechnika (USSR), No. 10, October 1975.

73. R.J. Moran, "Shunt Compensation with Solid State Var Control System", Pacific Coast Electrical Association, Engineering and Operating Section Meeting, Los Angeles, California, March 1975.

74. R.J. Moran, C.J. Titus and J.B. Tice, "Solid-state Converters for Power System Voltage Control", Proc. American Power Conference, Vol. 37, pp. 1041-1047, 1975.

75. J.W. Motto, D.P. Orange and R.A. Otto, "The Static Var Generator and Alternative Approaches to Power System Var Compensation", Proc. of the American Power Conference, Vol. 37, pp. 1032-1040, 1975.

76. D. Proske, "Wattless Power Compensation by Means of Thyristor-controlled Capacitor Batteries", Polytech. Tijdschr. Elektrotech. Elektron (Netherlands), 30(5), March 1975.

77. D. Woodford and M.Z. Tarnawecky, "Compensation of Long Distance ac Transmission Lines by Shunt Reactance Controllers", IEEE Trans. PAS, Vol. PAS-94, No. 2, pp. 655-665, March-April 1975.

78. E.A. Pankratova, "Compensation of the Higher Harmonics of Currents Generated by a Controlled Static Source of Reactive Power", Elektrichestvo (USSR), No. 12, December 1975.

79. "Variable Inductance Refines Correction", Electrical World, Vol. 183, No. 9, pp. 56-57, May 1975.

1976

80. R. Chauprade, "The Static Condenser - A Modern Solution for Reactive Energy Compensation", Rev. Jeumont-Schneider (France), No. 23, December 1976.

81. M. Erche, N.P. Nettler and D. Povh, "Performance of Static Compensators", Canadian Communications and Power Conference, Montreal, Quebec, October 1976.

82. E. Friedlander, "Transient Reactance Effects in Static Shunt Reactive Compensators for Long ac Lines", IEEE Trans. PAS, Vol. PAS-95, pp. 1669-1675, September-October 1976.

83. Y. George, "Static Compensators of Reactive Energy for Rolling Mill Systems", ACEC Rev., No. 1-2, pp. 23-33, 1976.

84. L.Gyugyi and R.A. Otto, "Static Shunt Compensation for Voltage Flicker Reduction and Power Factor Correction", Proc. of the American Power Conference, Chicago, Vol. 48, pp. 1271-1285, 1976.

85. L. Gyugyi, "Reactive Power Generation and Control by Thyristor Circuits", IEEE Power Semiconductor Specialist Conference, 1976.

86. L. Gyugyi and R. A. Otto, "Static Var Compensation of Electric Arc Furnaces". 8th Congress de Union Internationale d'Electrothermie, Sec. Va. Ref. No. 12, Liege, Belgium, 1976.

87. L. Gyugyi, W.J. Lordeon, D.P. Orange and R.A. Page, "The Application of Static Var Compensation Systems", IEEE Industry Application Annual Meeting, 76CH1122-IIA, pp. 1138-1144A, 1976.

88. V.R. Lepp, K.M. Sibgatulin and Y.N. Chevkasov, "A New Type of Saturable Reactor", Elektrotechnika (USSR) 47(12), 1976.

89. A. Olwegard, L. Ahlgren and H. Frank, "Thyristor-controlled Shunt Capacitors for Improving System Stability", CIGRE Paper No. 32-20, September 1976.

90. V.S. Orlov, "Influence of Frequency Variation on the Operation of a Static Parametric Compensator", Izv. Vuz. Energ.(USSR), No. 3, March 1976.

91. R.P. Stratford and D.E.Steeper, "Reactive Compensation and Harmonic Suppression for Industrial Power Systems Using Thyristor Converters", IEEE Transactions on Industry Applications, Vol. 1A-12, No. 3, pp. 232-254, May-June 1976.

92. Y. Sundberg, "The Arc Furnace as a Load on the Network", ASEA Journal, Vol. 49, No. 4, pp. 75-87, 1976.

93. H.L. Thanawala, W.O. Kelham and W.P. Williams, "The Application of Shunt Reactive Compensators in Conjunction with Line Series Capacitors to Increase the Transmission Capability of Long ac Lines", CIGRE Paper 31-09, September 1976.

1977

94. H. Aschenbach, W.Hanke and W. Hochstetter, "Controllable Static Reactive-power Compensators in Electric Supply Systems", the 2nd IFAC Symposium on Control in Power Electronics and Electrical Drives, Dusseldorf, October 1977.

95. R. Brehler and N.Kleinsorge, "Static Compensators - Var Control Using Thyristors", 30 th Annual Power Distribution Conference, Austin, Texas, October 24-26, 1977.

96. M. Cadoch, P. Czech, B. Poirier and D. McGillis, "The Performance of Static Compensators on 735 kV Equivalent Systems Under Load Rejection and Short-circuit Conditions", Canadian Electrical Association, Winnipeg, November 1977.

97. P. Charles, "Rapid Static Compensation of Reactive Power", Tech. Com. (France), Vol. 100-101, December 1977.

98. CIGRE Study Committee No. 31, Working Group 01, "Modelling of Static Shunt Var Systems (SVS) for Systems Analysis", ELECTRA, Vol.51, March 1977.

99. J.H. Cronin, W.J. Lordeon and G.B. Ostrowski, "Static Var Generators for Transmission Systems", Proc. American Power Conference, Vol. 39, pp. 1122-1143, 1977.

100. P.K. Dash, R.M. Mathur and A.E. Hammad, "Improvement of the Performance of a Superconducting Turboalternator Through Use of a Controllable Reactive Power Compensator", International Journal of Electrical Machines and Electromechanics, Vol. 2, pp. 73-86, 1977.

101. M. Depenbrock, "Compensation of Rapidly Varying Reactive Currents", ETS (A) (F.R. Germany), Vol. 98, pp. 408-411, June 1977.

102. H. Edelmann, "Steady-state Stability of a Three phase System with Steplessly Controllable Susceptance", Siemens Forsch.und Entwicklungsber. 6 (4), 1977.

103. F.J. Ellert and R. Moran "HVDC and Static Var Control Applications of Thyristors", IEEE/IAS International Semiconductor Power Converter Conference, Lake Buena Vista, Florida, pp. 497-508 (77CH1183-3 IA) March 27-31, 1977.

104. H. Frank and K. Petterson, "Raising the Production of Arc Furnaces by Stabilizing the Voltage with Thyristor-switched Capacitors", ASEA Journal, Vol. 50, No. 1, pp. 9-16, 1977.

105. E. Friedlander, Correction to "Transient Reactance Effect in Static Shunt Reactive Compensators for Long ac Lines", IEEE Trans. PAS, Vol. PAS-96(2), March-April 1977.

106. Y. George, "Application of Static Compensators to de Laminoirs Complex and EHV Power Systems", WELC, Moscow, June 1977.

107. W. Hochstetter, "Properties of Static Compensators for Power Supply Systems", Siemens Review, Vol. XLIV, No. 8, pp. 356-360, August 1977.

108. F. Iliceto and E. Cinieri, "Comparative Analysis of Series and Shunt Compensation Schemes for ac Transmission Systems", IEEE Trans. PAS, Vol. PAS-96, No. 6, pp. 1819-1830, 1977.

109. W. Kaufhold, D. Povh and H. Tyll, "Static Compensator Performance in Long-distance Transmission Systems", Siemens Forsch. und Entwickl. Berichte, Bd. 6, No. 5, pp. 286-292, 1977.

110. E.W. Kimbark, "How to Improve System Stability without Risking Sub-synchronous Resonance", IEEE Trans. PAS, Vol. PAS-96, No. 5, pp. 1608-1619, September-October 1977.

111. V.S. Lipatov, "Control System for Static Reactive Power Compensators", Elektroteckhnika (USSR), 48(9), 1977.

112. W. Meusel and H. Waldmann, "Co-ordinate Transformations of Multiterm Regulation System for the Compensation and Symmetrization of Three-phase Supplies", Siemens Forsch. Entwicklungsber. Res. Dev. Rep. Vol. 6, No. 1, pp. 29-38, 1977.

113. G.B. Ostrowski and S.D. Sherner, "Application of Control Strategies and Electronic Devices to Enhance Electrical Energy Transmission", ASME/IEEE Joint Power Generation Conference, Long Beach, CA., September 21, 1977.

114. S. Saraf, "Study of dc Controlled Saturated Reactor for Static Reactive Power Compensation",

M. Tech. Thesis, I.T. Banaras Hindu University, Varanasi, India, 1977.

115. G.G. Sironi and J.R. Van Hulse, "Transient Behaviour of a Static Compensation with Ferromagnetic Non-linearity", IEEE Trans. Magn., Vol. MAG-13, No. 5 pp. 1299-1301, September 1977.

116. T. Sjokvist, "Thyristor Switched Capacitors for Reactive Power Compensation", Iron and Steel Engineer, Vol. 54, No. 4, pp. 40-47, April 1977.

117. E. Wanner and Herbst, "Static Power Factor Compensators for Use with Arc Furnaces", Brown Boveri Review, Vol. 64, No. 2, pp. 124-134, 1977.

1978

118. M.P. Bahrman, L.P. Crane, F.L. Nylander and C.E. Wood, "Application of a Static Var System to the MP&L Transmission Network", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979..

119. R. Chakrabatri, S.K. Basu and S.P. Patra, "A Static Shunt Reactive Power Compensator Using High Speed Transducers", Electr. (India), 18 (21), November 15, 1978.

120. J. Cronin, G. Ostrowski, W.J. Lordeon and L. Gyugyi, "Transmission Voltage Support with Static Var Generators", IEEE PES 1978, Winter Power Meeting, New York, (78CH1295-5 PWR), Paper No. A78 108-3, January 19-February 3, 1978.

121. P. Czech and D. McGillis, "Hydro-Quebec's Experience in Planning, Designing and Implementing Static Compensation Systems", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108,1978 April-1979.

122. W.L. Davis and H.F. Erinker, "Static Var System Controls Line Voltage", Electrical World, Vol. 190, No. 2, July 15, 1978..

123. W.L. Davis and R.J. Newell, "Planning, Installation and Initial Operation of the Victory Hill Static Var Control", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI.Special Report EL-1047-SR, WS-78-108,April 1979.

124. F.P. DeMello, B.K. Johnson, L.N. Hannett, D. Birfet and J. Toulemonde, "Thyristor-controlled Reactors Analysis of Fundamental Frequency and Harmonic Effects", IEEE PES 1978 Winter Meeting, New York (78CH1294-5 PWR), Paper No. A78, 106-7, January 29-February 3, 1978.

125. R. Elsliger, Y. Hotte, J.C. Roy, "Optimization of Hydro-Quebec's 735 kV Dynamic-shunt-compensated System Using Static Compensators on a Large Scale", IEEE PES 1978 Winter Power Meeting, New York, (78CH1295-5 PWR), Paper No. A78, 107-5, January 29-February 3, 1978.

126. K. Engberg and S. Torseng, "Reactors and Capacitors Controlled by Thyristors for Optimum Power System Var Control", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

127. H. Frank and T. Petterson, "Thyristor-switched Shunt Capacitors and their Modelling for Transmission Applications", IEEE 1978 Power Engineering Society Winter Meeting, (78CH1295-5 PWR), Paper No. A78,105-9, January 29-February 3, 1978.

128. Y. George, A. Labart, G.Sironi and J. Van Hulse, "Analytical and Numerical Modelling of Saturable Reactors", ACEC Rev. (Belgium), No. 1-2, 1978.

129. L. Gyugyi, "Static Var Compensator with Continuously Variable Output and Minimum No Load Losses", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

130. L. Gyugyi, R.A. Otto and T.H. Putman, "Principles and Applications of Static, Thyristor-controlled Shunt Compensators", IEEE Trans. PAS, Vol. PAS-97, No. 5, pp. 1935-1945, September/October 1978.

131. A.E. Hammad and R.M. Mathur, "A New Thyristor-controlled Var Compensator Design", Canadian Communications and Power Conference, Montreal, October 1978.

132. M.H. Hanes and D.J. Page, "Light Triggered Thyristors and their Application to Switches in Static Var Compensators", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 5, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

133. H.H. Happ and K.A. Wirgau, "Static and Dynamic Var Compensation in System Planning", IEEE Trans. PAS, Vol. PAS-97, No. 5, pp. 1964-1978, September/October 1978.

134. R. Hauth, T. Humann and R.J.Newell, "Application of a Static Var System to Regulate System Voltage in Western Nebraska", IEEE Trans. PAS, Vol. PAS-97, No. 7, pp. 1955-1964, September/October 1978.

135. R. Hauth and R. Moran , "The Performance of Thyristor-controlled Static Var Systems in HVAC Applications", IEEE Tutorial Text 78EH135-4-PWR, IEEE/PAS Summer Meeting, Los Angeles, California, July 1978.

136. R. Hauth and R. Moran, "Introduction to Static Var System for Voltage and Var Control", IEEE Tutorial Text 78EH0135-4 PWR, pp. 48-55, IEEE Summer PAS Meeting, Los Angeles, Ca. July 1978.

137. R. Hauth and R. Moran, "The Basics of Applying Static Var Systems on HVAC Power Networks", EPRI Seminar on Transmission Static Var Systems. Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

138. A.T. Kefalas andd D. Mukhedkar, "Recent Bibliography on Static Shunt Var Systems (SVS)", IEEE PES 1978 Winter Power Meeting, January 19-February 3, 1978.

139. K. Konttinen, M. Ampuja, P. Ritmaki and S. Purves, "Fast Static Compensators for Transmission Lines and Industry", Elec. Review, (G.B.), June 30, 1978.

140. W.J. Lordeon, J.H. Cronin, R. Cooper and M. Brennan, "Transmission Static Var Generator,

Installation Description and Performance Results", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

141. R.M. Mathur, P.K. Dash and A.E. Hammad, "Transient and Small Signal Stability of a Superconducting Turbogenerator Operating with Thyristor-controlled Static Compensator", IEEE PES Summer Meeting, Paper No. F-78-661-1, Los Angeles, California, 1978.

142. R.J. Moran, "Static Var Control for the Steel Industry", Industrial Power Systems, GEC Schenectady (USA), Vol. 21, No. 1, pp. 4-7, March 1978.

143. D. O'Kelly and M. Abu Elnour, "Computation of Saturated Reactor Performance", IEEE 1978 PES Winter Meeting, New York, 78CH1295-5 PWR, Paper No. A78-270-1, January 29-February 3,1978.

144. G.B. Ostrowski, J.H. Cronin, W.J. Lordeon, "Static Var Generator Tested for Voltage Control", Transmission and Distribution, Vol. 30, No. 7, pp. 32, 33, 36, 38, July 1978.

145. K. Reichert, R. Baehr and J. Gerth, "Reactor-transformer for Controllable Static Compensators", CIGRE Paper 12-05, September 1978.

146. P. Ritamaki, E. Saarelainen, "New Low-loss Static Compensator Improves Steel Production and Quality of Power Systems", Sahkoe (Finland), 51, May/June 1978.

147. G. Roberge and A. Doyon, "Control of an Inductance of Variable Permeability and Application to Static Compensators", Canadian Communications and Power Conference, Montreal, October 18-20, 1978.

148. H.E. Schweikardt, G. Romegialli and K. Reichert "Closed Loop Control of Static Var Sources (SVS) on EHV Transmission Lines", IEEE Trans. PAS, Vol. PAS-97, No. 4, July/August 1978.

149. H.E. Schweickardt, "Static Var Sources, their Alternatives and Use in Transmission Systems", EPRI, Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

150. H.E. Schweickardt and G. Romegialli, "The Static Var Source in EHV Transmission Systems and its Control", Brown Boveri Review, No. 9,1978.

151. A. Seki, J. Nishidai and K. Murotani, "Suppression of Flicker Due to Arc Furnaces by a Thyristor-controlled Var Compensator", IEEE 1978 Power Engineering Society Summer Meeting, (78 CH1361-5 PWR), Paper No. A78 590-2, July 1978.

152. H.L. Thanawala, W.P. Williams and D.J. Young, "Static Var Compensation - Ten Years of Experience of Design and Operation Using Saturated Reactors", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

153. C.E. Wood: M.P. Barhman and F.L. Nylander, "Application of a Static Var System to the MP&L Transmission Network", EPRI Seminar on Transmission Static Var Systems, Duluth, Minnesota, October 4, 1978, EPRI Special Report EL-1047-SR, WS-78-108, April 1979.

<u>1979</u>

154. J.D. Ainsworth, H. Thanawala and W.P. Williams, "Comparison of the Operating Characteristics of Static Compensators Using Saturated Reactors and Thyristor Controlled Reactors as the Variable Elements", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

155. M.O. Bahrman and L.P. Crane, "Operating Experience with a Static Var Generator on the Minnesota Power and Light System", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

156. J. Belanger, L. Dias, S. Moraes and S. Frontin, "Application of Static Controller on the Furnas (Brazil) 138 kV Transmission System", International Symposium on Controllec Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

157. R. Chakrabarti, S.K.Basu and P.K. Chattopadhyay, "Computer Aided Analysis on Harmonic Reduction by Interconnection and Interaction in Parametric Shunt Compensator", J. Inst. Eng. (India), Electr. Eng. Div., Vol. 59, PT, EL-5, April 1979.

158. Z. Cerovsky, "Calculation of Steady-states of Loads in Static Compensators of Reactive Power", Elektrotech. Obs. (Czechoslovakia), 68(4) April, 1979.

159. C.B. Cooper and R. Yacamini, "Choice of Analytical and Modelling Methods for Reactive Compensation Equipment", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, University of Birmingham, September 1979, IEE Digest N. 1979/52, London (also published in Proc. IEE, Vol. 128, P&C, No. 6, pp. 402-406, November 1981).

160. P. Czech, S.Y.M.Hung, N.H. Hụynh and G. Scott, "TNA Study of Static Compensator Performance on the 1982-83 James Bay System; Results and Analysis", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

161. K. Engberg and S. Ivner, "Static Var Systems for Voltage Control During Steady-state and Transient Conditions", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

162. M.M. Gavrilovic, G. Sybille, V.Q. Do and J.Y. Lemay, "Controlled Reactive Compensation Modelling on the IREQ Power System Simulator", International Sympsoium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

163. M.M. Gavrilovic, J. Belanger, V.Q. Do and J.Y. Lemay, "Modelling Techniques for Studying Controlled Reactive Compensation on the IREQ Power System Simulator", Canadian Electrical Association, Spring Meeting, Vancouver, March, 1979.

164. L. Gyugyi et al. , "Principles and Application of Static Thyristor Controlled Shunt Compensator", Paper A78 108-31, IEEE PAS Winter Meeting, New York, February 4-9, 1979 (also IEEE PAS, Vol. PAS-97, No. 5, May 1979).

165. L. Gyugyi and W.P. Matty, "Static Var Generator with Minimum No-load Losses for Transmission Line Compensation", American Power Conference, Chicago, April, 23-25, 1979.

166. L. Gyugyi and E.R. Taylor, Jr., "Operating and Performance Characteristics of Static Thyristor-controlled Shunt Compensators", Internatioanl Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

167. L. Gyugyi, "Reactive Power Generation and Control by Thyristor Circuits", IEEE Trans. Ind. Appl., Vol.1A-15, No. 5, pp. 521-532, September/October 1979.

168. A.E. Hammad and R.M. Mathur, "A New Generalized Concept for the Design of Thyristor Phase-Controlled Var Compensators, I - Steady-state Performance", IEEE Trans. PAS, Vol. PAS-98, No. 1, pp. 219-226, January-February 1979.

169. I. Hosono, M. Yano, M. Takeda, S. Yuya and S. Sueda, "Suppression and Measurement of Arc Furnace Flicker with a Large Static Var Compensator", IEEE Trans. PAS, Vol. PAS-98, No. 6, pp. 2276-2284, November/December 1979.

170. Y. Hotte and S.Y.M.Hung, "Voltage and Reactive Power Control on Hydro-Quebec's 735 kV Transmission Systems", Report 31 79 (GT01) 02 DTI, CIGRE Study Committe 31, Vancouver, B.C., Canada, July 8-13, 1979.

171. IEEE Industry Applications Society, "IEEE Guide of Harmonic Control and Reactive Compensation of Static Power Converters", (Draft), January 1979.

172. W. Juling, H. Tyll and M. Weingand, "Effect of Static Compensators on the Dynamic Performance of AC Systems", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

173. S.C.Kapoor, "Dynamic Stability of Long Transmission Systems with Static Compensators and Synchronous Machines", IEEE Trans. PAS, Vol. PAS-98, No. 1, pp. 124-134, January/February 1979.

174. J.J. Keane, D. Chu, R. Gutman, M.E. Rahman and O. Veraas, "Application of Static Var Compensators for Steady-state and Dynamic Voltage Control", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

175. R.W. Lye and G.M. McAllister, "The Rimouski Static Compensator A Pioneer on the Hydro-Quebec System", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

176. R.M. Mathur, "Thyristor-controlled Compensators Evaluation of a New Concept", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

177. R.M. Mathur and A.E. Hammad, "A New Generalised Concept for the Design of Thyristor Phase-controlled Var Compensators. II - Transient Performance", IEEE Trans. PAS, Vol. PAS-98, No. 1, pp. 227-237, January/February 1979.

178. G. Nicola, G. Santagostino, L. Baggini and G. Borgonovo, "Studies Concerning the Possible Application of SVS's on the Future UHV Transmission System on ENEL", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

179. Y. Ogihara, M. Inoue and K. Murotani, "Improvement of Steady-state and Transient Stability by Static Var Compensator", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

180. R.E. Owen, "Distribution System Harmonics Effects on Equipment and Operation", Pacific Coast Electrical Association, Engineering and Operating Conference, Los Angeles, March 15-16,1979.

181. S.P. Patra, S.K. Basu and R. Chakrabatri, "Static Reactive Power Compensation Using Phase-controlled Thyristors", J. Inst. Eng. (India), Electr. Eng. Div., Vol. 59, PT. EL-5, April 1979.

182. S.P. Patra, S.K. Basu and R. Chakrabatri, "Automatic Reactive Power Compensation Using Phase Angle Control of Transformers", J. Inst. Eng. (India), Electr. Eng. Div., Vol. 59, PT,EL-5, April 1979.

183. P. Pelletier and O. Bourgault, "Short-circuit at the 230 kV Rimouski Substation and Performance of the Thyristor-controlled Reactor-type Static Compensator", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

184. P. Pelletier and O. Bourgault, "Essais de Courts-circuits au compensateur Statique du Poste Rimouski; 4-5 juillet 1978, 30-31 janvier 1979", Rapport No. 7960, Essais de recherche et analyse, Hydro-Quebec.

185. T.H. Putman and D.G. Ramey, "A Modulated Inductance Stabiliser for Power System Subject to Subsynchronous Resonance", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

186. K. Reichert, L. Terens, J. Durr and W.M. Pfyl, "Harmonic Interaction Between Static Var Systems and the Network, Problems, Analysis and Solutions," International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

187. R.G. Schieman, "Power Factor Correction of Static Drives with Capacitors", IEEE, Industry Applications Society, IEEE-IAS Annual Meeting, Paper 79CH1484-5 IA, pp. 749-756, 1979.

188. H.E.Schweikardt, W.M. Pfyl and G. Romegialli, "Laurentides - The First 735 kV Static Var System, Description and First Operational Results", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

189. H.E. Schweikardt, "Uses and Control of Static Compensators in EHV Systems", Neue Tech. (Switzerland), 21(2), 15 February 1979.

190. C.M. Stairs and N.L. Williams, "Static Compensators for Hydro-Quebec's 735 kV Nemiskau Switching Station", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September, 1979.

191. V.S. Subba Rao, G.S. Raju, B.R.M. Gandhi, N. Bhagavathy, R.S. Gorayan and S. Saraf, "DC Controlled Double Zig-Zag Connected Saturable Reactor", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

192. S. Torseng, "Thyristor-controlled Static Shunt Compensators", Int. Power Generation (GB), 2(4), June 1979.

193. K.A. Walshe and C.B. Cooper, "Slope Reactance Effects in Single-phase Saturated Reactors", Proc. IEE, Vol. 126, No. 8, pp. 771-776, 1979.

194. D.A. Woodford, "The Application of Controlled Reactive Compensation for Single-pole Switching on Long EHV Line Sections", International Symposium on Controlled Reactive Compensation, IREQ, Varennes, Quebec, September 1979.

195. D.J. Young, "Static Shunt Compensators - Saturated Reactor Types", Presented to IEE Technical Seminar on Reactive Compensation in Power Systems at University of Birmingham in September 1979, IEE Technical Digest No. 1979/52, September 1979.

1980

196. J.D. Ainsworth, A. Gavrilovic and H.L. Thanawala, "Overvoltage Control by Different Types of Reactive Power Compensators in AC-DC Systems", 1980 International Conference on Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

197. J.D. Ainsworth, A.Gavrilovic and H.L. Thanawala, "Static and Synchronous Compensators for HVDC Transmission Convertors Connected to Weak AC Systems", CIGRE Paper No. 31-01, September 1980.

198. P.H. Ashmole, "Fundamental Reactive Power Control Requirements", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, IEE Digest No. 1980/41, London, September 8-9, 1980.

199. M.P. Bahrman, "Overvoltage and Var Compensation Considerations at the Square Butte HVDC Transmission Systems", 1980 International Conference on Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

200. J.P. Bowles, "Alternative Techniques and Optimization of Voltage and Reactive Power Control at Converter Stations", 1980 International Conference on Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

201. S.B. Cooper and S. Assair Hussayni, "Thyristor Switched Reactors for Distribution Systems", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, IEE Digest No. 1980/41, London, September 8-9, 1980.

202. P. Czech, H. Holm, K. Reichert and H.E. Schweikardt, "Static Var Systems in Power Transmission, Principles, Solutions, Applications, Experiences with a 450 MVa Unit in a 735 kV System, CIGRE Paper No. 32-05, September 1980.

203. P. Czech and D. McGillis, "Static Compensators and Their Relation to System Stability", Presented at the American Power Conference, Chicago, Vol. 42, pp. 726-731, 1980.

204. A. Doyon, J.M. Pelletier and J. Parrent, "The Rimouski Static Compensator - Characteristics, Performance and the Effect on the Stability of the Hydro-Quebec System", IEEE Canadian Communications and Power Conference, Montreal, October, 15-17, 1980.

205. M.Z. El Sadek and A.E. Hammad, "Optimization of the Parameters of Static Compensation Systems Operated by Thyristors and Used for Transmission System Stabilization", IEEE Canadian Communications and Power Conference, Montreal, October 15-16, 1980.

206. K. Engberg, L. Hermansson and S. Torseng, "Experience and Position Report of Thyristor Controlled Capacitor and Reactors in Transmission Systems", 1980 International Conference on Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

207. H. Fiebiger, B. Godenzi, F. Volker, Y. George and G. Legas, "Thyristor Static Compensator for the CERN Intermediate Booster Accelerator", ACEC Rev. (Belgium), No. 3, pp. 2-6, 1980.

208. C.E. Grund, G. Breuer and R.P. Petersson, "AD/DC System Dynamic Performance - Transient Stability Augmentation with Dynamic Reactive Power Compensation", IEEE Trans. PAS, Vol. PAS-99, No.4 pp.1493-1502.

209. L. Gyugyi and E. Taylor, "Characteristics of Static Thyristor-controlled Shunt Compensators for Power Transmission System Applications", IEEE Trans. PAS, Vol. PAS-99, No. 5, pp. 1795-1804, 1980.

210. L. Gyugyi, "Control of Shunt Compensation - Viewpoint One", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, IEE Digest No. 1980/41, London, September 8-9,1980.

211. N. Huynh, G. Scott, P. Czech and M.Hung, "Technical Specifications for the Static Compensators for the James Bay Transmission System", IEEE Canadian Communications and Power Conference, Montreal, October 15-17, 1980.

212. S.C. Kapoor, "Dynamic Stability of Static Compensator-synchronous Generator Combination", IEEE 1980 Power Engineering Society Summer Meeting, Paper 80 SM 627-0, Minneapolis, Minnesota, July 13-18, 1980.

213. R.M. Mathur, "Non-characteristic Harmonics Generated by Thyristor Controlled Reactors", IEEE Communication and Power Conference, pp. 6-9, October 1980.

214. M. McGranagahn and R. Rocamora, "Hybrid Model Optimizes Static Var Design", Electrical World (USA) Vol. 194, No. 9, pp. 85-86, December 1980.

215. D.McGillis, N.H. Huynh, G.Scott, "The Role of Static Compensators in Meeting AC System Control Requirements", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, London, September 8-9, 1980.

216. S.A. Miske, R.L. Hauth, F. Nozari and J.R. Moran, "Static Var Systems : Dynamic Shunt Compensation for Transmission Systems", Presented to the Pacific Coast Electrical Association Engineering and

Operating Conference, March 19-20, 1980.

217. R.J. Newall et al., "Staged Field Testing of the Victory Hill Static Var Control", IEEE Trans. PAS, Vol. PAS 99, No. 2, pp. 426-433, 1980.

218. H.B. Norman and M.F. Hadingham, "Present and Future Use of Static Compensators to Control Voltage Level and Balance on the ESCOM System", Proceedings of the IFAC Symposium on Automatic Control in Power Generation Distribution and Protection, September 15-19, 1980, Pretoria, South Africa, Pergamon, Oxford, England.

219. H.S. Pastel, R.L. Hauth, R.V. Pohl and G.S. Breuer, "Voltage and Var Compensation Studies for Integrated DC Links into AC Systems", 1980 International Conference on Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

220. C.A.O. Peixoto, J.A. Jardini, C.D. Clarke and J.D. Mountford, "Simulator and Digital Studies on Var Compensation for the Itaipu HVDC Transmission System", 1980 International Conference on Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

221. P. Pelletier and G. Bourgault, "Short Circuits at the Rimouski Station with 230 kV Network and Static Compensator Behaviour with Thyristor Controlled Inductance", Canadian Electr. Eng. H., Vol. 5, No. 2, pp. 15-18, April 1980.

222. W. Pfyl, "Electronic Power Converters in Static Var Systems : A Modern Concept for Optimizing Energy Transmission Across Long HVAC Lines", from Electronics to Microelectronics, Proceedings of the Fourth European Conference on Electronics (EUROCON 1980), Stuttgart, Germany, March 24-28, 1980, Edited by W.A. Kaiser and W.E. Proebster, pp. 456-458, North-Holland Publishing Co., New York, 1980.

223. G. Romegialli and H. Beeler, "Control of Shunt Compensation - Viewpoint Two", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, IEE Digest No. 1980/41, London, September 8-9, 1980.

224. E.A. Taylor Jr., L. Gyugyi and J. Lordeon, "Overvoltage Requirements for Static Var Compensations in Transmission Systems", 1980 International Conference Overvoltages and Compensation on Integrated AC-DC Systems, Winnipeg, Canada, July 8-12, 1980.

225. H.L. Thanawala, "Control of Shunt Compensation - Viewpoint Three", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, IEE Digest No. 1980/41, London, September 8-9, 1980.

226. S. Torseng, "Thyristor-switched Capacitors", IEE Technical Seminar on Control of Reactive Compensation for AC Power Systems, IEE Digest No. 1980/41, London, September 8-9, 1980.

227. J.J. Trageser, "Power Usage and Electrical Circuit Analysis for Electric Arc Furnaces", IEEE Trans. Industry Applications, Vol. IA-16, pp. 277-284, 1980.

228. K. Walve, "Reactive Power and Voltage Regulation in the Swedish High Voltage System", CIGRE Paper No. 31-08, September 1980.

229. C. Xuan-San, "Dynamic Analysis of Saturable-reactor Used in the Static Compensator of Reactive Power", J. Quing Hua Unive., China, Vol. 20, No. 1, pp. 33-43, 1980.

230. D.J. Young, "Saturated Reactors", IEE Technical Seminar on Control of Reactive Compensation for AC Power System, IEE Digest No. 1980/41, London, September 8-9, 1980.

1981

231. J. Andruszkiewicz, M. Ampuja and P. Ritamaki, "Thyristor Controlled Static Compensator in Industrial Applications", Energetyka, Poland, March 1981, 35(3), pp. 92-95.

232. N. Bagavathy, V.S.Subbarao and G.S. Raju, "Performance of Saturable Reactors in Power Systems under Different Winding and Core Arrangements", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 125-128.

233. M. Boidin, M. Compas, X. Henry and R. Rouget, "The Static Compensator - A Means for Limiting the Disturbances on Electric Networks", Rev. Jeumont-Schneider, France, No. 31, pp. 29-36, March 1981.

234. R.T. Byerly, R.J. Bennon, E.R. Taylor Jr and. D.T. Poznaniak, "A Study of Static Reactive Power Compensators for High Voltage Power Systems", Report DOE/NBM-1009, Prepared for US Department of Energy by Westinghouse Electric Corporation, May 1981.

235. N.L. Diseko, M.L. Woodhouse, H.L. Thanawala, B.R. Andersen, A.M. Crawshaw and J.E. Rowe, "Application of a Digital Computer Program to Transient Analysis and Design of HVDC and ac Thyristor Valves", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3,1981, IEE Conference Publication No. 205, pp. 167-170.

236. R.A. Dixon, J.A.K. Douglas and D.A. Brereton, "The Design Requirements and Site Testing of a 40 MVA Thyristor Controlled Static Compensator for the 330 kV Transmission System in Zambia", Equipment for AC and DC Transmission, London, November 30-December 3, 1980, IEE Conference Publication No. 205, pp. 33-37.

237. X.D. Do and Y. Hotte, "Effect of Static Compensators on the Stability of AC Systems", Compte Rendus des Sciences de l'Academie des Sciences, Series II - Mecanique Physique, Vol. 293, No. 5, p. 341, 1981.

238. R. Fujiwara, S. Abe, S. Takeda and Y. Obata, "Dynamic Stability Improvement of Power System by Means of a Static Var System", Elect. Eng. in Japan (USA Edition), Vol. 101, No. 1, January/ February 1981.

239. A. Gavrilovic, A. J. Heath and W.P. Williams, "Reduction of Flicker by Alternative Types of Static Compensators", International Conference on Electricity Distribution, Brighton, England, June 15, 1981, IEE Publication No. 197, pp. 86-90.

240. A. Gavrilovic, "Variable Static Equipment for Transmission of Electrical Power", GEC Journal of Science and Technology (GB), Vol. 48, No. 1, pp. 32-34, 1981.

241. J. Gopalachar, K. Parthasarathy and B.S.R. Iyengar, "Steady-state and Dynamic Performance of Compensated 400 kV Lines", Journal of Institute of Engineers (India) Electrical Engineering Division, Vol. 62, Pt. EL3, pp. 114-120, December 1981.

242. L. Gyugyi, "Control of Shunt Compensation with Reference to New Design Concepts", Proc. IEE, Vol. 128, Pt. C; No. 6, pp. 374-381, November 1981.

243. A Hammad and W. Pfyl, "System Planning for a Large HV Network Incorporating Static Var Compensators and HVDC Systems", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November30-December 3, 1981, IEE Conference Publication No. 205, pp. 13-16.

244. L.A. Harris and I.M.Welch, "Dynamic Reactive Compensation for the 2000 MW DC Link", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication 205, pp. 21-24.

245. Y. Harumoto, E. Kawageo, M. Yano, E. Tamaki, Y. Yamamoto and T. Matsuura, "New Static Var Supply and Control System Using Force-commutated Inverters", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 29-32.

246. O. Hauge and P. Meringdal, "The 360 MVar TCR Plant for Var Compensation in the 420 kV Interconnection Between Norway and Sweden", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 47-51.

247. H. Inoh, A. Doi and H. Kinoshita, "Analytical Method to Improve Dynamic Voltage Stability in Power System", Elect. Eng. in Japan (USA Edition), Vol. 101, No. 3, May/June 1981.

248. H. Inoh, A. Doi and H. Kinoshita, "A New Control Method for Static Var Source During Power System Disturbances", Trans. Institute of Electrical Eng. (Japan), Vol. 101, No. 5, pp. 111-117, September-October 1981.

249. K.M. Jones, "Application, Philosophy and Operating Experience Concerning Three AC Saturated Reactor Type Static Compensator Installations", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 42-26.

250. S.C. Kapoor, "Dynamic Stability of Static Compensator-synchronous Generator Combination", IEEE, PAS, Vol. PAS-100, pp. 1694-1702, April 1981.

251. W. Kaufhold and H. Tyll, "Static Compensators Analysis of Performance by Network Analyzer Studies", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 96-99.

252. V.V. Khoudiakov and V.N. Ivakin, "Static Compensators for Power Systems and Industry", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication, No. 205, pp. 25-28.

253. H. Koniski, H. Amano, A. Watanabe, T. Kawai and T. Kamo, "Studies on Var and AC Voltage Control by HVDC Converters", IEE International Conference on Thyristor, and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication 205, pp. 182-185.

254. M.P. Lima Jr., "SVC Application to the Furnas System", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp.17-20.

255. R.H. Lasseter and K.G. Fehrle, "Digital Transient Simulation of Static Var Control Systems", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Publication No. 205, pp. 118-121.

256. L.R. Lowry, L. Gyugyi, N.G. Hingorani and F.L. Nylander, "Field Testing of Light-triggered Thyristors in an Electric Utility Application", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 92-95.

257. R.M. Mathur, "A Study of Non-Characteristic Harmonics Generated by Thyristor Phase Controlled Reactors", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 117-120.

258. R.M. Mathur, M.Z. Tarnawecky and D.A. Woodford, "Evaluation of Static Compensators", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Publication No. 205, pp. 1-4.

259. D. McGillis, N.H. Huynh, G. Scott, "The Role of Static Compensators in Meeting AC System Control Requirements with Particular Reference to the James Bay System", Proc. IEE, Vol. 128, Pt. C, No. 6, pp. 389-393, November 1981.

260. T.J.E. Miller and P. Chadwick, "An Analysis of Switching Transients in Thyristor Switched Capacitor Compensated Systems", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 104-107.

261. D. Nelles, "Influence of Static Compensators on Transient Stability", Proceedings of the Seventh Power Systems Computation Conference, Lausanne, Switzerland, July 12-17, 1981, Published by Westbury House, Guildford, England, 1981.

262. K. Olsen, "On Specification of Requirements of Significance for Economic Dimensioning of SVC",

IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 5-8.

263. A. Olwegard, K. Walve, G. Waglund, H. Frank and S. Torseng, "Improvement of Transmission Capacity by Thyristor Controlled Reactive Power", IEEE 1981 Power Engineering Society Winter Meeting, Paper No. 81 WM 092-6, February 1981.

264. D.G. Ramey, I.A. Whyte, J.W. Dorney and F.H. Kroening, "Application of the Dynamic Stabiliser to Solve an SSR Problem", Proc. of the American Power Conference, Vol. 43, pp. 605-609, 1981.

265. D.G. Ramey, D.S. Kimmel, J.W. Dorney and F. H. Kroening, "Dynamic Stabiliser Test at the San Juan Station", IEEE, PAS, Vol. PAS-100, No. 12, pp. 5011-5019, December 1981.

266. P. Ritamaki and M.F. McGranaghan, "Static Compensator Control Systems and Their Simultaion on a TNA", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication, No. 205, pp. 52-55.

267. G. Romegialli and H. Beeler, "Problems and Concepts of Static Compensator Control", Proc. IEE, Pt. C, Vol. 128, No. 6, pp. 382-388, November 1981.

268. B.S. Sharma and Y. George, "Experience and Lessons of India's First Static Compensator in Power System", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication, No. 205, pp. 38-41.

269. Y. Sumi, Y. Harumoto, T. Hasegawa, M. Yano, K. Ideka and T. Matsuuri, "New Static Var Control Using Force-commutated Inverters", IEEE, PES Winter Power Meeting, Paper No. 81WM228-6, 1981.

270. H. Suzuki, S. Mine, T. Kasahara and J. Inou, "Stability Improvement of Local Power Unbalance System by Static Var Compensators", IEE International Conference of Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 9-12.

271. H.L. Thanawala, J.D. Ainsworth and W.P. Williams, "Operating Characteristics of Static Compensators Using Saturated and Thyristor-controlled Reactors", GEC Journal of Science and Technology (GB), Vol. 47, No. 3, pp. 142-148, 1981.

272. H.L. Thanawala, W.O. Kelham and A.M. Crawshaw, "Static Compensators Using Thyristor-controlled Saturated Reactors or Low Reactance Linear Reactors", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 80-85.

273. S. Torseng, "Shunt-connected Reactors and Capacitors Controlled by Thyristors", Proc. IEE, Vol. 128, Pt. C, No. 6, pp. 366-373, November 1981.

274. Ch. Tuttas, "Thyristor-controlled Saturated Reactor - A New Design of Static Var Systems", IEE International Conference on Thyristor and Variable Static Equipment for AC and DC Transmission, London, November 30-December 3, 1981, IEE Conference Publication No. 205, pp. 77-79.

275. V.A. Venikov, V.A. Stroev and Tawfik, "Optimal Control of Electrical Power Systems Containing Controlled Reactors Part 1 : Effect of Controlled Reactors on the Transient Stability Limit", IEEE 1981 Power Engineering Society Winter Meeting, Paper No. 81 WM 106-4, February 1981.

276. V.A. Venikov, V.A. Stroev and Tawfik, "Optimal Control of Transients in Electrical Power Systems Containing Controlled Reactors Part 2 : Optimal Control Problem Solution", IEEE 1981 Power Engineering Society Winter Meeting, Paper No. 81 WM 107-2, February 1981.

277. O. Wasynczuk, "Damping Shaft Torsional Oscillations with Application to High Speed Reclosure", IEEE, PAS, Vol. PAS-100, pp. 1089-1095, March 1981.

1982

278. H. Allon, G.E. Gardner,L.A. Harris, I.M. Welch, H.L. Thanawala and D.J. Young, "Dynamic Compensation for the England-France 2000 MW HVDC Link", CIGRE, Paper No. 14-04, September 1982.

279. H. Boenig and F. Cibulka, "A Static Var Compensator Using a Superconducting Coil", IEEE 1982, Power Engineering Society Winter Meeting, Paper 82 WM 177-4, New York. January 31-February 5, 1982 (Published IEEE, PAS, Vol. PAS-101, pp. 3988-3996, October 1982).

280. P. Bordignon, A. Boselli, F. Profumo, "Compensazione Statica della Potenza Reattiva Mediante Valvole a Tiristori in Media Tensione", l'Elettrotecnica (Italy), Vol. LXXI, pp. 633-644,1982.

281. R.T. Byerly, D.T. Poznaniak and E.R. Taylor, "Static Reactive Compensation for Power Transmission Systems", IEEE 1982 Power Engineering Society Winter Meeting, Paper 82 WM 179-0, New York, January 31-February 5, 1982 (Published IEEE, PAS, Vol. PAS-101, pp. 3997-4005, October 1982).

282. H. Frank, "Experience of Thyristor-controlled Shunt Compensators in Transmission and Distribution Systems", CEPSI, Far East Conference on Electric Power Supply Industry, Bangkok, Thailand, November 1982.

283. M. M. Gavrilovic, "Static Compensator Structures : Review and Analysis", Spring Meeting of the Canadian Electrical Association, Montreal, March 15-18, 1982.

284. O. Hauge, P. Meringdal, H. Frank and K. Engberg, "The 360 MVar Static Compensator in Hasle, Norway", CIGRE, Paper No. 31-10, September 1982.

285. R.L. Hauth, S.A. Miske and F. Nozari, "The Role and Benefits of Static Var Systems in High Voltage Power System Applications", IEEE 1982 Power Engineering Society Winter Meeting, Paper 82 WM 076-8, New York, January 31-February 5, 1982 (Published IEEE,PAS,Vol. PAS-101, pp. 3761-3770,

October 1982).

286. R.H. Lasseter and S.Y. Lee, "Digital Simulation of Static Var System Transients", IEEE 1982 Power Engineering Society Winter Meeting, Paper 82 WM 178-2, New York, January 31-February 5, 1982 (Published IEEE, PAS, Vol. PAS-101, pp. 4171-4177, October 1982).

287. M.F. McGranaghan, R.G. Rocamora and J.G. Koepfinger, "Simulation of Static Var System (SVS) Performance on a Transient Network Analyser", IEEE 1982 Power Engineering Society Winter Meeting, Paper 82 WM 151-9, New York, January 31-February 5, 1982.

288. M.F. McGranaghan, R.G. Rocamora, J.G. Koepfinger, L.W. Ester and J.R. Bailey, "Design of a Generalized Static Var System Model for TNA Simulation", IEEE 1982 Power Engineering Society Winter Meeting, Paper 82 WM 154-3, New York, January 31-February 5, 1982 (also IEEE, Vol. PAS-101, pp. 3413-3420, September 1982).

289. T.J.E. Miller, Editor, "Reactive Power Control in Electric Power Systems", John Wiley & Sons, New York, 1982.

290. S.A. Miske Jr., F. Nozari, T. Miller, R. Moran and S. Matraszek, "Static Reactive Power Compensators for High Voltage Power Systems", Report DOE/NBM-1010 Prepared for US Department of Energy by General Electric Company, March 1982.

291. K. Reichert, "Controllable Reactive Compensation", Electric Power and Energy Systems, Vol. 4, pp. 51-61, 1982.

292. G. Scott and Do. Xuan-Dai, "TNA Study of Dynamic Performance of Static Compensators on the James Bay System : Results and Analysis", Seventeenth Universities Power Engineering Conference, University of Manchester, Inst. of Science and Tech. England, 30 March-1 April 1982.

293. K. Srinivasan, G.E. Desrochers and G.E. Desrosiers, "Static Compensator Loss Estimation from Digital Measurement of Voltages and Currents", IEEE 1982 Power Engineering Society Summer Meeting, Paper 82 SM 373-9, San Francisco, California, July 19-23, 1982 (Published IEEE PAS, Vol. PAS-102, pp. 578-585, March 1983).

294. M. Takeda, "Static Var Compensators for Power Transmission Lines", Mitsubishi Electric Advance, pp. 1-4, June 1982.

295. H.L. Thanawala, W.C. Kelham and A.M. Crawshaw, "Static Compensators Using Thyristor Control with Saturated or Low Reactance Linear Reactors", GEC Journal of Science and Technology, Vol. 48, No. 3, pp. 163-169, 1982.

296. H.L. Thanawala, A.J. Heath and D.J. Young, "The Enhancement of AC Power Transfer Over Long Distances", CEPSI, Far East Conference on, Electric Supply Industry, Bangkok, Thailand, November 1982.

1983

297. F. Aboytes, G. Arroyo and G. Villa, "Application of Static Var Compensators in Longitudinal Power Systems", IEEE, PAS, Vol. PAS-102, pp. 3460-3466, October 1983.

298. F. Aboytes, G. Arroyo and G. Villa, "Application of Static Compensators in Longitudinal Power Systems", IEEE 1983 Power Industry Computer Application Conference PICA-83, pp. 130-136 1983.

299. J. Belanger, J. Sybille, J. Lemay, "Load Rejection in Hydro-Quebec 735 kV System : Overvoltages and their Reduction", Internal Report, IREQ, Varennes, Quebec, Canada, December 1983.

300. R. Barbieri, E. Campanari and A. Gabrielli, "Fenomeni Energetici nel Funzionamento di Generatori Statici di Potenza Reattiva", l'Energia Elettrica (Italy), No. 2, pp. 57-66, 1983.

301. T. Fukao, M. Matsui, I. Hieda and N. Eguchi, "A Novel Static Var Generator Using Cycloconverter Operating in Circulating Current Mode", International Power Electronics Conference, Tokyo, 1983, Vol. 2, pp. 1642-1652, March 27-31, 1983.

302. A.W. Grainger, R.L. Bolden, R.H. Craven, R. Thornton and G.N. Allen, "Views on Application of Static Var Compensators and the Modelling of Loads in Relation to Supply Systems in Australia", Paper Presented to CIGRE Study Committee 38 Meeting, Montreaux, Switzerland, October 2-7, 1983.

303. A. Hammad, K. Sadek, H. Kolsch and G. Guth, "Incorporating AC Voltage Regulation in HVDC Scheme Controllers and Designs", Proceedings of the Symposium on Urban Applications of HVDC Power Transmission, 24-26 October 1983, Philadelphia, USA, pp. 315-332, 1983.

304. T. Hara, O. Motoyoshi, S. Konishi, K. Mukaimumine, Y. Yanagiya and K. Ishida, "Components for Static Var Compensator", Fuji Electric Review (Japan), Vol. 29, No. 4, pp. 135-142,1983.

305. Y. Harumoto, E. Kawageo, M. Itoh and T. Matsuura, "Application of SVG Using Force Commutated Inverters for Improvement of System Stabilities" International Power Electronics Conference, Tokyo 1983, Vol. 21, pp. 1630-1641, March 27-31, 1983.

306. IEEE PES, Substations Committee, Working Group 79.2 on Static Var Compensators in Substations, "Bibliography of Static Var Compensators", IEEE, PAS, Vol. PAS-102, No. 12, pp. 3744-3752, December 1983.

307. M. Iwasaki, K. Oyama,and Y. Tsunehiro, "Current-fed Inverter with Static Var Generator for Induction Morot Drive", Electrical Eng. in Japan (USA Edition), Vol. 103, No. 3, May-June 1983.

308. K. Kogai, T. Maeda, K. Nishimura, Y. Uemura and S. Sato, "Improvement of System Dynamic Stability by Static Var Compensator", International Power Electronics Conference, Tokyo 1983, Vol. 2, pp. 1621-1629, March 27-31, 1983.

309. A. Le Du, Ph. Adam, L. Ahlgren, G.L. Brewer, L.E. Juhlin, Y. Laiho, D. Povh and D.J. Young, "Use of Static or Synchronous Compensators in HVDC Systems", CIGRE, Working Group 14-03 Report, Electra, No. 91, pp. 51-92, December 1983.

310. Guang-Oi Nie, Zong-Gan Wag, Rong-Guang Zhon, Shou-Sun Chen and Shu-Jun Chen, "The Effects of Static Var Systems on Reducing the System Volta-

ge Fluctuation and Improving System Stability", J. Tsinghua University (China), Vol. 23, No. 2, pp. 61-74, 1983.

311. T. Nishikawa, K. Murabayashi and A. Aoyama, "Overvoltage Protection of Static Var Compensation System", IEEE, PAS, Vol. PAS-102, pp. 2335-2340, July 1983.

312. H.K. Patel and G.K. Dubey, "Harmonic Reduction in Static Var Compensator by Sequence Control of Transformer Taps", Proc. IEE, Pt. C, Vol. 130, No. 6, pp. 300-305, November 1983.

313. R.S. Ramshaw, J. Carr and A. Venkataramana, "Static Var Systems", IEEE International Electrical and Electronics Conference, University of Waterloo, Ontario, Canada, 1983.

314. K. Takenaka and Y. Yoshida, "Improvement in the Operating Characteristics of HVDC Transmission Systems by a Static Reactive Power Compensator", International Power Electronics Conference, Tokyo 1983, Vol. 2, pp. 1609-1620, March 27-31, 1983.

315. K. Tam and R.H.Lasseter, "Alternative Twelve Pulse Arrangement for Static Var Control Applications", IEEE, PAS, Vol. PAS-102, pp.3728-3735, December 1983.

316. E.R. Taylor, J.E. O'Neil and D.T. Poznaniak, "SVC Compensation of Very Long High Voltage Lines for Limited Loads", Proc. of the American Power Conference, Vol. 45, pp. 663-667, Chicago, USA, April 18-20, 1983.

317. A. Watanabe, Y. Kokai, T. Kano and T.Kawai, "Combined Control of Static Var Compensator and HVDC Converter", International Power Electronics Conference, Tokyo 1983, Vol. 1, pp. 105-115, 1983.

318. S. Yokokawa, S. Imaizumi, O. Motoyoshi, S. Konishi and K. Ishida, "Control System of Static Var Compensator", Fuji Electric Review (Japan), Vol. 29, No. 4, pp. 143-151, 1983.

1984.

319. A. Alexandrovitz, A. Yair and E. Epstein, "Investigation of a Switching Var Compensator", IEEE, 13th Convention of Electrical and Electronics Engineers, Tel-Aviv, Israel, 22-24 March 1984.

320. A. Alexandrovitz, A. Yair and E. Epstein, "Analysis of a Static Var Compensator with Optimal Energy Storage Element", IEEE Trans. Ind. Electron., Vol. IE-31, No. 1, pp. 28-33, February 1984.

321. J. Belanger, G. Scott, T. Andersson and S. Torseng, "Gain Supervisor for Thyristor-controlled Shunt Compensators", CIGRE, Paper No. 38-01, September 1984.

322. C. Boisdon and G. Dronin, "Les Systemes de Compensation Statique Rapide dans les Reseaux Industriels", Revue General d'Electricité, pp. 797-807, 1984.

323. M. Brucoli, F. Torelli and M. Trovato, "Coordinated Control of Static Var Compensators in Long Distance AC Transmission Systems", Workshop on Very Long Distance AC Transmission Systems, University of Pisa, Italy, September 1984.

324. D. Flueckiger et al., "Application and Integrated Performance Aspects of Static Var Systems in Connection with HVDC", Proc. of the International Conference on DC Power Transmission, Montreal, Canada, June 4-8, 1984.

325. E. Gaglioti, G. Santagostino, F. Leone, F. Profumo, R. Rosati and L. Valfre, "Evaluation of Transient Performance of a SVC for Voltage Support in a Transmission System with Low Short Circuit Power", CIGRE, Paper No. 38-12, September 1984.

326. A. Gavrilovic, A.J.Heath, C. Horwill and H.L. Thanawala, "Improving the Utilisation of Electrical Power Systems by Reactive Power Control", BEAMA Technical Seminar, Jakarta, Indonesia, October 1984.

327. P.V. Goosen, R.D. Macfarlane, H. Pesch, P. Sieber and M. Schubert, "FC/TCR Type Static Compensators in ESCOM's 132 kV Network", CIGRE, Paper No. 38-09, September 1984.

328. R. Gutman, J.J. Keane, M. Ea; Rahman and O. Veraas, "Application and Operation of a Static Var System on a Power System - American Electric Power Experience, Part I : System Studies", IEEE PES, Summer Meeting, Paper No. 84 SM 634-2, 1984 also IEEE, PAS, Vol. PAS-104, No. 7, pp. 1868-1874, June 1985.

329. R. Gutman, J.J. Keane, M. Ea. Rahman and O. Veraas, "Application and Operation of a Static Var System on a Power System - American Electric Power Experience, Part II : Equipment Design and Installation", IEEE, PES, Summer Meeting, Paper No. 84 SM 635-9, 1984, also IEEE, PAS, Vol. PAS-104, No. 7, pp. 1875-1882, June 1985.

330. A.E. Hammad and M. El-Sadek, "Application of a Thyristor-controlled Var Compensator for Damping Subsynchronous Oscillations in Power Systems", IEEE, PAS, Vol. PAS-103, No. 1, pp. 198-212, January 1984.

331. G.L. Kusic and I.A. Whyte, "Three Phase Steady-state Static Var Generator Filter Design for Power Systems", IEEE, PAS, Vol. PAS-103, No. 4, pp. 811-818, April 1984.

332. C.O. Lingstrom, K. Walve, G.Waglund, H. Frank and S. Ivner, "The 200 MVar Static Compensator in Hagby, Sweden", CIGRE, Paper No 38-02, September 1984.

333. R.M. Mathur, Editor, "Static Compensators for Reactive Power Control", Canadian Electrical Association, Montreal, 1984.

334. S.A. Miske Jr., R.J. Piwko, J.B. Tice and J.A. Whitacre, "Control Modelling and Simulator Studies for a Static Var Compensator Applied to a Weak AC System Incorporating an HVDC Installation"; CIGRE, Paper No. 38-07, September 1984.

335. T. Ohyama, K. Yamashita, T. Maeda, H. Suzuki and S. Mine, "Effective Application of Static Var Compensators to Damp Oscillations", IEEE, PES, Summer Meeting, Paper No. 84 SM 587-2,1984 also IEEE PAS, Vol. PAS-104, No. 6, pp. 1405-1410, June 1985.

336. B. Ooi and M.H. Banakar, "Co-ordination of Static Var Compensators with Long Distance Radial Transmission System for Damping Improvement", IEEE, PAS, Vol. PAS-103, No. 2, pp.265-274, February 1984.

337. H. Pesch, S.Ranada, M. Schubert, P. Sieber, P.V. Goosen and R.D. Macfarlane, "Static Var Compensators for Stabilising Traction and Transmission Systems in South Africa", IEE International Conference on Power Electronics and Variable Speed Drives, London, May, 1984.

338. E.R. Taylor Jr. J.E. O'Neil, D.T. Poznaniak, "Static Compensators Aid Long Distance Transmission", Electrical Review International (GB) Vol. 1, No. 4, pp. 44-46, May 1984.

339. G. Zini, "Basic Considerations on Very Long Distance AC Transmission Systems with Voltage Support", Workshop on Very Long Distance Transmission Systems, University of Pisa, Italy, September 1984.

1985

340. N.C. Abi-Samra, R.F. Smith, T.E. McDermott and M.B. Chidester, "Analysis of Thyristor-controlled Shunt SSR Counter-measures", IEEE Paper No. 84 SM 681-3, IEEE PAS, Vol. PAS-104 pp. 584-597, March 1985.

341. D.F. Binns and T. Matthews, "Microprocessor-controlled Power System Voltage Stabiliser", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

342. R.L. Bolden, "Use of Stabilising Signals on Static Compensators to Enhance the Damping of Power Systems", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

343. L.X. Bui and H.L. Nakra, "Representation of Static Compensators and Generators for the Study of Temporary Overvoltages at a Converter Station", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

344. C. Compagnion, F. Lacroux, A. Astorg, M. Dubreuil and M. Moller, "'Les Ancizes' : The First Static Var Compensator on the French Network", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

345. C.B. Cooper and B.J. Pontes Parente, "Some Advantages of Digital Control for Static Compensators", Fourth International Conference on AC and DC Power Transmission, IEEE Conference Publication No. 255, London, September 1985.

346. P.M. Cowan and H.J.A. Kirkby, "The Harmonic Performance of Static Var Compensators with Individual Phase Control", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

347. H. Dupas and D. McGillis, "The Forced-Outage Unavailability of Large Static Compensators", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

348. A.M. Crawshaw, H.L. Thanawala and S.B. Mukhopadhyaya, "Design and Application of a TCR Static Var Compensator for Paraguay". Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

349. B. Ehmcke, B. Friedrich, H. Tyll and U. Weingarten, "Planning, Design and Commissioning of SVC for an Extended Interconnected 220 kV System", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

350. K. Engberg, H. Frank and B. Klerfors, "Thyristor Switched Capacitors, TSC, in Theory and Practice", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

351. I.A. Erinmez, D.J. Coates and H. Lu, "The Application of Static Compensators on the UK Transmission Network", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

352. K.R. Frearson and R.H. Craven, "The Nebo Static Var Compensator - An Application of an SVC for Transmission Voltage Control", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November, 1985.

353. R.A. Gawler and R.L. Bolden, "Application of Controlled Static Compensators to Extend Transmission Capability in the Victorian Power System", Electric Energy Conference, Newcastle, Australia, October 1985.

354. D. Geddy, "The Prediction of Harmonic Voltages in Transmission Systems Produced by SVCs", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

355. P. Goosen and P.M. Cowan, "Performance of FC/TCR Static Compensators on the South African 400 kV Network", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

356. A.P. Guarini and R.D.Angel , "Digital Programme for Calculating Harmonic Currents in Thyristor-controlled Reactors", Fourth International Conference on AC and DC Power Transmission,IEE Conference Publication No. 255, London, September 1985.

357. L.Gyugyi and F. Cibulka, "Overvoltage Protection of Thyristor Valves in Static Var Compensators", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

358. O. Hauge, P. Meringdal, L. Vormedal, H. Frank andK. Engberg, "Five Years of Operational Experience with the 360 MVar Hasle Static Compensator", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

359. A. Howard-Taylor and S. Stock, "Capricornia Electricity Board Operating Experience with a 60 MVar Static Var Systems Compensator", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

360. P. Jovanovic, "Automatic Controlled Reactive Power Electromagnetic Compensators in High Voltage Power Systems", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication, No. 255, London, September 1985.

361. P.K. Kalra, "Steady-state Analysis of Six Pulse Thyristor-Controlled Reactor Under Non-ideal Conditions", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

362. S.C. Kapoor, A.K. Chakravarty and K. Ramesh, "Site Simulator for Static Var System", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

363. G. Ledwich, "Control Schemes for Damping by Static Var Compensator", Symposium of Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

364. Z.Y. Liu and C. Jun, "A Study of Misfiring of TSC and on Analysis of an Actual Case", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

365. A. Longo and G. Zini, "Sistemi Statici di Produzione di Potenza Reattiva Regolazione con Continuita di Riequilibratura del Carico", l'Energia Elettrica (Italy), No. 2, pp. 143-156, 1985.

366. S. Lowe and V. Galea, "Practical Considerations in Selecting SVCs for ECNSW", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

367. P. Muttik, "SVC Design and Rating Considerations", Symposium of Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

368. S. Nyati, S.R. Atmuri, V. Koschik, R.M. Mathur and D. Flueckiger, "Effectiveness of Var Controllers Connected at the Converter Bus of an HVDC Link Feeding into a Weak System", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No.255, London, September 1985.

369. M. O'Brien and G. Ledwick, "Placement of Static Compensators for Stability Improvement", Proc. IEE, Pt. C, Vol. 132, No. 1, pp. 30-35, January 1985.

370. C. Parker and G. Waite, "Planning Considerations Determining the Need for Static Var Compensators for the Broken Hill - NSW - Victoria Interconnection", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

371. V.R. Sastry, D.V. Hill and C.J.Lee, "Static Var Compensators for Balancing Single Phase Traction Loads in Queensland Central Region", Symposium of Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

372. J.R. Stewart, "Operating Experience with Saturated Reactor Type Compensators in the Eastern Goldfields Interconnection", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

373. H.L. Thanawala, K.A. Walshe, R. Hayes, D. Gardner, A.R. Banerjee, N.M. MacLeod, W.O. Kelham and J.J. Price, "Design and Operational Features of the Shunt-Compensated 220kV 654 KM Transmission Line to the Eastern Goldfields of Western Australia", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

374. H. Thanawala, "Static Var Compensators for Transmission Systems", GEC Review, Vol. 1, No. 2,1985.

375. S. Torseng, "Some Utility Applications of Static Compensators", Symposium on Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

376. S.K. Tso and P.T. Ho, "Contribution of a Microprocessor-based TCR Compensator to System Damping", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

377. K.A. Walshe, D.J. Young, R.W. Oxenham and R. Hayes, "Review of Four Saturated Reactor Installations in Australia", Fourth International Conference on AC and DC Power Transmission ,IEE Conference Publication No. 255, London, September 1985.

378. K. Walshe, "Development of SVC Design", Symposium of Static Var Systems, Capricornia Institute, Rockhampton, Australia, November 1985.

379. R. Yacamini and K. Dostmohamed, "The Stability of HVDC Schemes with Reactive Compensators on the Inverter Busbars", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

380. D.J. Young, M.J. Dabbs, C. Horwill and H.L. Thanawala, "The Static Compensators for the 200 MW HVDC Cross Channel Link", Fourth International Conference on AC and DC Power Transmission, IEE Conference Publication No. 255, London, September 1985.

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