

**ANALYSIS AND OPTIMIZATION
OF SVC USE
IN TRANSMISSION SYSTEMS**

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CHAPTER 1

INTRODUCTION AND SUMMARY

by
T. Peterson (Sweden)

1.1 INTRODUCTION

Around 1978, the thyristor-controlled Static Var Compensator (SVC) made its breakthrough for transmission system applications. Since then, there has been an almost explosive increase in the number of SVCs installed. By 1990, approximately 195 transmission system SVCs with a total control range of about 31 000 Mvar were installed or under way, worldwide. (Industrial applications are outside the scope of this report.)

In September 1986, the CIGRE Study Committee 38 decided to form a Task Force No.4, "Analysis and Optimization of SVC Use in Transmission Systems", as part of the activities of Working Group 38.01, now WG 38.05. The terms of reference established were: "The Task Force will study the use of Static Var Compensators (SVC), including placing and sizing, in typical and potential transmission applications. Comparisons with other means will be made. The results will be summarised into an illustrative report, for the purpose of guidance to prospective users in their planning work". This work is a continuation of the efforts of Task Force No.2 "Static Var Compensators" [1] and of Task Force No.3 "Reactive Power Compensation Analysis and Planning Procedure" [2], both of WG 38.01.

At the first Task Force meeting, it was decided to treat only common SVC applications for the purposes of voltage control and stability improvement, but not applications for special purposes which would be few in number.

In order to share the work efforts, the subject matters of the Task Force were grouped into subtasks assigned to five subgroups, corresponding to Chapters 2 to 6, as listed in the "Contents". This grouping should also make it easier for the readers of this report to concentrate on one topic at a time. It should be noted, however, that the different topics are interrelated.

For SVC definitions, descriptions and characteristics, see References [1] and [2]. For convenience, a brief introductory SVC survey is found in Appendix 1-I. Appendix 1-II contains a review of key terms used in this report. Appendix 1-III briefly discusses SVC in relation to power transmission security.

The Task Force members hope that this report will be of practical value to utility planning engineers and others involved in application of SVCs on transmission systems.

1.2 SUMMARY

Static Var Compensators are an excellent means for providing easily and rapidly controllable shunt reactive-power compensation, i.e. dynamic shunt compensation. Automatic control of the voltage at the point of connection of the SVC is the primary function of the majority of existing transmission SVCs. Some of these SVCs also provide valuable improvement of synchronous stability by increasing synchronizing power margins and/or damping of synchronous machine electromechanical rotor oscillations.

Table 1.1 : Technical/economic attractiveness of reactive compensation devices, on a rising scale: A, AA, AAA

| Function | Technical/economic attractiveness of reactive comp. means | | | | |
|---|---|------------|-------------|-----|-------------|
| | Shunt react. | Shunt cap. | Sync. comp. | SVC | Series cap. |
| Steady-state voltage control and stability: | | | | | |
| - Coarse reactive power balance and voltage control | AAA | AAA | - | - | A |
| - High-performance voltage control | - | - | AA | AAA | - |
| Dynamic voltage control for large disturbances | - | - | AA | AAA | - |
| Reduction of temporary over-voltages | AA | - | AA | AA | A |
| Improving first-swing transient stability | - | - | - | AA | AAA |
| Damping of power oscillations | - | - | A | AA | - |

It is difficult to make a concise, generally valid comparison between different reactive compensation means, integrating both technical and economic considerations. Table 1.1 is a possible illustration of such a

comparison.

In addition to the common applications for voltage control and stability improvement, SVCs are also in use, or can be used, for special purposes that take advantage of the SVC's excellent control characteristics:

- Balancing of an unsymmetrical, fluctuating load of an electric railway system.
- Damping of subsynchronous resonance which might appear in a series-compensated transmission system and a steam-turbine generating unit.
- Improvement of frequency control in a small system with fluctuating load; improvement can be obtained through load modulation via voltage modulation (so far applied only in a steel-plant system).

Following is a summary of Chapters 2-6 contained in this report.

Chapter 2: Steady-state Voltage Control and Stability

The aim of the steady-state voltage control of a transmission system is to keep the bus voltages within fairly narrow limits and to maintain a reasonably flat voltage profile, while the power transferred varies. The generators of almost any power system provide the primary voltage control. Two other major means of voltage control are the use of transformer on-load tap changers and dispersed reactive-power shunt compensation.

SVCs are not the lowest cost shunt compensation means and are therefore utilized only for high-performance voltage control, where needed, and usually as a complement to traditional shunt compensation devices. The term high-performance voltage control is referred here to the control qualities of continuity, rapidity, accuracy and frequency of control actions.

Chapter 2 discusses the use of traditional means and SVCs for steady-state voltage control, i.e. for coping with load variations during normal and outage operating conditions.

A case study of a long-distance EHV transmission system, suggested by Mr. A.Wey (BR), was performed in order to illustrate to what extent and where SVCs would be justified. To ensure a proper security level of the transmission system, a required minimum "MW distance" to voltage collapse was defined. To determine the necessary reactive power injections to satisfy this security criterion, a sensitivity analysis on MW transfer capacity was performed.

Conclusions, related to the steady-state voltage and stability control capability of SVCs:

- In cases of new installations of dynamic shunt compensation devices for high-performance voltage control, SVCs have virtually replaced synchronous

compensators due to benefits in cost, maintenance and performance characteristics of the SVCs. Synchronous compensators were installed - and continue to be in service - in AC transmission systems at the receiving end of long, radial lines and at main buses within meshed networks, particularly in regions with little local generation. Nowadays, synchronous compensators are being installed only at some HVDC inverter stations, usually in order to increase the short-circuit level.

- The share of dynamic shunt compensation devices, i.e. SVCs in the total of new shunt compensation plant being installed, is increasing. Usually the purpose is to improve the voltage control on a bus adjacent to a load area, or to prevent voltage collapse following a line outage, etc. Where the prevention of fast voltage collapse is of interest, full advantage can be taken of the rapidity of SVC voltage control.

Chapter 3: Dynamic (Fundamental - Frequency) Voltage Control

SVCs are often operated in steady state as "floating" with zero reactive power output under normal system conditions, but they stand ready for rapid action upon a disturbance. Full advantage is taken of the SVC fast voltage control action during large disturbances.

In order to illustrate SVC's dynamic voltage control capability during large disturbances, two case studies were performed. One study is named "Voltage control problems of load centers, with and without local generation". The other study is named "Voltage control problems of interconnected systems".

Conclusions, related to the dynamic voltage control capability of SVCs:

- SVCs are an excellent means for dynamic voltage control during large disturbances. SVCs with sufficiently high capacitive ratings can in many cases prevent fast voltage collapse caused by line faults, forced outages of power system components, etc., if no other countermeasures are applied. SVCs with sufficiently high inductive ratings, at least for short time, can effectively and very rapidly reduce high power-frequency overvoltages in cases of unpredicted load dropping, system separation, frequency-activated load shedding, etc.

Chapter 4: Reduction of Temporary and Switching Overvoltages

The terms temporary and switching (transient) overvoltages are used here in the sense of IEC Publ.71-1 (Insulation Coordination).

The power-frequency component is usually the dominating component of temporary overvoltages. Chapter 3, "Dynamic Voltage Control", demonstrates that SVCs can rapidly and effectively reduce power-

frequency overvoltages, if the SVC has sufficiently large inductive rating.

Harmonic components of a temporary overvoltage, which are caused by saturation of transformers, are reduced at the same time as the power-frequency component because of lower consequent saturation.

Care should be exercised to ensure that the SVC itself will not significantly worsen overvoltages, for example through operation in the capacitive range during conditions of high overvoltage. Temporary overvoltages are usually preceded by a very low power-frequency voltage on one or more phases, e.g. during line short-circuit faults. If the SVC voltage regulator is free, it controls the SVC to the capacitive limit during this time. After the fault is cleared, excessive overvoltages can appear for one or two power-frequency cycles, particularly if the short-circuit MVA of the system is low. This condition should be avoided by temporarily overriding the normal voltage regulator action during faults.

SVCs have only a marginal influence on switching overvoltages in power systems. Switching overvoltages are usually limited to the protective level of the surge arresters.

Chapter 4 gives summaries of studies performed by means of a transient network analyzer (TNA) and an electro-magnetic transients program (EMTP). These studies have been performed by others outside the framework of this Task Force activities. The summaries describe overvoltages and also transients in conjunction with single-pole switching.

Conclusions, related to the reduction of temporary and switching overvoltages by means of SVCs:

- In spite of being a technically feasible and excellent means for reducing high temporary overvoltages, so far few SVCs have been installed only for this specific purpose, primarily because of their cost. Permanently connected shunt reactors are usually more cost effective than SVCs for reducing temporary overvoltages.
- It is usually advisable to override the normal voltage regulator control by so-called "severe undervoltage control" during times of severe undervoltage conditions. This should automatically force the SVC into, or at least toward, the inductive range, when the power-frequency voltage of one or more phases has dropped below a certain value, e.g. 65 %. TSC steps of the SVC should be blocked.
- In cases where it is of interest to study the reduction of power-frequency overvoltages by means of SVCs, a conventional stability type program is usually the most suitable study tool. In special cases, where more detailed results are required, including

harmonics and fast transients, a TNA or an EMTP may be needed.

Chapter 5: Improving First-Swing Transient Stability

A great variety of measures exists for improving transient stability in cases where stability is inadequate, often due to long lines. Rapid fault clearing, rapid reclosing, and series compensation are widely accepted as cost-effective and reliable first-swing stability aids. Another possible measure is dynamic shunt compensation by SVCs. It is also referred to as "voltage support" when discussed for this purpose.

The cost effectiveness of SVCs for providing first-swing stability in severe cases, where stringent stability criteria are applied, was studied using a generic case of a system with two radial 600 km EHV transmission lines from a power station into a relatively large system. Comparisons of a single SVC at the transmission midpoint were made with the use of an additional line and with the use of series capacitors. The following relative cost figures for increasing the stability limit from 0.8 p.u. (based on the surge impedance load (SIL) of one line) to 1.5 p.u. were derived: third line/ SVC/ series capacitors = 1.00/ 0.27/ 0.20.

Another study, performed outside the framework of TF4 activities, on a system with two 900 km EHV transmission lines and dispersed SVCs at four stations indicated that a total short-time reactive power injection from the SVCs of not less than 2.8 p.u. (on SIL of one line) would be needed to provide a stability limit of 1.4 p.u.

Conclusions, related to the improvement of the transient stability by means of SVCs:

- In cases of severe stability problems of radial transmission systems, where long lines are involved and stringent stability criteria are applied, dynamic shunt compensation by SVCs is usually more costly than series compensation to provide first-swing stability.
- In cases of less severe stability problems, e.g. of meshed systems, dynamic shunt compensation by SVCs may be attractive, especially if there is also a need for high-performance voltage control with respect to load areas.
- A combination of series compensation and dynamic shunt compensation by SVCs may be an optimum solution in many cases.

Chapter 6: Damping of Power Oscillations

Synchronous machine electromechanical oscillations show up as power and voltage oscillations in the network. The oscillation frequencies are usually within the range of 0.2 to 2.0 Hz. In many cases, the inherent damping of the power system can be low. The genera-

tor excitation system gains at the oscillation frequencies play a very important role and should therefore be carefully selected. Traditional means for improving damping are the use of damper windings on the synchronous machines and the use of Power System Stabilizers (PSS) in the excitation systems.

Damping may also be improved by the use of SVCs. Usually, these SVCs are then equipped with a supplementary controller modulating the SVC action, a so-called power oscillation damper (POD). The damping improvement is obtained due to two effects. The one is the direct voltage influence on power flow between the machines and the other one is the indirect voltage influence via the loads.

Chapter 6 discusses how damping can be achieved by means of SVCs, methods and models for analysis, POD input signals and control strategies. Further, a case study of an SVC in a simple two-machine system is used to illustrate the increase in power transfer capability as determined by steady-state (oscillatory) stability.

The article "Example of Reinforcing an AC Interconnection between two Large Networks by Use of SVC", by Mr. J. Falck Christensen and Mr. T. Østrup (DK), Electra No. 132, Oct. 1990, has been discussed and reviewed by this Task Force.

Conclusions, related to the damping of power system oscillations by means of SVCs:

- At appropriate locations, SVCs can be utilized to improve the damping of synchronous machine electromechanical oscillations. This may be valuable, especially in cases of insufficiently damped low-frequency inter-area oscillations. Whether an SVC can provide damping improvement or not depends primarily on the network configuration and the location of the dominating generators, load areas and the SVC. Both, the SVC location and size are usually determined with regard to other reasons than damping.
- A study should usually be performed for each application where damping improvement is required in order to determine if the desired damping improvement can be achieved and to establish the POD parameter values to be set.
- Both frequency-domain analysis based upon a linearized description of the power system and time-domain simulations are useful. Frequency-domain analysis - in the form of eigenvalue/eigenvector calculations, sensitivity calculations, frequency scanning or similar - applies to the small-disturbance stability of the power system. Time-domain simulation by means of a transient stability type program is the only practical method to use when studying the large-disturbance stability of a large power system.

APPENDIX 1-I

Introductory SVC Survey

A Static Var Compensator (SVC) is a static shunt reactive device, the reactive power generation or absorption of which either is inherently varying strongly with the voltage, or can be varied by means of thyristor switches. The adjective "static" means that, unlike the synchronous compensator, the SVC has no moving primary part.

Existing and planned SVCs can be grouped into three classes:

- SVCs of the self-saturated iron-core reactor type. This type was introduced before the thyristor-controlled SVC was developed. Only few transmission SVCs of this type are in use.
- Thyristor-controlled or switched SVCs. They account for more than 95 %, in terms of Mvar, of all transmission SVCs. Only this type will be discussed in more detail in this Appendix.
- "Advanced" SVCs of force-commutated inverter type. This class of SVCs, utilizing a thyristor switched converter, should still be considered under development; there is a variety of concepts being discussed. Only few SVCs of this type are in use.

Thyristor-controlled SVCs

An SVC is typically comprised of a transformer, reactors, capacitors and bidirectional thyristor valves. There is a variety of main circuit arrangements. Figures 1.1 and 1.2 show two common schemes:

- FC/TCR : Fixed Capacitor(or Filter)/Thyristor-(phase-angle-) Controlled Reactor
- TSC/TCR : Thyristor-Switched Capacitors/Thyristor-Controlled Reactor (phase-angle-controlled)

Two control principles are in use: TSC and TCR. From a power-frequency point of view both can be considered as a variable reactance, the former being a step-wise variable capacitive reactance and the latter a continuously variable inductive reactance. Also a thyristor-switched reactor (TSR) can be used. The TCR and TSC are often connected in delta, although shown as star connected in Figures 1.1 and 1.2. The reasons for delta connection are a possibly more favourable utilization of the thyristor valves and, in TCR cases, trapping of harmonic currents of zero-sequence character (3rd, 9th etc.).

Figure 1.3 shows a generalized steady-state characteristic of an SVC: current versus voltage.

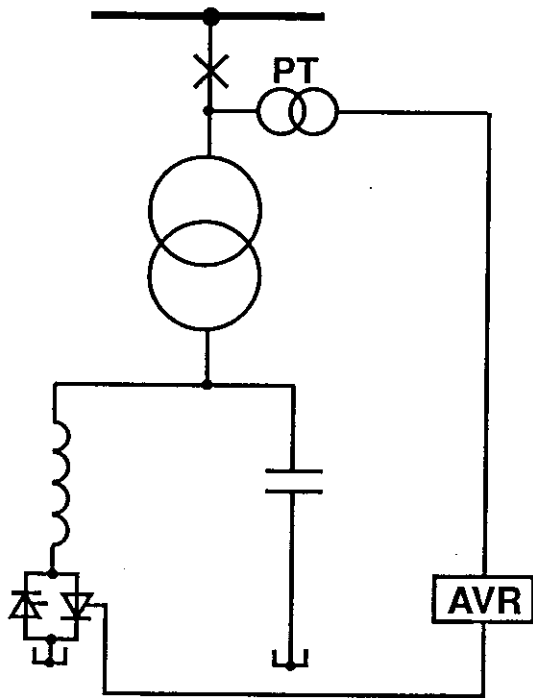


Fig. 1.1 : SVC of the FC/TCR type

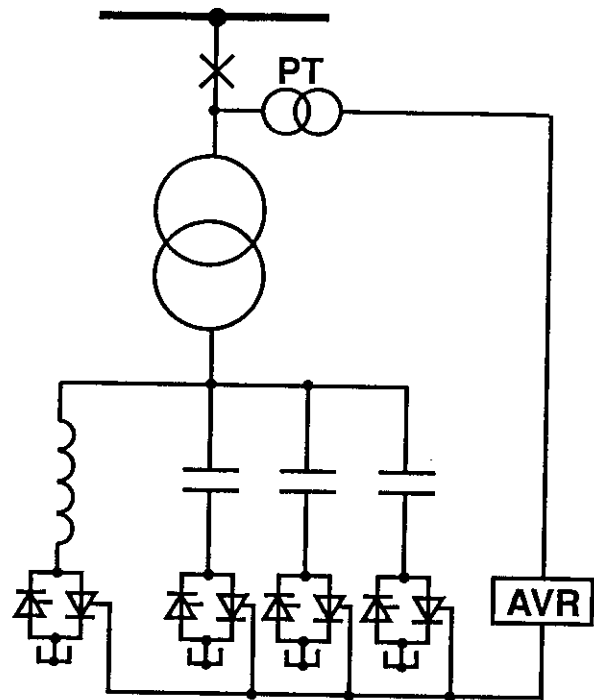


Fig. 1.2 : SVC of the TSC/TCR type

The small-signal performance of an SVC with closed-loop voltage control may be characterized by its step-response time. It is defined here as the time required to achieve 90 % of the called-for change in voltage, for a step change in the reference voltage. The step change must be small enough for the SVC not to hit a limit. The step-response time depends on the external power system impedance. It is typically less than a few cycles of the power-frequency voltage at minimum fault level.

The large-signal performance is essentially characterized by the actuating time of the SVC triggering and main circuits only. For a large voltage deviation, the SVC response time is typically of the order of one power-frequency cycle, considering the power-frequency voltage component only.

The losses of an SVC are very much dependent on the type of SVC main circuit arrangement and on the operating point, but are usually below 1 % of the Mvar rating for most of the operating range.

SVCs in use range in size from a few Mvar up to 600 Mvar control range, with nominal voltages up to 765 kV. Usually, an SVC has a separate transformer, but in some few cases the controllable elements are connected directly to the tertiary winding of a system transformer.

APPENDIX 1-II

Key Terms for Stability

The stability of a large power system is a complex subject with different phenomena and aspects involved. A review of some terms and facts is given below in order to clarify the terminology used in this report.

Synchronous stability is the ability of a power system to retain the synchronous machines in synchronism without sustained rotor oscillations. From an analytical point of view, it is useful to make a distinction between steady-state and transient stability [3,4].

A power system is **steady-state stable** for a particular steady-state operating condition if, following any small disturbance, it reaches a steady-state operating condition identical or close to the predisturbance operating condition. This is also known as small-disturbance stability.

A power system is **transiently stable** for a particular steady-state operating condition and for a particular disturbance if, following that disturbance, it reaches an acceptable steady-state operating condition. The disturbance is assumed not to be small in the preceding meaning, e.g. occurrence and clearance of a short-circuit in the network.

When transient instability occurs for a severe disturbance, it usually, but not necessarily, appears during

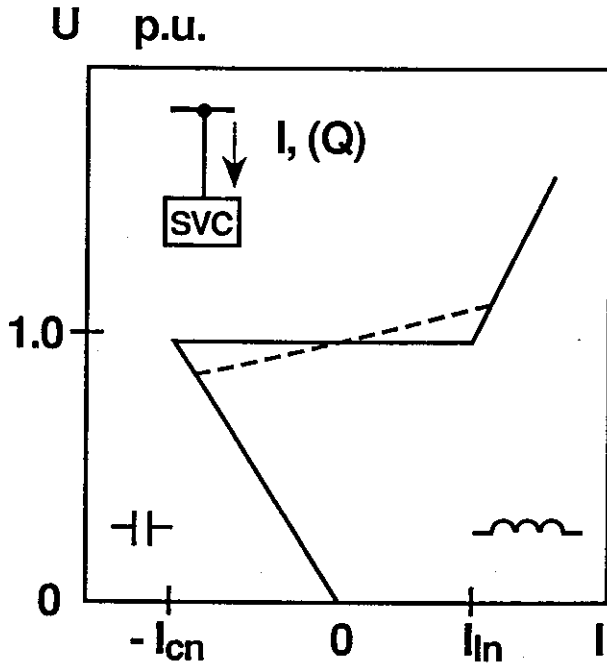


Fig. 1.3 : SVC steady-state characteristic:
 - - - with control slope

the first swing and within one second. The behaviour during the subsequent swings is very much a matter of damping of a non-linear system in contrast to the damping of a linearized system; the latter is usually studied for steady-state stability assessment.

Practical cases of transient instability are often blends of synchronous instability (angle instability) and voltage collapse.

Voltage collapse is an uncontrollable process leading to a severe voltage depression without inherent recovery. The voltages do not necessarily decrease to zero but to low values, making the continued proper operation of a small or large part of a power system impossible. The key cause of voltage collapse is usually inadequate supply of reactive power.

SIL

Particularly when we are dealing with long EHV lines, the so-called Surge Impedance Load (SIL), or natural load, of an uncompensated line is a convenient value frequently used for reference purposes. It is given approximately by:

$$SIL = U^2 \sqrt{b/x} \quad \text{MW}$$

where U = nominal voltage, kV
 line-line

b = line susceptance mho/km

x = line reactance ohm/km

A lossless line (a reasonable approximation of an EHV line when discussing reactive matters) transferring SIL MW at unity power factor and with equal voltages at both line ends has reactive power balance. The reactive power loss due to the line inductance is equal to the reactive power generated by the line capacitance.

APPENDIX 1-III

SVC in Relation to Power Transmission Security

The N-1 condition in a power system is defined by outage of a line, transformer, generator, etc. Outages usually disturb the balance of reactive power. Depending on the actual network conditions it may be important to provide sufficient reactive power reserves in order to maintain a given power transmission capability when limited by first-swing stability or voltage collapse considerations. Since SVCs are an excellent means for dynamic shunt compensation, they are well suited to act as sources of reactive power reserve.

The availability of reactive power reserves is an important factor to consider when comparing SVCs with other means of achieving a desired level of power transmission security. The N-1 criterion can also be applied to the SVC itself; for example, two parallel-operating SVCs of half the size may be preferable to one larger SVC for reliability or maintenance reasons.

CHAPTER 2

STEADY STATE VOLTAGE CONTROL AND STABILITY

by

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 - 2.2 Traditional methods of voltage control
 - 2.3 Voltage control by SVC
 - 2.4 Case study
 - 2.5 Conclusion
- Appendix 2-I: System Characteristics
Appendix 2-II: Method for Calculating Distance to Voltage Collapse

2.1 INTRODUCTION

Steady state voltage on a transmission system must be maintained within a fairly narrow range, around the nominal, at every point on the system in order to preserve system integrity and to provide a satisfactory voltage to the consumers. The upper voltage limit of the transmission system is set by the highest voltage for which the plant is designed with respect to electrical stress and transformer saturation. The lower voltage limit is normally determined by the need to avoid the overloading of lines and transformers, to prevent the shutting down of generating units due to auxiliary system problems, to reduce losses or to be above the critical voltage with respect to voltage collapse for a given power transfer.

In the early development of power systems, small generating units were connected locally at sub-transmission level. The transmission system was generally used to interconnect generation in order to pool capacity and therefore flows on the network were small compared with system size. There were a few notable exceptions where hydro stations were developed, here high voltage transmission systems were introduced to transfer large blocks of power. With the development of large generating sets and the subsequent retirement of the smaller and more expensive generating plant connected to the sub-transmission networks the role of transmission system has changed to that of bulk carrier of power. It is therefore not surprising that steady state voltage control has emerged as one of the dominant factors in the planning and operation of power systems .

There are signs that the worldwide trend to utilise large units in new generation developments is on the wane. It is likely, however, that many of the new, smaller generation projects will be developed by non-

utilities at less predictable locations and transmission systems will be used more extensively for trans-national power trading.

The generators of almost every power system provide the primary means of voltage control. Two other major means of voltage control are the use of transformer on-load tap changers and dispersed reactive compensation.

This chapter first discusses voltage control by traditional means and then shows how it can be supplemented by SVCs to provide a more refined control. It demonstrates by way of a case study the use of shunt compensation, including SVCs, to enhance the voltage control on a long radial network. A long distance radial network, rather than a more mature mesh network was used, as it shows more clearly the important relationship between reactive reserves and the ability to control voltage. It also demonstrates the use of SVC to maximise the capability of such a network.

The case study includes a sensitivity analysis on MW transfer capacity with respect to voltage collapse and a technique for calculating distance to collapse is developed in Appendix 2-II.

2.2 TRADITIONAL METHODS OF VOLTAGE CONTROL

The shunt reactor, shunt capacitor and synchronous compensator are the traditional devices installed for the sole purpose of shunt reactive compensation. The characteristics of these devices are described fully in Appendix 1 of [2].

Other methods which can be used for voltage control are series compensation, the operation of generators as synchronous compensators, and transformer tap stagger. Network reconfiguration by virtue of consequent reduction of the system Mvar requirements can also be considered as a method of voltage control.

2.2.1 Dedicated Devices

Shunt Capacitors and Reactors

Fixed and breaker switched shunt reactors and shunt capacitors are used to provide coarse voltage control and reactive power balance. Three applications are described below:

The first application is on the National Grid Company (ex CEGB) transmission system in England and Wales [5]. Mechanically switched capacitors (MSC) are automatically controlled by a two-mode microprocessor. The voltage mode ensures the insertion of capacitors to support the transmission network when an outage, local or remote, causes the voltage to fall below some fixed threshold. Under normal system conditions, the megavar mode allows the capacitors to be switched on and off proportionally to the local substation reactive demand. This type of control was selected because the time-scale for providing the required Mvar support was considered too short for manual system switching but not fast enough to warrant the speed of switching by thyristors; also the number of switching operations was moderate, one on-off operation per day. The limits of such an application are the possibility of hunting occurring when the system becomes weak and the risk of interactions between several MSCs located in close electrical proximity. In the NGC (ex CEGB) transmission system, these solutions are complemented by SVCs in selected locations.

The second application is a long radial 220/132 kV HV transmission system [6]. Hydro-power plants, connected at 220 kV, supply an isolated demand centre over a local 132 kV network. The 220 kV compensating devices are fixed shunt reactor installed in every substation, all of the same rating. The aim of the compensation is to limit overvoltages at the receiving end of long lines at times of light load. An SVC, however, has been planned for the 132 kV network in order to provide some dynamic compensation which is proportional to line loading.

The third application can be found on the French HV transmission system [7]. Capacitors and reactors located on the French HV network play an important part in the voltage control and in the reactive power management. After several studies and experimentations, it was decided to include the capacitors in the secondary voltage regulation (termed RST). The RST divides the power network into distinct geographical areas, called "zones", and controls the voltage profile separately in each zone by local primary and automatic actions on the voltage controllers of the generators concerned. In order to control the reactive power available in the zone and distribute the Mvar load equally between the units, their participation in the secondary voltage regulation is proportional to their capabilities, on the basis of a signal N called "level" generated at the control centre. The HV capacitors located in each zone are also switched on or off according to the level N . After a delay (3 minutes) other capacitors can be switched on (or off) by the control logic. This method of control avoids interaction between the controlling generators and capacitors.

Generally, under normal system conditions, the capacitors are switched on in order to keep available reac-

tive power of the generator units as a reserve. These reserves can immediately cope with incidents which could otherwise lead to a voltage collapse if the generators reach their reactive limits. However, if the amount of capacitors becomes large, difficulties of management under normal system conditions can appear due to the risk of overvoltages at the nodes where capacitors are connected. The choice for compensation is then a compromise between two boundaries: the risk of overvoltages from a high voltage pattern under normal system conditions and the risk of voltage collapse from a low voltage pattern after outages. In the future, as the amount of shunt capacitors increases, the margin between these two boundaries will narrow and then more advanced control methods will be required.

Synchronous Compensators

Synchronous compensators were installed in the past and are still in use for high performance voltage control in transmission systems. In recent years, for new installations, the synchronous compensator has been virtually superseded by SVC for this function because of lower overall cost and higher reliability.

2.2.2 Other Methods

Series Compensation

Series capacitors [8] lead to a substantial decrease in the transmission angle, an increase in the voltage at the receiving end of the long lines and to a reduction in the reactive losses at times of heavy loading. Distinctive uses can be found on long distance transmission system and large meshed network.

On the long distance transmission system, series capacitors are often installed when the distance in km is roughly equal to, or higher than the voltage level in kV. The main reasons for its use are to increase the transmission load capability under normal system conditions and to improve the transient stability of the network by reducing the electrical distance. It is generally recommended to choose the highest possible degree of compensation paying attention to the ferroresonance, relay protection and subsynchronous resonance phenomena. On multi-circuit lines the same degree of compensation must be used in order to obtain the same power flow in each circuit. At times, this solution is complemented by shunt reactors or SVC .

On large, meshed transmission systems and for the medium distances (about 200 to 300 km on a 380 kV network) series capacitors may be used in order to reduce reactive losses during contingencies and thus reduce the risk of voltage collapse. The degree of compensation will depend on the amount of shunt capacitors installed and maximum current limits of the equipment (lines and series capacitors) under normal system conditions and after outages. If these limits cannot be reached due to technical problems (subsynchronous

chronous resonance for example), the impedance of series capacitors must be reduced to take into account the actual constraint or the constraint itself must be removed, if feasible and technically and economically. It is generally not economic to install series capacitors of small size.

Var Operation of Generators as Synchronous Compensators

In many countries, hydroelectric generators are run as synchronous compensators by injecting compressed air into turbines. Similarly gas-turbine generators are run as synchronous compensators by adding automatic clutches to decouple the turbine. Such application can be found in many countries: United Kingdom, Sweden, Canada, New Zealand and Turkey [9].

An example of this is the City of Istanbul. At times the City is supplied only by distant hydro-electric plants and then the local reactive power needs are important. Three solutions were considered: shunt capacitors, SVCs and de-clutched gas-turbine generators. The best technical and economical solution was to equip the gas-turbine generators in Thrace, near Istanbul, for operation as the synchronous compensators. This allows an increase in the local reactive power reserves (supply or absorption) and thus avoids the risk of voltage collapse. This also benefits the stability of the network by increasing the number of voltage support points.

Transformer Tap Stagger

Transformer tap stagger is the technique by which parallel transformers are operated on different tap positions, thus causing a circulating current and increasing the reactive power losses. The effectiveness of this technique increases with the number of transformers working in parallel (the amount varies from 8 Mvar for 2 transformers in parallel to 100 Mvar for 4 transformers).

At light-load, when there is surplus of Mvar, the network reactive power absorption can be increased by tap stagger. This is used on the United Kingdom network where tap stagger on 400/132 kV and 275/132 kV transformers supplement HV and tertiary connected reactors at times of light load.

Network Reconfiguration

In planning and actual operation, one method to reduce reactive losses during contingencies is to reconfigure the network. For example, at peak time the outage of the line AB (Figure 2.1) increases the reactive losses of the system by 900 Mvar. A diversion (dotted line, Figure 2.1), to connect the line AB into the Substation C, reduces by half the reactive power needs of the system after the outage of the section BC. Such a scheme can avoid voltage collapse in critical situations

and has been used on the French meshed network in three different areas.

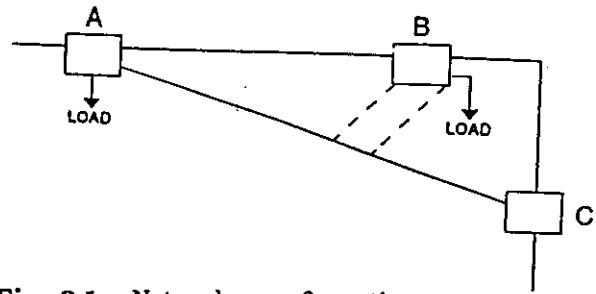


Fig. 2.1 : Network reconfiguration

At off-peak time the disconnection of some circuits is occasionally used in operation; this is done on condition that the reliability of the system or equipment is not compromised.

On a long transmission system, installing additional substations is generally of great help as it not only eases switching operations but also can reduce the voltage problem.

Besides line diversions and installing additional substations, reinforcement of the network by building of new circuits is also an alternative solution to voltage problems, but they are difficult to justify economically for that purpose as compensation devices are usually much cheaper and environmentally less controversial than EHV lines.

2.3 VOLTAGE CONTROL BY SVC

The SVC is primarily a device for high performance voltage control and is increasingly installed in transmission systems as a complement to shunt reactors and shunt capacitors.

The characteristics of the SVCs are described comprehensively in [1]. However, one aspect of the control strategy with special reference to steady state voltage control is discussed below.

In normal operation the SVC has to be operated at a low output ('float') so as to maintain a certain reserve capacity of reactive generation/consumption for disturbances. This can be achieved by adding an additional slow Mvar loop to the controller but one which allows the SVC to change its output rapidly to counteract transient disturbances. When the disturbance results in a new operating point the Mvar control loop returns the SVC slowly to its reference value as shown in Fig 2.2. An alternative method is for the SVC control to be linked to nearby switched elements which are activated when the SVC output moves outside of some predetermined range.

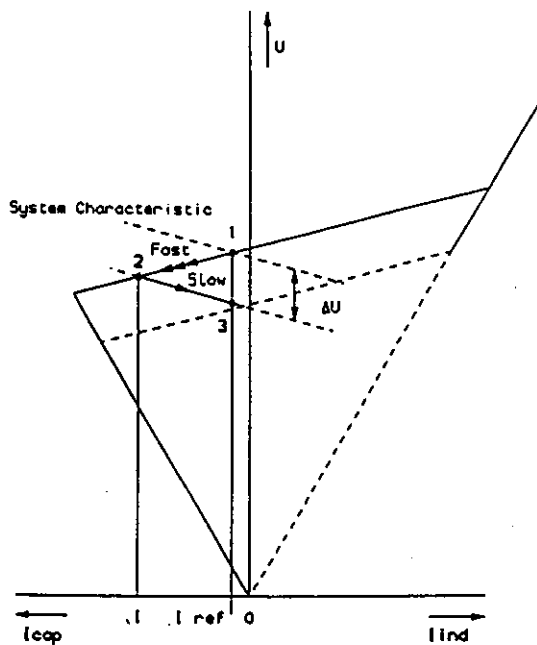


Fig. 2.2 : Action of var reserve control

2.4 CASE STUDY

2.4.1 Network

In order to demonstrate the ability of the SVC to enhance the transmission capability the test system shown in Fig 2.3 was analysed. Its main characteristics are given in Appendix 2-I.

The system consists of a generation complex connected to a large metropolitan system by two 500 kV circuits with a total route length of 1000 km . Between the large system and the generation complex are two intermediate points, at each of which the 500 kV circuits are bussed and a local load supplied. Each section of line is 50 % compensated by series capacitors. The generation complex is also connected to a small isolated system by a 300 km 500 kV single circuit.

The 500 kV network is connected to the large system by 5x750 MVA transformers and to the small system by a single 750 MVA unit.

2.4.2 Voltage Criteria

To determine the reactive compensation required to give an acceptable level of security to the network the following criteria were adopted:

- (i) the voltage level for normal operating condition should be in the range of 95 % to 105 % of nominal.

- (ii) for any (n-1) contingency the voltage should be in the range 90 % to 110 %.
- (iii) during energisation the voltage should not exceed 110 % of nominal.
- (iv) for the complete loss of load in the small system, the remaining system should be secure for any (n-1) contingency.

A secure system for planning purposes has been defined as one for which there is to be a planning margin $P_{min(-1)}$. In addition to this there should be some MW distance, $P_{min(-2)}$, from the critical voltage. The relationship between, $P_{min(-1)}$, $P_{min(-2)}$ and the critical voltage, is shown on Fig 2.4

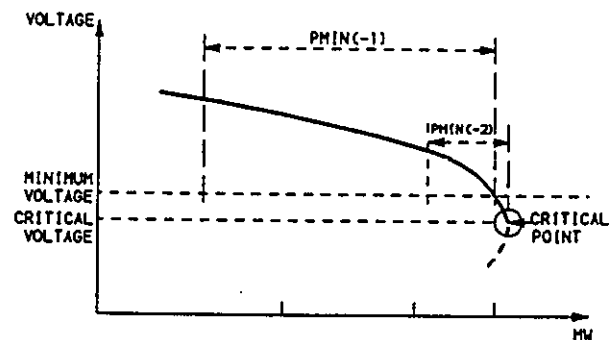


Fig. 2.4 : Distance to voltage collapse used in reactive power security evaluation

An outline of the method used to calculate the MW distance to voltage collapse is given in Appendix 2-II. It is based on the methods described in References [10] - [12]

2.4.3 Results

The strategy adopted to obtain the quantity of reactive compensation required is as follows:

- a) Determine the inductive compensation needed to energise the network.
- b) For minimum and maximum demand conditions determine the amount of compensation required which for normal conditions minimise I^2r losses and for the contingencies minimise the total compensation needed. An optimal power flow (OPF) program was used for this study.
- c) Having obtained the necessary compensation from a) and b) apply the sensitivity method described in Appendix 2-II.

2.4.3.1 Energisation

The inductive shunt compensation needed to energise a single circuit from the generation complex to the large system, a distance of 1000 km was determined.

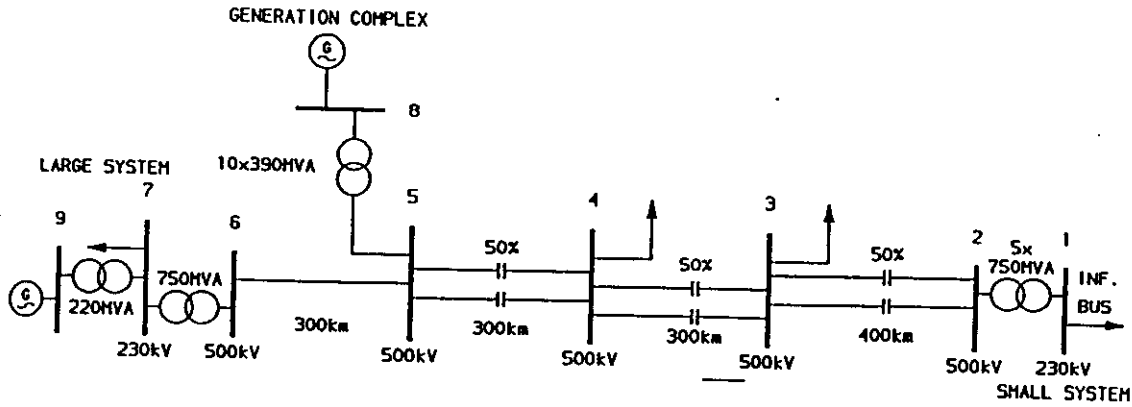


Fig. 2.3 : Test network

With 4 generators at the complex the inductive compensation required was 300 Mvar at each of Nodes 2, 3, and 4..

The energisation of the line to the small system could be achieved without any inductive compensation, however as described in paragraph 2.4.3.2 below inductive compensation of 200 Mvar was required at Node 6 to meet the voltage requirements at minimum load in the small system.

Additional shunt reactive absorption may be required at times when the transmission is lightly loaded and where it is required to keep both lines in service for security reasons.

2.4.3.2 Minimum Load Conditions

Under normal conditions, with both long-distance lines in service and minimum loads at the intermediate points and the small system, the MW transfer from the generation complex to the large system is 2800 MW, i.e 2.4 p.u on 1168 MW, the SIL of one line. At Nodes 3 and 4 the inductive compensation required is some 242 Mvar. At Node 6 inductive compensation of 200 Mvar is required to restrict the voltage to its upper limit.

The most severe contingency is the outage of circuit in section 2-3. This requires capacitive compensation of 400 Mvar at Node 2, 500 Mvar at Node 3 and 182 Mvar at Node 4.

All other outages are contained within the above Mvar envelope.

The resulting voltage profile and required compensation are shown in Table 2.1.

2.4.3.3 Maximum Load Conditions

Under normal conditions, with both long-distance lines in service and the increased loads at the intermediate points and the small system, the MW transfer to large system reduces to 2400MW(2.05 SIL). The compensation required is less than that determined for the minimum load.

At Node 3, the inductive compensation from the OPF study is in excess of that required for line energisation. This is due to the objective function used which minimises I^2r losses and thus by keeping the system voltage high, 1.05 p.u, maximising BV^2 gain of the circuits.

The resulting voltage profile and required compensation are shown in Table 2.2.

2.4.3.4 Sensitivity Analysis

The compensation shown in Table 2.3 covers the two extreme conditions of the energisation of the system and 2800MW (2.40 SIL) transfer to the large system whilst satisfying conditions i) - iv) of the voltage criteria.

Starting with the 2800 MW transfer case and outage of line 2-3 the transfer was increased using the method described in Appendix 2-II. This was done to obtain a MW-transfer margin whilst satisfying voltage criterion (iv). The margins defined were :

$$\begin{aligned} P_{\min(-1)} &= 220 \text{ MW}(0.19 \text{ SIL}) \\ P_{\min(-2)} &= 20 \text{ MW}(0.02 \text{ SIL}) \end{aligned}$$

A secure system thus should have a transmission capacity of 3020 MW (2.59 SIL) into the large system.

Table 2.1 : Minimum Load 300 MW at the intermediate stations, 2800 MW (2.40 SIL) transfer to the large system

| Case / Node | Large System | | Intermediate Points | | Hydro Station | | Small System | |
|-------------------|--------------|-------|---------------------|-------|---------------|-------|--------------|-------|
| | 1 | 2 | 3 | 4 | 5 | 8 | 6 | 7 |
| Normal | | | | | | | | |
| U p.u. | 1.044 | 1.050 | 1.050 | 1.050 | 1.050 | 1.000 | 1.040 | 1.031 |
| Q Mvar | | 381 | -242 | -242 | | -332 | -200 | |
| Outage Line 4-5 | | | | | | | | |
| U p.u. | 1.044 | 1.037 | 0.990 | 0.950 | 1.016 | 1.000 | 1.041 | 1.031 |
| Q Mvar | 417 | 381 | | 50 | | 827 | -92 | |
| Outage Line 3-4 | | | | | | | | |
| U p.u. | 1.044 | 1.027 | 0.950 | 0.950 | 1.023 | 1.000 | 0.992 | 1.031 |
| Q Mvar | 749 | 381 | -242 | -242 | | -332 | -200 | |
| Outage Line 2-3 | | | | | | | | |
| U p.u. | 1.044 | 0.976 | 0.985 | 0.999 | 1.000 | 1.000 | 1.041 | 1.031 |
| Q Mvar | 800 | 400 | 500 | 182 | | -319 | -199 | |
| Min. Compensation | | 381 | -242 | -242 | 0 | 0 | -200 | 0 |
| Max. Compensation | | 400 | 500 | 182 | 0 | 0 | -92 | 0 |

Compensation : - inductive, + capacitive

Table 2.2 : Maximum Load 1000 MW, 2400 MW(2.05 SIL) transfer to the large system

| Case / Node | Large System | | Intermediate Points | | Hydro Station | | Small System | |
|-------------------|--------------|-------|---------------------|-------|---------------|-------|--------------|-------|
| | 1 | 2 | 3 | 4 | 5 | 8 | 6 | 7 |
| Normal | | | | | | | | |
| U p.u. | 1.047 | 1.050 | 1.050 | 1.050 | 1.050 | 1.026 | 1.049 | 1.012 |
| Q Mvar | | 134 | -377 | -237 | | -351 | 50 | |
| Outage Line 4-5 | | | | | | | | |
| U p.u. | 1.045 | 1.043 | 1.050 | 1.025 | 1.028 | 1.000 | 1.049 | 1.012 |
| Q Mvar | 134 | | | | | 226 | 128 | |
| Outage Line 3-4 | | | | | | | | |
| U p.u. | 1.049 | 1.040 | 1.009 | 1.009 | 1.037 | 1.000 | 1.049 | 1.012 |
| Q Mvar | 388 | 134 | | | | 0 | 97 | |
| Outage Line 2-3 | | | | | | | | |
| U p.u. | 1.050 | 1.029 | 1.014 | 1.040 | 1.047 | 1.000 | 1.050 | 1.013 |
| Q Mvar | 800 | 289 | 46 | | | -267 | 66 | |
| Min. Compensation | | 134 | -377 | -237 | 0 | 0 | 50 | 0 |
| Max. Compensation | | 289 | 46 | 0 | 0 | 0 | 128 | 0 |

Compensation : - inductive, + capacitive

Table 2.3 : Compensation Required to support 2.4 SIL (2800 MW)

| Node | 2 | 3 | 4 | 6 | Total |
|-----------|-----|-----|-----|-----|-------|
| Ind. Mvar | 300 | 300 | 300 | 200 | 1100 |
| Cap. Mvar | 400 | 500 | 200 | | 1100 |

Table 2.4 : Active power transmission capacity into large system for different amount and location of reactive power compensation.

| Case | Reactive Power Compensation at bus no | | | Sum of Reactive Power Compensation (Mvar) | MW transfer Capacity into Large System (SIL) |
|------|---------------------------------------|------|-----|---|--|
| | 2 | 3 | 4 | | |
| 1 | 750 | 900 | 200 | 1850 | 2.56 |
| 2 | 850 | 900 | 200 | 1950 | 2.57 |
| 3 | 750 | 900 | 300 | 1950 | 2.58 |
| 4 | 750 | 1000 | 200 | 1950 | 2.59 |

The transmission capacity into the large system is increased to 2985 MW (2.56 SIL) by increasing the compensation to 1850 Mvar, Case 1 in Table 2.4.

An additional 100 Mvar was installed at Node 2, 3 and 4 in turn, Cases 2, 4 and 3, respectively, in Table 2.4. Note only case 4 satisfies voltage criterion (iv)

The variation in the transmission capacity into the large system as function of amount and location of Mvar compensation is shown in Figure 2.5. Curves 1, 2, 3 and 4 refer to Cases 1, 2, 3 and 4 respectively in Table 2.4.

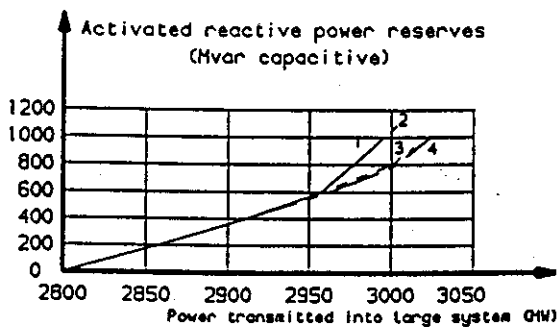


Fig. 2.5 : Variation of power transmission capacity of the large system with installed Mvar capacity

The Mvar compensation necessary for outage of line 2-3, was then tested on the outage of lines 3-4 and 4-5 in turn. Figure 2.6 shows that the power transmission capacities became higher for these outages.

The required capacitive compensation is therefore:
 750 Mvar at bus 2
 1000 Mvar at bus 3
 200 Mvar at bus 4

This is sufficient for the outage of any line section in combination with loss of load in the small system.

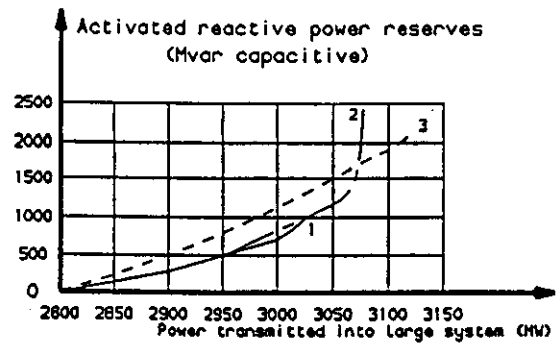


Fig. 2.6 : Transmission capacity for different line outages

2.4.4 Required Characteristics of Compensation

The components of total compensation which need to be provided as SVC are determined primarily by the amount of compensation required for fast control of the voltage after line tripping. Consider the values shown in Tables 2.1 and 2.2. The maximum Mvar swings, that is the difference between the nodal Mvar required for normal condition and that for the worst contingency, is given as 150 Mvar at Node 2, 740 Mvar at Node 3, 420 Mvar at Node 4 and 110 Mvar at Node 6. Not all of the Mvar swing need be met by SVC, some can be provided by the use of switched reactors and switched capacitors as long as they are part of the control scheme for the SVC. In addition consideration must be given to switching duty imposed on the circuit breakers for the range of possible operating conditions. This duty may dictate that the size of SVC normal daily variation of reactive requirements in the network be taken up by the SVCs thus limiting the switching duty on the circuit breakers controlling the reactors, or capacitors

The sensitivity analysis provides an indication of the need for some margin. It increases the amount of total compensation significantly, 900 Mvar capacitive, all of which must be fast acting. This additional compensation should not be regarded as an optional extra but as that needed to safeguard against voltage collapse for the inevitable practical variations in MW and Mvar from predicted values.

2.4.5 Summary and Concluding remarks on the Case Study

Table 2.5 shows a proposal for the locations, types and sizes of reactive power compensation devices, based on the studies performed with respect to static steady-state conditions.

The SVCs are provided primarily to give the necessary support so that the network can move from the normal state, all circuits in, to any contingent state without

Table 2.5 : Proposed Compensation schedule for Test Network

| Node | 2 | 3 | 4 | 6 |
|-------------------|-----|-----|-----|-----|
| <u>Fixed *</u> | | | | |
| Inductive (Mvar) | 300 | 300 | 300 | 200 |
| Capacitive (Mvar) | 400 | 400 | | |
| <u>SVC</u> | | | | |
| Inductive (mVar) | 175 | 300 | 100 | |
| Capacitive (Mvar) | 350 | 600 | 200 | |

* Permanently connected or breaker switched

voltage collapse. SVCs, being automatic in operation, also provide the necessary voltage control which allows the daily fluctuation in MW transfer across the network to take place without the need for complex operational procedure.

The studies performed have treated steady-state conditions as determined by power-flow calculations and thus give no information on what compensation might be required with respect to the dynamic behaviour of the power system.

The studies have been performed for a network with a 50% series compensation. It may well be that a higher degree of series compensation would have been more advantageous for the steady-state voltage control and stability of the network.

2.5 CONCLUSION

There is a variety of shunt power compensation devices to achieve steady state voltage control and reactive power balance on transmission systems. The shunt reactors, shunt capacitors, synchronous compensators and SVCs make up the dedicated devices for this sole purpose. In some systems generators are used as synchronous compensators. In the UK, at light load, tap stagger is used for absorption of reactive power.

The choice of type and mix of compensation has to be based on integrated technical and economic studies for each individual system. Naturally, the utility practice will play a substantial role in the final decision.

In cases of new installations of dynamic shunt compensation for high-performance voltage control, SVCs have virtually replaced synchronous compensators. SVC now offer the benefit of improved performance, lower overall cost and reduced maintenance. Synchronous compensators are now installed only in the

special case of HVDC inverter station where the short circuit level and sometimes rotational inertia are of paramount importance.

In general the share of dynamic compensation is increasing, in particular SVCs, due to the need to improve the voltage control on buses adjacent to load areas which are devoid of generation. Where the prevention of voltage collapse is of interest full advantage can be taken of the speed of SVC controls.

Appendix 2-I

System Characteristics (See Fig 2.3 for line diagram)

Transmission Lines

$$R = 0.016255 \Omega / \text{km}$$

$$X = 0.275 \Omega / \text{km}$$

$$B = 6.0 \cdot 10^{-6} \Omega^{-1} / \text{km}$$

$$f = 50 \text{ hz}$$

Series compensation 50%

Small System

Transformer: 750 MVA, 500/230 kV, Impedance 12%

Load: 100 MW, pf 0.85 - 600 MW, pf 0.90

Local thermal generation: 220 MVA, pf 0.90

Large System regarded as infinite

Transformer: 750 MVA, 500/230 kV, Impedance 12%

Load: Any power that could be delivered by the transmission network

Intermediate Buses 3 and 4): Load:

100 MW, pf 0.85 - 200 MW, pf 0.95

No local generation

Hydro generation plant: 10 x 390 MVA, pf 0.90

Appendix 2-II

Methods for calculating the distance to voltage collapse

General outline of sensitivity technique

Following is a description of the sensitivity techniques used for calculation of "distance" to voltage collapse is given.

The variables can be classified as follows:

- x - state variables (voltages and angles at load buses)
- u - control variables (generator bus voltages, MW production, Mvar compensation)
- p - parameters (input values, i.e. MW and Mvar load)
- w - dependent variables (generators reactive power production, reference bus MW production)

In sensitivity calculations the mathematical relations between state variables and control variables or parameters are of interest. Further of interest are the relations between dependent variables and control variables or parameters.

The load flow equation can be given as:

$$g(x, u, p) = 0 \quad (1)$$

A Taylor series expansion of equation (1) provides the relation:

$$\Delta g = g_x \Delta x + g_u \Delta u + g_p \Delta p = 0 \quad (2)$$

From equation (2) the sensitivity in state variables x can be expressed as:

$$\Delta x = -g_x^{-1} g_u \Delta u - g_x^{-1} g_p \Delta p \quad (3)$$

or

$$\Delta x = S_{xu} \Delta u + S_{xp} \Delta p \quad (4)$$

where

- S_{xu} - sensitivities in state variables x to variations in control variables u
- S_{xp} - sensitivities in state variables x to variations in input values p

The dependent variables w also are functions of the state variables x , control variables u , and parameters p . Thus

$$w = w(x, u, p) \quad (5)$$

A Taylor series expansion of equation (5) yields

$$\Delta w = w_x \Delta x + w_u \Delta u + w_p \Delta p \quad (6)$$

Inserting equation (3) into equation (6) and observing that $w_p = 0$, the sensitivity in dependent variables w can be expressed as:

$$\Delta w = (-w_x g_x^{-1} g_u + w_u) \Delta u - w_x g_x^{-1} g_p \Delta p \quad (7)$$

or

$$\Delta w = S_{wu} \Delta u + S_{wp} \Delta p \quad (8)$$

where

- S_{wu} - sensitivities in dependent variables w to variations in control variables u
- S_{wp} - sensitivities in dependent variables w to variations in input values p

In the above equations $g_x, g_u, g_p, w_x, w_u, w_p$ are matrices consisting of the partial derivatives of the vectors g and w with respect to state variables x , control variables u , and parameters p .

How these sensitivity matrices can be used in calculation of the voltage stability and reactive power reserve conditions in a network will be outlined in the following.

Calculation of MW-distance to voltage collapse

The sensitivity in reactive power generation to active and reactive load variations at specific buses is given by sensitivity matrix S_{wp} .

When increasing the MW-load at bus i the change of reactive power at generator j is given as

$$\Delta Q_{ji_p} = \frac{dQ_{ji}}{dP_i} \Delta P_i = S_{wp}(j, i_p) \Delta P_i \quad (9)$$

where $S_{wp}(j, i_p)$ means matrix element related to reactive generation at bus j and active load at bus i

The reactive power reserves available at bus i , when increasing the MW-load until voltage collapse is reached can be calculated as

$$\Delta Q_{res}(i_p) = \sum_{n=1}^{n_{maxi_p}} \left[\sum_{j=1}^{n_g} S_{wp}(j, i_p) \Delta P_i^n \right] \quad (10)$$

and this MW-distance to collapse is given as

$$\Delta P_{ic} = \sum_{n=1}^{n_{maxi_p}} \Delta P_i^n \quad (11)$$

where n_{maxi_p} is the number of steps in the calculation of MW-distance to voltage collapse when increasing the active load at bus i

CHAPTER 3

DYNAMIC (FUNDAMENTAL FREQUENCY) VOLTAGE CONTROL

by

K. Reichert (Switzerland, Coordinator), T. K. Østrup (Denmark)

Contents :

- 3.1 Introduction
- 3.2 The use of SVCs for improvement of voltage control
- 3.3 Methods of analysis
- 3.4 SVC models
- 3.5 Case studies :
 - a) Voltage control problems of load centers, with and without local generation
 - b) Voltage control problems of interconnected systems
- 3.6 SVC installation aspects
- 3.7 Conclusions

3.1 Introduction

Dynamic, fundamental frequency overvoltages or undervoltages will occur in inter-connected power systems and load centers, with and without generation, if:

- the reactive power requirement of the transmission system interconnecting the power systems or feeding the load centers is not compensated according to the loading situation,
- the interconnecting transmission system is weakened due to disturbances (i.e. line outages) or high loading and therefore has a high impedance with respect to the load,
- the reactive power demand of the power system or the load center is not balanced by the supply, due to isolation, load rejection or load shedding, insufficient local generation, inadequate reactive power compensation and voltage support, specific load characteristics, etc.

The worst situation will arise if network splitting takes place, because in this case the change in the power transmission occurs at the same time as the network and the power system are weakened. Load shedding following the network splitting can make the voltage control even more difficult.

In case of network splitting, normally, the exporting area being subject to load rejection is exposed to overvoltages. The importing area is in the first instance exposed to low voltages, but if load shedding takes place the low voltages can change rapidly to overvoltages.

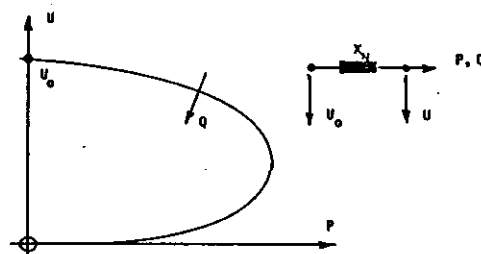


Fig. 3.1 : Typical voltage-power characteristic of a transmission system

Voltage collapse phenomena will arise at load centers being connected via a weak transmission line (high impedance) if the power transfer exceeds a critical value. This basic phenomenon can be explained by means of the quasi-steady-state receiving end voltage-versus-power characteristic (Fig. 3.1). The problem becomes a dynamic one if the load center has local generation, induction motor load and voltage sensitive load, which is usual (e.g. Fig. 3.2).

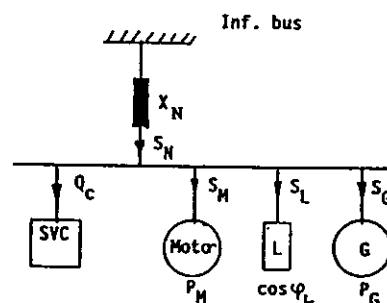


Fig. 3.2 : Generic system (load center) for dynamic voltage stability studies with zero power transfer ($S_N = 0$) from inf. bus under normal conditions

The generators may lose their synchronism if the angle against the power system exceeds a critical value resulting in negative synchronising torque.

The generators may also become unstable if the gain of their excitation system is too large thus providing negative damping to the system.

Following large disturbances (short-circuits) at the load center or on the transmission line, the voltage at the terminal of the induction motor may drop to a

very low level resulting in motor stalling if the voltage drops below a critical value. During this event the induction motor will draw very high reactive currents which further aggravate the voltage collapse problem.

3.2. Use of SVCs for Improvement of Voltage Control

SVCs are well suited to solve or to reduce dynamic, fundamental frequency voltage control problems by providing reactive power compensation during transmission line disturbances, load rejection or shedding, load variations etc., because they are fast and can be placed at crucial locations, in the problem area or at the load center.

SVCs designed according to the system requirement can control dynamic overvoltages or undervoltages as follows :

- SVCs stabilise the voltage at the load centers according to their reactive generation/absorption capabilities,
- SVCs decrease the reactive loading of the transmission line,
- SVCs improve the power transfer capacity of transmission lines by appropriate voltage control at intermediate points of the transmission system,
- SVCs operating on voltage-error-control can enhance the synchronizing torque of the system by providing a portion of the system's reactive power,
- SVCs with additional damping control reduce the negative damping effect. i.e. the destabilizing influence of high-gain-generator-AVR without PSS,
- SVCs can provide the reactive power drawn by induction motors during starting and stalling.

Low voltages occurring due to generator overloading before load shedding takes place are difficult to be counteracted by SVCs alone. High initial excitation on the generators makes it easier to control the voltage. It is necessary to have a good combination of voltage regulation from generators and SVCs to get a proper voltage control.

3.3 Method of Analysis

The problems of dynamic voltage stability are associated with the fundamental frequency, transient be-

haviour of the system. The dynamic overvoltage or undervoltage has to be controlled immediately following the disturbance. The analysis required covers a few seconds of real time, usually 5 - 10 seconds, including secondary events such as loads hedding which may take place after a few seconds. The characteristic low frequency oscillatory modes, in the order of 0.5 - 2 cycles per second, which are associated with these dynamic overvoltages, determine the phenomenon. Transient and subtransient effects of the generators and motors as well as AVR-transients have to be considered in the analysis. Methods for large disturbance studies are appropriate for analysing this problem. Electromagnetic transients in the network and in the SVC components can be ignored in these studies as the disturbance being evaluated is the result of electromechanical oscillations and voltage control interactions. Modelling of the rotor circuits of machines should be included as in the usual transient stability studies [1]. Saturation effects should be included only in the generator models. All this features together means that ordinary Transient Stability Programs are well suited for these investigations.

3.4 SVC models

The SVC models appropriate for dynamic voltage control problems are of the controlled variable susceptance or current type with limits on Y_c . The controller uses the voltage error as input and has the transfer function : $K_c/(1 + pT_c)$ in the following studies, which is appropriate for voltage control only [1].

3.5 Case studies

a) Voltage control problems of load centers, with and without local generation

A typical system to study the dynamic voltage control problem consists of a load area with local generation fed from the main network via a transmission line. The load consists of induction motors with inertia and constant torque and of loads with constant power and power factor as a worst case condition. (Fig. 3.2)

The motor load percentage was considered to be variable, but the constant P,Q-load was adjusted such that the net import of active and reactive power from power system (infinite bus) through the transmission line was zero.

Data of the generic system :
(pu-basis : nominal power rating S_{Gn} of generation)

Generator : (overexcited)

| | | | | | | |
|---------|---|---------|---|------------|---|---------|
| P | = | 0.85 pu | ; | Q | = | 0.52 pu |
| X_d | = | 2.9 pu | ; | $X_{q''}$ | = | 2.8 pu |
| X_q' | = | 0.48 pu | ; | $X_{q'}$ | = | 0.35 pu |
| T_d' | = | 0.8 s | ; | $T_{dq''}$ | = | 4.8 s |
| T_d'' | = | 0.65 s | ; | T_q' | = | 0.52 s |
| H | = | 5.0 s | | | | |

Generator-AVR-Transfer-Function :

$$U_f/U = K_G/(1 + pT_G) ; K_G = 20 ; T_G = 1.1 s$$

Induction motor :

$$X_h = 3.6 pu ; X_r = X_s = 0.1 pu ; R_r = 0.03 pu ; H = 3 s$$

Transmission line :

$$X_N = 0.1 \div 0.5 pu$$

SVC-AVR-Transfer-Function :

$$U_c/U = K_c/(1 + pT_c) ; K_c = 150 ; T_c = 0.1 s$$

Remark : Many SVC controller transfer functions are possible and in use. The transfer function used for the case study is considered an adequate model for dynamic voltage control problems.

For the evaluation of the SVC requirement the following cases have been studied :

- Outage of the local generator, i.e. loading of the transmission line by the load
- Starting of the motor
- 3-phase-fault at the load center with fault clearance after 0.2 s, considering back-up protection or usual clearing times in distribution systems.

The criteria for the determination of the capacitive rating Q_c (≤ 0 according to the sign convention for reactive power) of the SVC were :

- Stability of the generator, with respect to the transient and steady state
- System voltage : ≥ 0.9 pu

The results of the studies can be summarized as follows:

In the case of generator outage the voltage collapse can be prevented if the SVC is rated according to Fig. 3.3. The ratio of induction motor load P_M to generation P_G seems to have only a minor effect on the stability limit. The voltage collapse problem does not exist if the network impedance X_N is smaller than 0.3 pu.

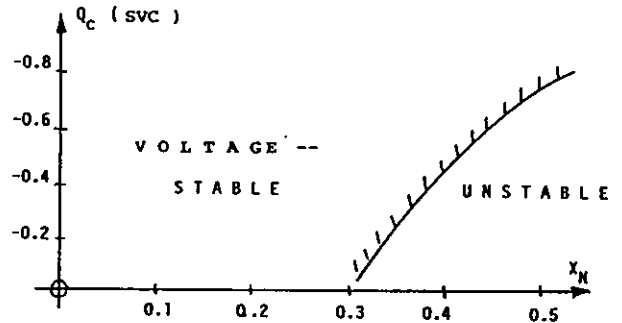


Fig. 3.3 : SVC requirements for generator outage, or system without local generation to solve voltage stability problem

These results were achieved by means of a stability program, see Fig. 3.4 but the same results could have been also the result of a load flow type calculation using an appropriate induction machine model.

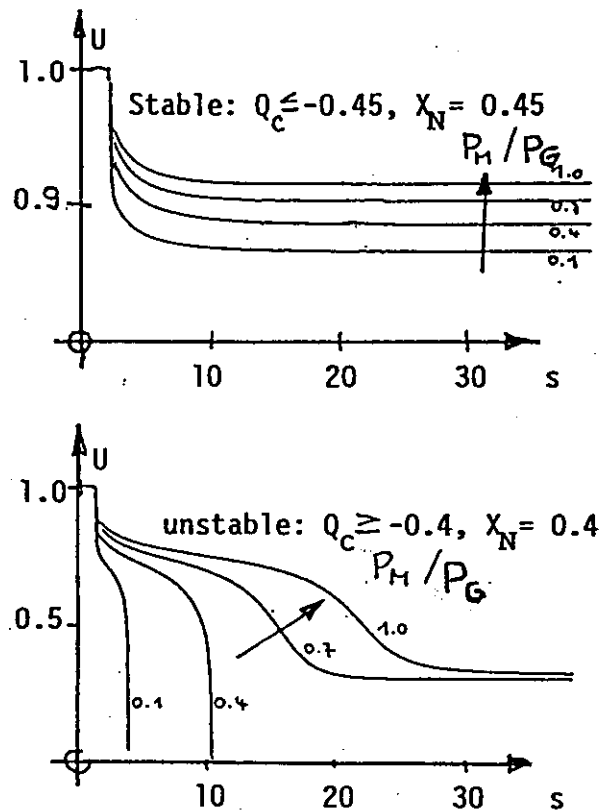


Fig. 3.4 : Transient performance of the load center voltage for generator outage with P/Q-load

In case of motor starting the voltage collapse problem will not occur if the network impedance X_N is below 0.1 p.u. and if the motor load is much smaller than the constant load: (see Fig. 3.5) The simulation (see Fig. 3.6) shows that the generator is contributing to the reactive power requirements of the motor and experiencing large rotor angle oscillations.

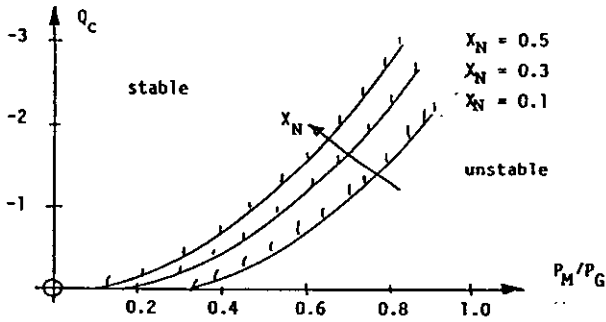


Fig. 3.5 : SVC requirements for motor starting with $U > 0.9$ pu

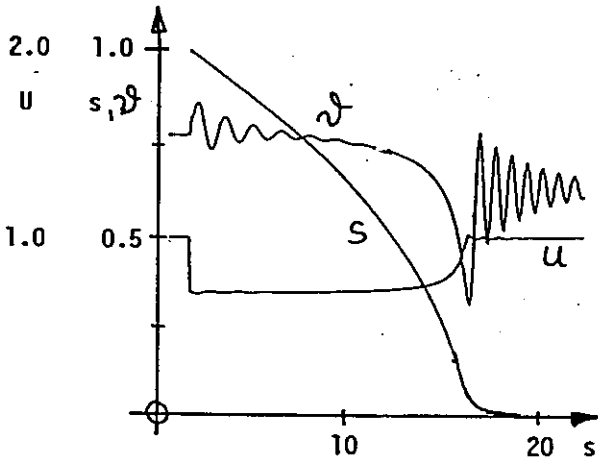


Fig. 3.6 : Transient performance of the motor and the generator for motor starting

A 3-phase short circuit at the load center with subsequent fault clearance after 0.2 s (a typical value) may cause first-swing instability as well as instabilities (see Fig. 3.7) caused by insufficient damping or synchronizing power after fault clearance. The effects of the generator-AVR and the SVC-control schemes and parameters are predominant. Pure voltage control as provided by the SVC-AVR-transfer function used in the studies (see sect. 3.5) seems to be not sufficient to provide enough damping. The stability limit (see Fig. 3.8) for 3-phase-faults does not depend much on the size of the motor load but it sets the highest requirements on the capacitive rating of the SVC.

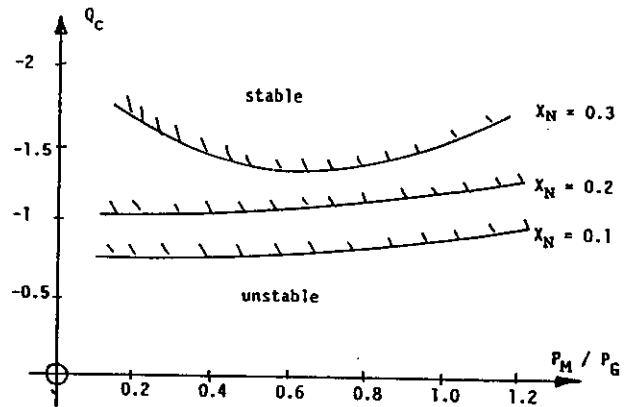


Fig. 3.8 : SVC requirements for 3-phase faults with fault clearing after 0.2 sec

b) Voltage control problems of interconnected systems

The investigations were made for a small network (peak load : 2400 MW) connected to a large system by a few tie lines. Fig. 3.9 shows a simplified diagram of the system.

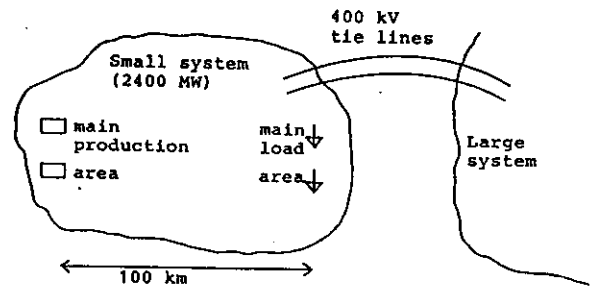


Fig. 3.9 : Simplified system diagram. The 400 kV-tie lines are tripped in the case study

The network is highly meshed and is geographically small with about 100 km between the largest power stations and the main consumption area. All units are thermal with turbo-generators.

The investigated SVC has a controller with a gain $K = 20$ and a time constant $T = 0.1s$.

Fig. 3.10 shows typical curves for voltage and frequency in a case where 50 % of the area active load is imported and the tie lines are tripped followed by 50 % load shedding. No SVC is in operation. The MW production of the generators is near maximum prior to the fault and the reactive power exchange on the tie lines is negligible.

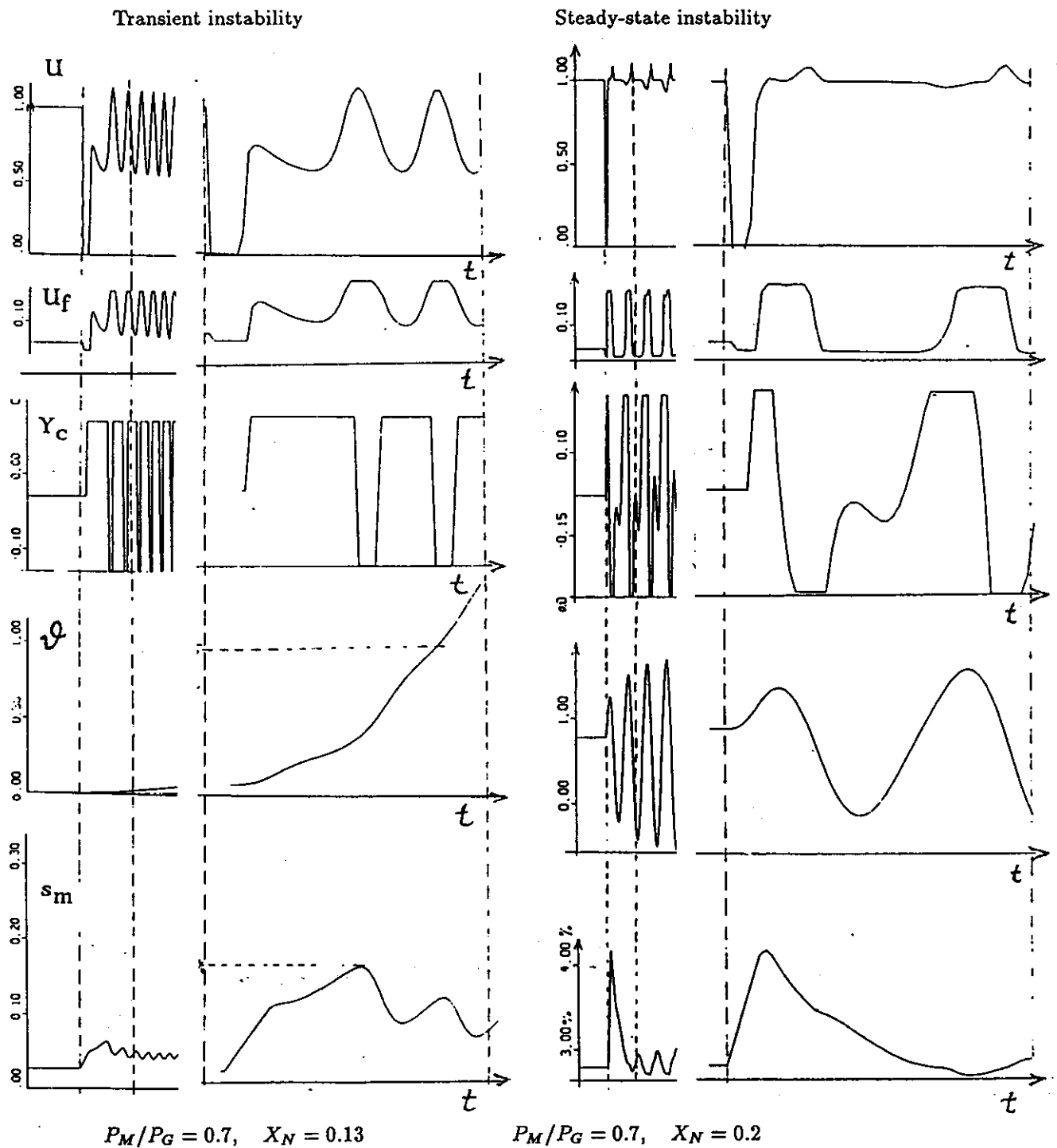


Fig. 3.7 : Transient performance of the generator for 3-phase-faults with fault clearing

- | | |
|------------------------------|---|
| U = load center voltage, | U_f = generator field voltage |
| Y_c = SVC- admittance, | ϑ = generator angle to inf. bus |
| s_m = induction motor slip | |

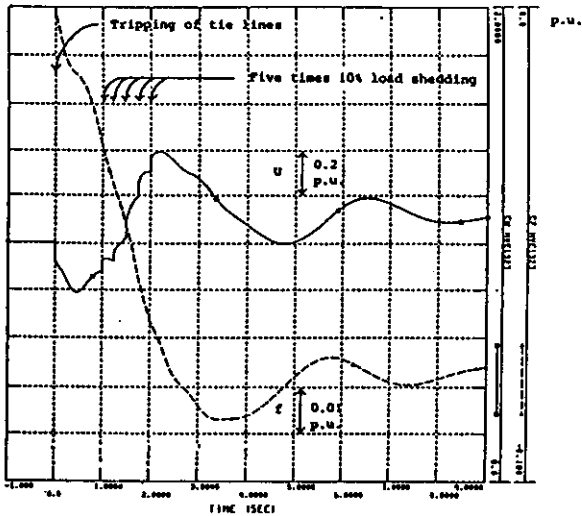


Fig. 3.10 : Voltage and frequency in a case of tripping of tie lines, with 5x10 % load shedding, 1600 MW load, 800 MW import, 200 Mvar from generators, no SVC

The tripping of the tie lines gives an immediate voltage drop, which is followed by a further voltage decrease mainly due to changes in the generator angles. The voltage remains low until load shedding takes place, after which the low voltages are immediately followed by high voltages. The generator AVRs reduce the overvoltages during the next few seconds, but the voltage control is rather slow after the load shedding when the network is weak and the reactive power production at the generators is low.

Due to the voltage dependency of the load the frequency curve is very dependent on the voltage curve.

Fig. 3.11 shows active and reactive power from a single 300 MVA generator unit with static excitation in the same event as mentioned above (some power oscillations are present during the first seconds). Just after the line tripping the generators must supply active power to the whole load (minus a fraction due to the drop in voltage and thereby in the load) instead of half of it, as is the case before the fault. This leads to a heavy overloading of the previously full loaded generators giving a large voltage drop in the network.

As the voltage drop is created at the generator terminal it is difficult to counteract with components installed in the network.

Fig. 3.12 shows that the voltage characteristics of the load greatly influences the post-fault voltage variations. In a real network the characteristics are not well known and vary according to place and time. If the voltage deviations become larger than about 0.2 p.u. for a prolonged period, the network behaviour cannot be easily predicted and might therefore not be under control.

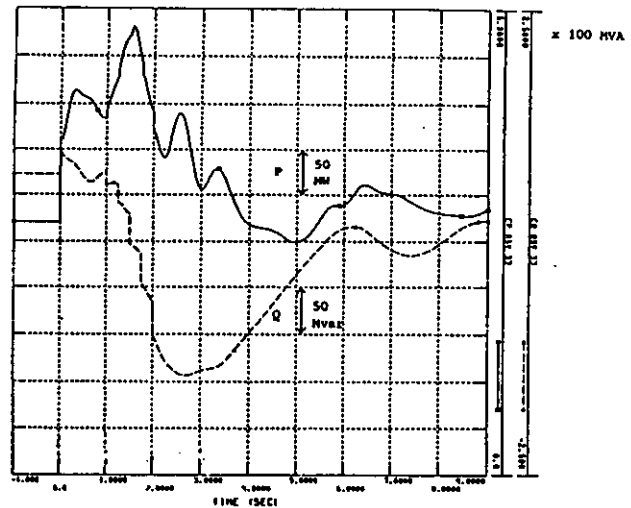


Fig. 3.11 : Generator MW and Mvar in case of tripping of tie lines and 5x10 % load shedding, with 1600 MW load, 800 MW import, 200 Mvar from generators, no SVC

The full drawn curve on Fig. 3.12 is calculated with the same load characteristic as the other figures. The load model is different for high and low voltages, but still simple. This model has been chosen to give results which are neither too pessimistic nor too optimistic.

Fig. 3.13 and 3.14 show the influence of the initial generator excitation and of an SVC near the load center.

High initial excitation gives a more efficient voltage regulation and reduces the voltage variations in both directions. The SVC can further effectively reduce the overvoltages but has little effect on the initial low voltages. This is because the SVC causes the loads to be larger just after the network splitting due to increased voltage at the loads and this increases the overloading of the generators and thereby gives lower generator terminal voltages and larger generator swings. This is further illustrated on Figure 3.15, where the size of the SVC is varied. A large SVC, which is able to hold the network voltage and the loads at a high level can in this case create such large problems for the generators that stability is lost.

A supplementary control signal to the SVC could be considered. A frequency measurement can be used to lower the voltage near the loads in cases with low frequency. This will decrease the loads and thereby ease the control of the system as shown on Figure 3.16. Here the SVC becomes a reactor after 100 ms, due to such a frequency signal. The system is now well controlled in all the cases and nearly without overvoltages with the largest SVC. However, the initial low voltages still exist. In general it can be risky to have a controller which measures a value (here frequency) which has no

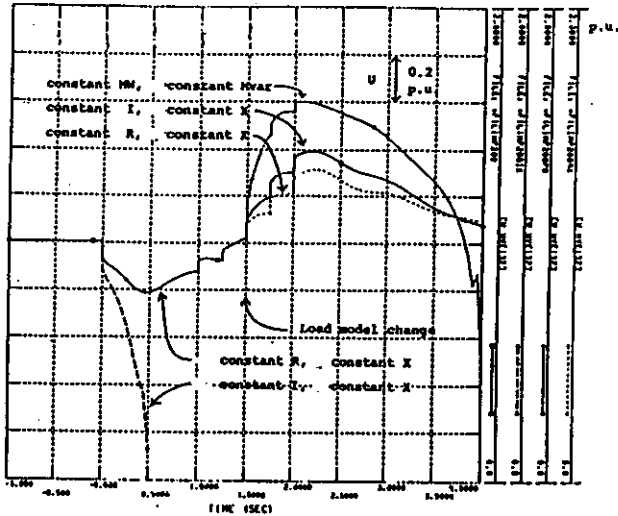


Fig. 3.12 : Voltage in case of tripping of tie lines, 5x10% load shedding, with 1600 MW load, 800 MW import, 200 Mvar from generators, no SVC, different load models

direct connection with the controlled quantity (here voltage).

Finally, Figures 3.17 and 3.18 show the case with load rejection. 50% of the generation is exported through the tie lines prior to their tripping. A high initial generator excitation reduces the overvoltages as in the previous examples. The SVC can limit the overvoltages so much that the initial jump in voltage is never exceeded.

3.7 SVC Installation aspects

For load centers having local generation and motor load, connected to the main grid via a high-impedance ($X_N > 0.3$ pu) transmission line, the installation of an SVC at the load center can contribute to the solution of the voltage collapse problem. Depending on the amount of motor load the minimum reactive power output (capacitive) of the SVC will be in order of 0.8 - 1.5 p.u. on the basis of the nominal rated power S_{GN} of the generator.

Special attention should be paid to the SVC-control. It is advisable to use additional signals derived from the powerflow in the transmission line or from the system frequency to compensate for the negative damping effect of the generator-AVR. The influence of frequency signals (or other stabilising signals) can be limited, or blocked, so as not to produce an excessive voltage reduction, without losing the overall damping improvement.

SVCs in smaller parts of an interconnected system are well suited to deal with overvoltages created by load

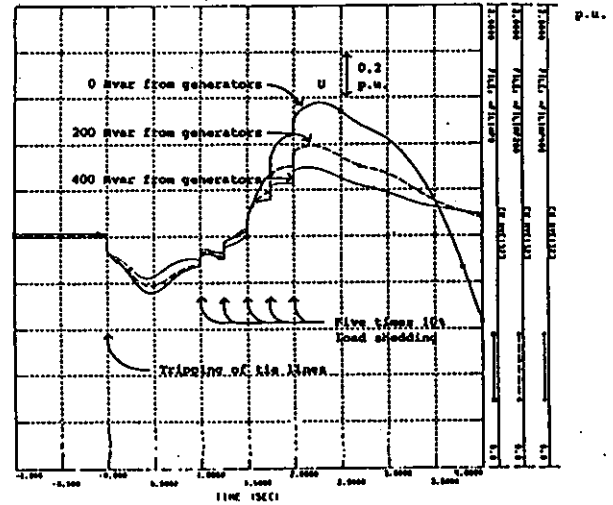


Fig. 3.13 : Voltage in case of tripping of tie lines, 5x10% load shedding, with 1600 MW load, 800 MW import, 0, 200 and 400 Mvar from generators, no SVC

rejection or load shedding as a result of splitting of the system. They will be efficient if located in the transmission network near the places where splitting of the system is likely to occur. Even a moderate SVC size of 1/4 of the interrupted Mvar will have an appreciable effect. However, the control of the SVC has to be coordinated with the voltage control of the generators, especially for dealing with the low voltages due to heavy overloads on the generators which can precede a load shedding.

3.7 Conclusions

SVCs are excellent means for preventing the voltage collapse in case of generator outage and induction motor starting in load centers being connected via a large impedance to a power system as well as for controlling overvoltages after load shedding and load rejection in interconnected systems. But likewise a high initial excitation on the generators will limit the occurrence of overvoltages. Whilst high initial generation excitation has been shown to be beneficial in the event of tripping of tie lines, it could be more critical for the loss of a generator.

During transients pure voltage control as provided by the usual SVC-AVRs is not sufficient to provide enough damping.

SVCs are not effective for controlling the voltage drops appearing in connection with frequency drops which occur before load shedding takes place. However, these low voltages can still be counteracted by using a high initial excitation on the generators.

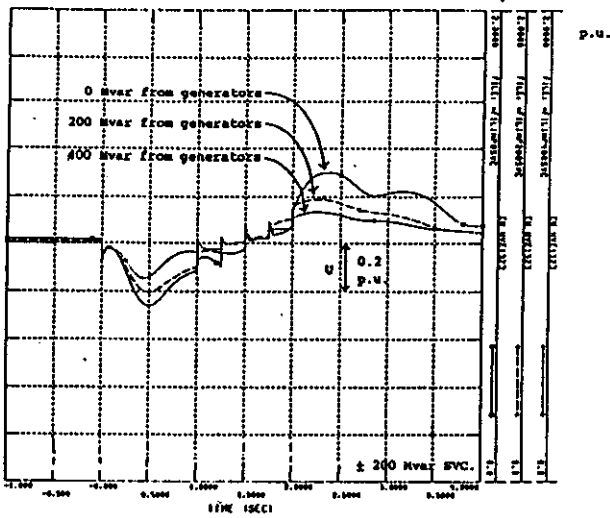


Fig. 3.14 : Voltage in case of tripping of tie lines, 5x10% load shedding, with 1600 MW load, 800 MW import, 0, 200 and 400 Mvar from generators, ± 200 Mvar SVC

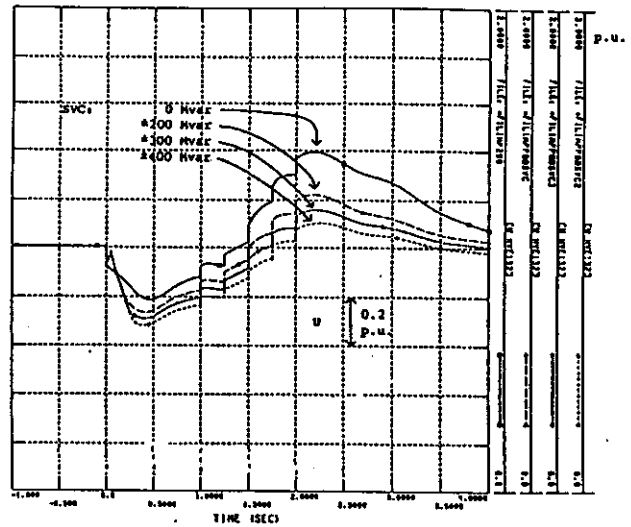


Fig. 3.16 : Voltage in case of tripping of tie lines, 5x10% load shedding, with 1600 MW load, 800 MW import, 200 Mvar from generators, different sizes of SVC: 0, ± 200 , ± 300 and ± 400 Mvar and frequency signal in SVC-control

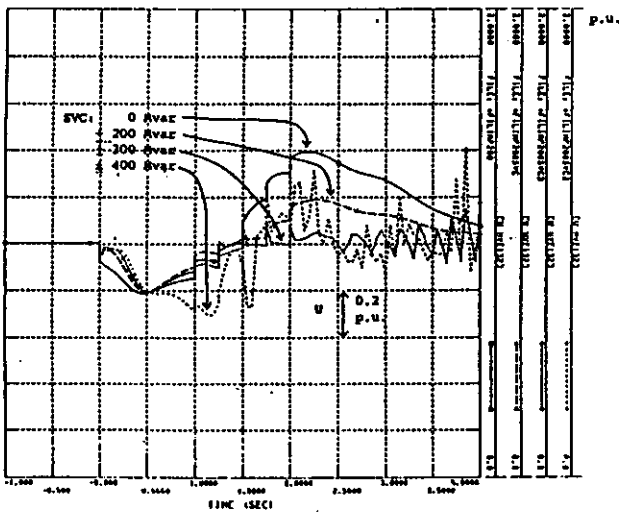


Fig. 3.15 : Voltage in case of tripping of tie lines, 5x10% load shedding, with 1600 MW load, 800 MW import, 200 Mvar from generators, different sizes of SVC: 0, ± 200 , ± 300 and ± 400 Mvar

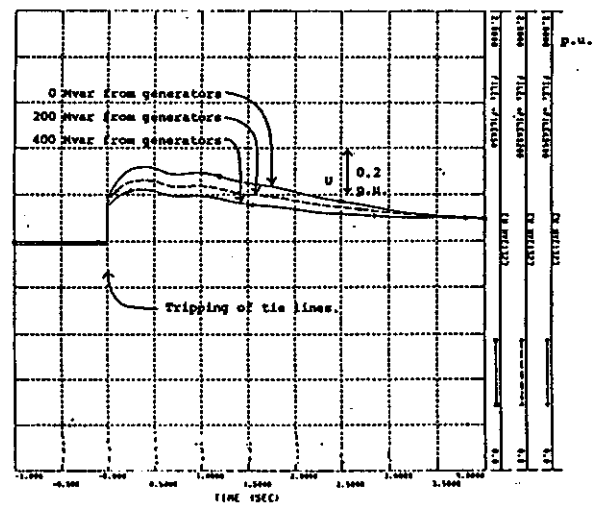


Fig. 3.17 : Voltage in case of tripping of tie lines, load shedding, with 800 MW load, 800 MW import, 0, 200 and 400 Mvar from generators, no SVC

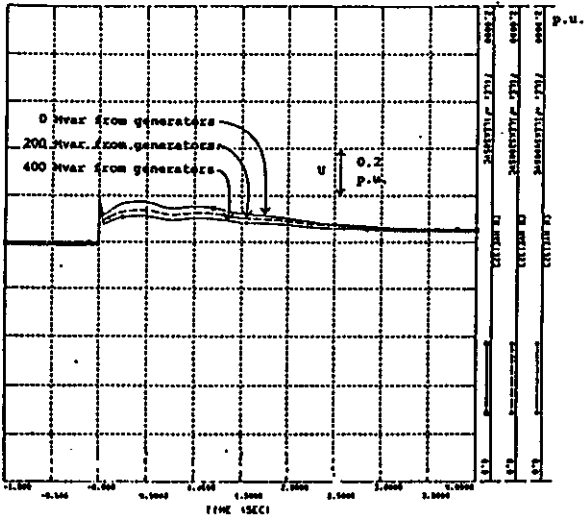


Fig. 3.18 : Voltage in case of load shedding, with 800 MW load, 800 MW import, 0, 200 and 400 Mvar from generators, SVC with \pm Mvar

CHAPTER 4

TRANSIENT AND TEMPORARY OVERVOLTAGE CONTROL

by

A. Schiappacasse (Italy - Coordinator)

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- 4.0 Introduction
- 4.1 Overvoltage control in interconnections between two weak systems
- 4.2 Voltage control in weak transmission systems
- 4.3 Higher flexibility of HVDC back-to-back links
- 4.4 Conclusions
- Appendix

4.0 INTRODUCTION

Perturbations such as three-phase fault, fault clearing, single pole operation, line energization, load rejection, line dropping and line opening in out-of-phase conditions produce transient and temporary overvoltages. The transient behaviour of the system under these typical perturbations is analyzed here both with and without the voltage control provided by the SVC. Different possible network locations of the SVC have been examined.

The studies described here cover the most typical cases and are based on investigations carried out both by means of digital computer programs and by means of a TNA interfaced with the SVC control boards typically used in the industry. Emphasis is directed towards highlighting the benefits of SVCs for control of transient and temporary overvoltages; in addition details on the adequate modelling techniques are presented.

4.1 OVERVOLTAGE CONTROL IN INTERCONNECTIONS BETWEEN TWO WEAK SYSTEMS

4.1.1 Problem Statement and Type of Network

The generic system to study this subject was a 550 kV interconnection between two weak systems, having a total length of about 1400 km (the network scheme is shown in Fig. 4.1). The network includes SVC, synchronous compensators and fixed reactors used for overvoltage control.

Two modes of SVC connection have been examined:

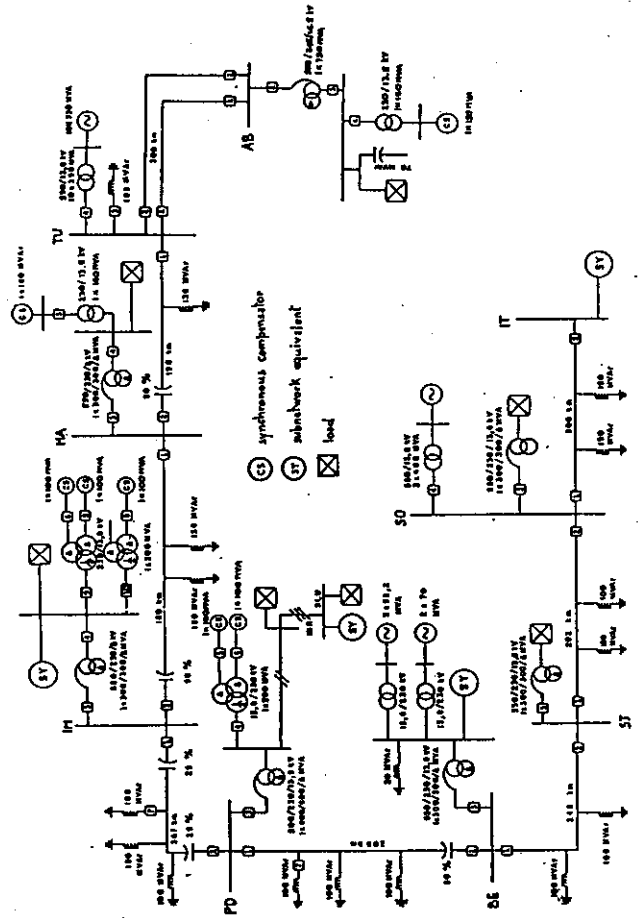


Fig. 4.1 : Network scheme

- 1) SVCs replacing the synchronous compensators at stations PD (2x100 Mvar) and IM (3x100 Mvar), but being connected to the 13.8 kV busbars;
- 2) SVCs replacing both the synchronous compensators and the line shunt reactors at stations PD (2x100 Mvar +3x100 Mvar +1x150 Mvar) and IM (3x100 Mvar +1x100 Mvar +1x150 Mvar), but being connected to the 550 kV busbars.

In order to evaluate the induced transient overvoltages on the system, for each of the above described configurations, the following predefined list of fault tests has been considered:

- single pole reclosing, mainly oriented to the evaluation of the secondary-arc extinction and phase-to-ground overvoltages;
- load rejection and line dropping;
- energization of lines and transformers;

- line opening in out-of-phase conditions.

4.1.2 SVC Scheme and Method of Analysis

The scheme of Static Var Compensator (SVC) utilized in the studies consists of Thyristor Controlled Reactors (TCR) with their necessary filtering circuits.

The inductive-capacitive range of the SVC has been predetermined on the basis of previous load flow and transient stability calculations.

The analysis has been carried out using a TNA (Transient Network Analyzer) for modelling all the network elements; the SVCs have been represented with a detailed analog model interfaced with the TNA as described in the appendix.

4.1.3 Tests carries out and Results

The tests have been performed on line from station IM to station PD.

Single pole reclosing

The most significant results are given in Fig. 4.2.

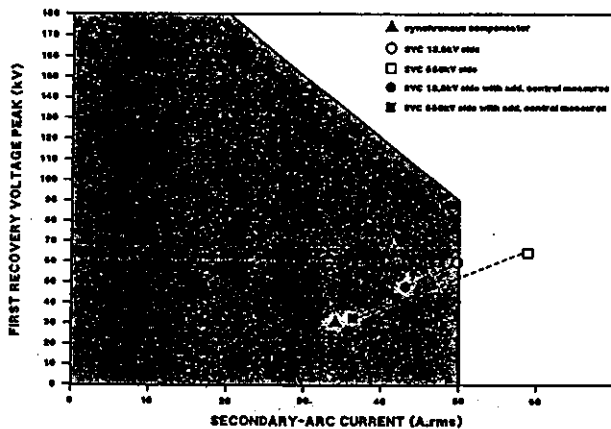


Fig. 4.2 : Single pole reclosing tests

The shaded area represents, for this particular 550 kV system, the zone where the secondary-arc has the maximum extinction probability within a time of 500 ms as given by experimental data.

This area is defined by the values of the first recovery voltage peak of 180 kV, the secondary-arc current of 50A and by the arc characteristics of the line insulators.

The following conclusions can be drawn:

- SVCs are effective for secondary arc extinction if the harmonic current injections are minimized by additional control measures (TCRs in full conduction during fault clearing) or by connecting the SVCs to the 13.8 kV side of stepdown transformer;

- SVCs are effective for reducing recovery overvoltages if properly rated and controlled.

All the tests have been executed without surge arresters in order to evaluate the overvoltage stresses which can be imposed on the arresters.

Load rejection and line dropping

SVCs equipped with no additional control measures do not improve the overvoltage situation, as indicated in Fig. 4.3.

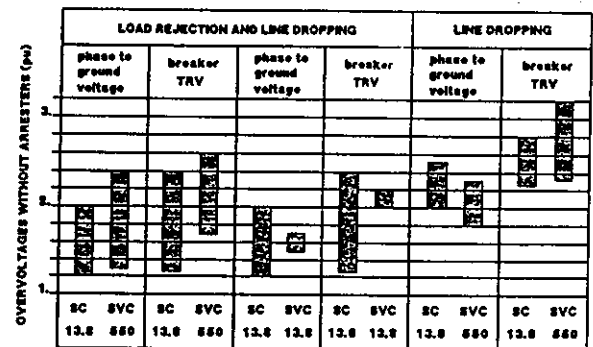


Fig. 4.3 : Load rejection and line dropping tests

In some cases breaker TRV can reach 3.2 pu, but this may still be within acceptable limits. SVCs connected to the 13.8 kV side of step-down transformer offer in this case a considerable reduction of overvoltages.

Energization of lines

The influence of some of the SVC regulator parameters on the overvoltages was investigated. In Fig. 4.4 the results relates to the integration time constant τ of a generic PID controller to be used in the regulation scheme. As can be seen, the overvoltages with the SVC in service are higher than those for the case with line reactors (and synchronous compensators).

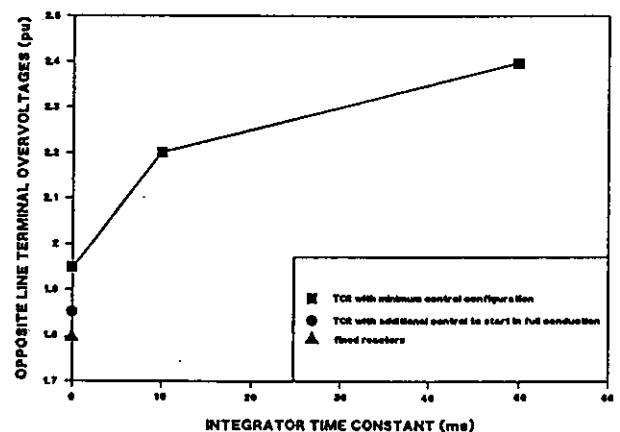


Fig. 4.4 : Line energization tests

The overvoltages are influenced considerably by the PID controller parameters: it was assumed a normal range for τ from 10 to 15 ms. The adoption of the control measure to start the TCRs in full conduction is effective for controlling energization overvoltages. Implementation of this measure, however, is complicated due to the need to transmit the corresponding command signals over a long distance. The SVC transformer characteristics also influence the overvoltages; in particular a transformer with winding connections star-neutral-earthed/delta further reduces these overvoltages but such connection is inconsistent with the problem of the secondary-arc extinction ($X_o/X_1 \ll 1$) during single pole reclosing.

Line opening in out-of-phase conditions

This transient analysis was performed assuming that a line opens following a single phase fault and then recloses. Line opening is performed by a circuit breaker located close to the electrical center of the interconnection (station PD). The most significant results for this case are summarised in Figure 4.5.

| line to ground voltage after opening | breaker Transient Recovery Voltage (pu) | | |
|--------------------------------------|---|--------------|---------------|
| | synchr. cond. | SVC on 550kV | SVC on 13.8kV |
| 1.2 pu | < 3.0 | < 3.3 | 2.95 |
| 1.4 pu | | 3.6 | 3.75 |

Figure 4.5 : Line opening in out-of-phase conditions

With SVCs connected on the 550 kV side the overvoltages are close to their acceptable limits; the TRV across the line circuit breakers is, however, generally higher with SVCs than with traditional shunt compensation by means of synchronous compensators. This is because the line voltage is very low just before the opening operation and therefore the TCRs are at minimum conduction, unless additional signals are adopted to force the TCRs into full conduction before the opening of the line.

4.2 VOLTAGE CONTROL IN WEAK TRANSMISSION SYSTEMS

4.2.1 Problem Statement and Type of Network

The generic system to study this problem was a long weak transmission system feeding a load area supported by an SVC of the TCR+MSC type, rated +105/-45 Mvar, connected to the 132 kV double-circuit transmission line (see Fig. 4.6).

The transmission system transfers low-cost power from a large system (2400 MW generation capacity) to an industrial load area of 146 MW, located 600 km away. The load area has a generation capacity of 112 MVA,

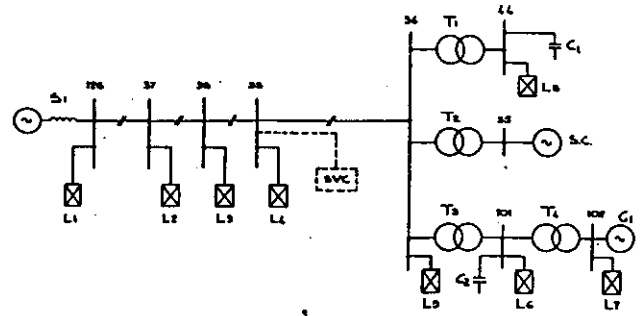


Fig. 4.6 : Network scheme

2x9 Mvar capacitor banks and 2x40 Mvar synchronous compensators. At the intermediate substations along the transmission lines, a total load of 40 MW is also supplied. Rating of SVC was selected to increase transmission capacity from 62 MW to 88 MW.

The performed tests included:

- three-phase fault to ground;
- single pole reclosing;
- load rejection;
- line energization.

4.2.2 SVC Scheme and Method of Analysis

The scheme of Static Var Compensator utilized in the studies consists of Thyristor Controlled Reactors (TCR) with their necessary filtering circuits. The transient overvoltage studies have been carried using both, TNA and EMTP, in order to compare the results; the adopted modelling techniques are described in the appendix.

4.2.3 Tests carried out and Results

Three phase fault

The system has been assumed to be in normal condition and the following perturbation has been considered:

- 0 ms : three phase fault to ground on line 35-36;
- 60 ms : insertion of HV capacitor bank at bus 35;
- 80 ms : fault clearing by switching out the faulted line.

Fig. 4.7 presents significant results of the TNA tests. Note that, at fault initiation, the SVC regulator output is forced to zero in order to limit the transient overvoltages when the fault is removed.

Single pole reclosing

The sequence of perturbations is as follows:

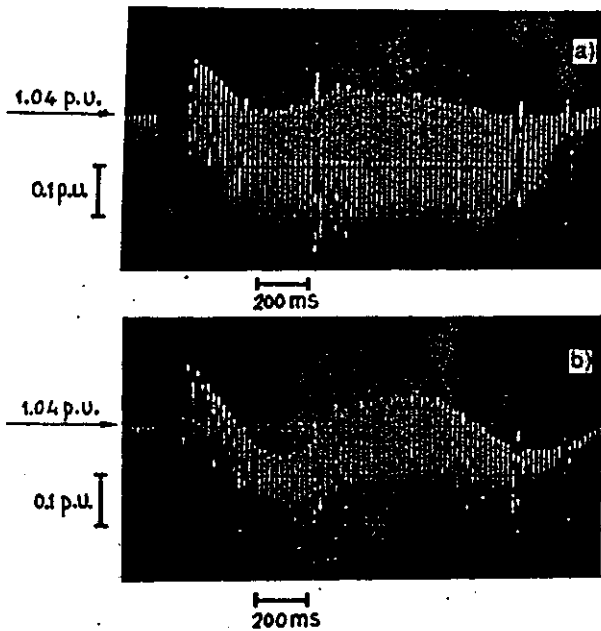


Fig. 4.7 : Three phase fault tests

- 0 ms : fault initiation on phase R of line 35-36;
- 120 ms : single pole opening;
- 680 ms : successful reclosure.

Fig. 4.8 shows the SVC response to this event using the two models (A analog, D digital) adopted for this study. For this system configuration, the possible presence of harmonics in the secondary-arc current during single pole operation does not cause any particular problem. In fact, most of the harmonic currents are caused by saturation of the transformers connected at bus 36 and not by the TCR operation.

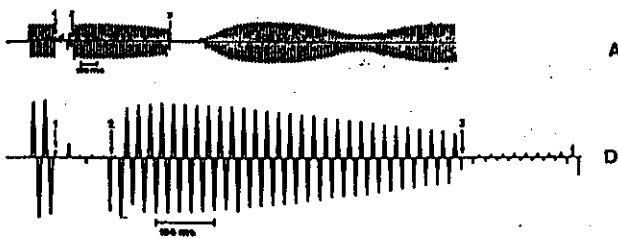


Fig. 4.8 : Single pole reclosing tests

Load rejection

A load rejection case has been considered with only one circuit in service between nodes 35 and 36. Fig. 4.9 shows some of the results obtained with TNA. It is worthwhile to mention that during the load rejection conditions, the TCR might reach its ceiling and thus stop its regulating action. It was also found that, if the TCR rating is increased to 115 Mvar, the SVC will always remain in regulation; proper sizing of the

SVC could be an important design consideration by this point of view.

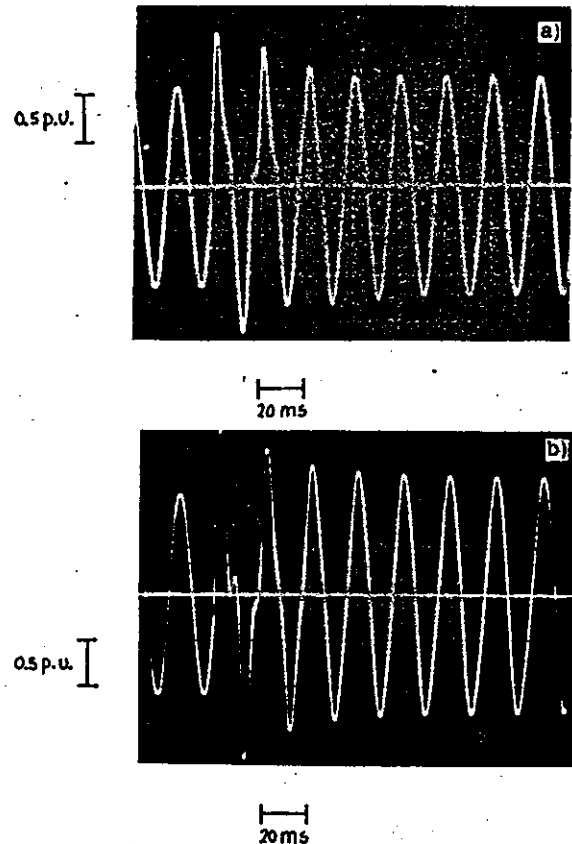


Fig. 4.9 : Load rejection tests

Energization of lines

Energization of the first line connecting nodes 35 and 36, starting from bus 35, was considered. Fig. 4.10 shows some of the results obtained with TNA. While the magnitude of overvoltages on the 132 kV system is not of concern, problems might arise due to their duration. The presence of the SVC limits temporary overvoltages to less than 1.05 pu, instead of 1.18 p.u. without the SVC. Another input, when designing, could be derived from these tests; it deals with the stability of the control scheme.

4.3 HIGHER FLEXIBILITY OF HVDC BACK-TO-BACK LINKS

4.3.1 Problem Statement and Type of Network

The problem studied concerns two interconnection, see Fig. 4.11, between the UCPTE network in Austria and the east european CMEA network; these interconnections include one at Wien Süd-Ost to Hungary and the other at Dürnröhr to Czechoslovakia.

This section is an abstract from a paper written by Dr. G. Moraw, Austria; see [17].

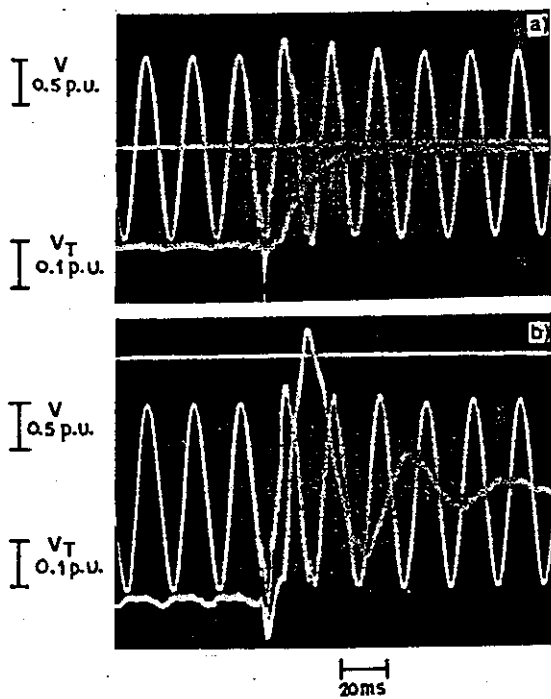


Fig. 4.10 : Line energization tests

Both interconnections are HVDC back-to-back links having a power rating of 550 MW each. To increase the flexibility of system operation an SVC, of TCR type having continuous power capability of 150 Mvar and short-time (500 ms) power capability of 580 Mvar will be installed at Dürnrrohr. This device will allow the connection of both HVDC links via a single 400 kV line to Hungary or to Czechoslovakia, as well as a parallel operation of the HVDC link at Dürnrrohr with the hydro power plant of Altenwörth.

During the planning phase several possible configurations have been investigated. Since under certain operating conditions the short circuit power on the east side of the HVDC links is very limited, high overvoltages can arise upon load rejection of one or both HVDC links. In this regard, studies have been performed to verify that the installation of a TCR with low order harmonic filters could solve the following problems:

- intolerable 50 Hz overvoltages
- resonances for low-order harmonics
- self-excitation of generators
- severe stresses for circuit breakers and arresters

4.3.2 SVC Scheme and Method of Analysis

An SVC of the TCR type has been located at the 400 kV busbar of Dürnrrohr; it consists of two groups of 3

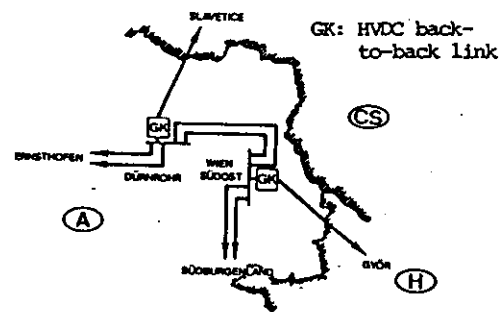


Fig. 4.11 : Network scheme

single phase reactors, each connected to one of the two secondary windings of a 400/16/16 kV transformer. Reduction of the low order harmonics is required for successful load rejection; this is accomplished with special filters installed at the 400 kV busbar. These additional filters are tuned for the 2nd and 3rd harmonics and are connected in parallel with the high-pass filters provided as part of the SVC installation. The SVC control principle is based on a constant voltage regulation. The analysis has been carried out using EMTP.

4.3.3 Simulations carried out and Results

Four possible operating configurations were analyzed.

Configuration 1

It is assumed that the system east of the HVDC link at Dürnrrohr (Austria) is connected to Győr (Hungary) using an auxiliary bus at Dürnrrohr, the 400 kV line Dürnrrohr - Wien Süd-Ost, an auxiliary bus at Wien Süd-Ost, and the 400 kV line Wien Süd-Ost - Győr. Alternatively, a connection of Wien Süd-Ost (Austria) with Slavetice (Czechoslovakia) could be operated.

Configuration 2

This configuration represents a parallel operation of the HVDC links at Dürnrrohr and Wien Süd-Ost to Hungary (or alternatively to Czechoslovakia).

Configuration 3

In this case, Slavetice is connected to Győr via Austria. Both HVDC stations are linked on their east side to this connection.

Configuration 4

This configuration connects the hydro power plant Altenwörth with Slavetice, including simultaneous export operation of the HVDC link at Dürnrrohr.

For configuration 2, the simultaneous load rejection of the HVDC links at Dürnrrohr and Wien Süd-Ost produces overvoltages up to 2.02 pu, which are un-

tolerable. For configuration 4, load rejection causes the Altenwörth hydro-generators not only to accelerate but to absorb MVARs produced by the filters of the HVDC link; this condition can result in self-excitation of the generators preventing further voltage control. This problem can be solved by the use of a suitable reactor. Since a conventional reactor circuit breaker is not fast enough, and since a variable amount of reactive power is needed for the different configurations, only a TCR can be used. The simulation of such load rejection cases is shown in Fig. 4.12 for configuration 2 and in Fig. 4.13 for configuration 4. These studies have been repeated with a TCR in service; as can be seen in Fig. 4.14 and 4.15, the load rejection overvoltages are reduced well below the limit of 1.3 pu.

These results show that the presence of a TCR device reduces the load rejection overvoltages to acceptable values.

As a result of this analysis it has been decided to install a TCR at Dürnröhr. This installation provides operational and economic advantages compared to alternative solutions such as ZnO-arresters, synchronous compensators, high-voltage resistors.

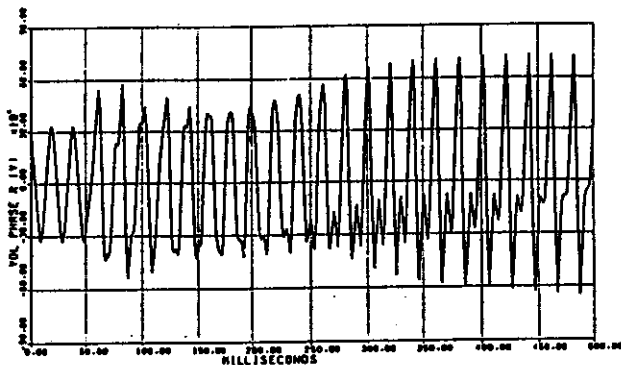


Fig. 4.12 : Load rejection case for configuration 2

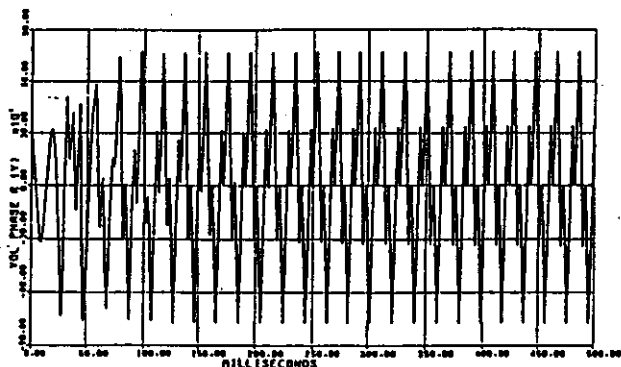


Fig. 4.13 : Load rejection case for configuration 4

4.4 CONCLUSIONS

This chapter focuses on the application of SVCs for

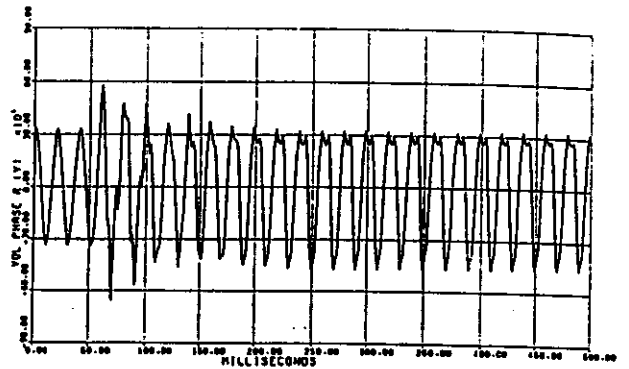


Fig. 4.14 : Load rejection case for configuration 2 with TCR

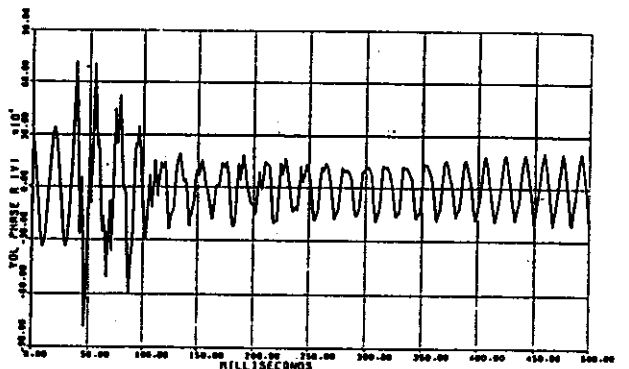


Fig. 4.15 : Load rejection case for configuration 4 with TCR

control of transient and temporary overvoltages caused by fault clearing, single pole operation, line and transformer energization, load rejection, line dropping and line opening in out-of-phase conditions.

The transient responses produced by these perturbations have been analyzed:

- both with and without the fast voltage control provided by SVCs;
- comparing SVCs with other, traditional solutions;
- using a variety of significant system configurations;
- using different simulation tools (analog/digital).

General conclusions and guidelines are that an SVC can reduce temporary overvoltages in all cases studied. It can also reduce transient overvoltages in almost all cases if certain measures to improve the SVC control are considered. Furthermore, both the type of the SVC connection to the network and its operating condition preceding the perturbations have an important influence on the effectiveness of the overvoltage control. Emphasis has to be directed to the modelling of the SVC and, in particular, to its control system. If a TNA is used, it is recommended to perform these studies interfacing the TNA with the SVC control module provided by the manufacturer. With regard to single pole reclosings, the presence of TCRs

may impede extinction of the induced secondary-arc due to the presence of TCR harmonic currents, unless additional control measures, such as forcing the TCR into continuous conduction, are provided. With regard to load rejections and line droppings, attention must be paid to the TRV of the involved circuit breakers, due to SVC operation. With regard to energizations, it should be pointed out that the overvoltages are influenced considerably by the parameters of the SVC regulators. In general, additional SVC control measures should be considered to obtain optimal performance for all conditions, including short circuit faults.

APPENDIX:

SVC MODEL FOR TNA STUDIES

The functional block scheme of the model for TNA is shown in Fig. 4.16; details about each single functional block are presented in the following.

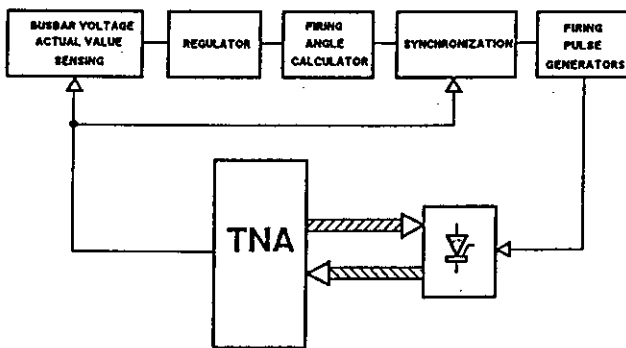


Fig. 4.16 : Functions to be included in the TNA model

TCR model

The power components of the SVC have been modelled on the TNA with the usual technique and interfaced with an SVC control board provided by the SVC manufacturer to drive the models of the thyristor valves. Electro-optic couplers have been adopted in order to isolate the ground of the TNA model from that of the control board. The thyristor valves have been modelled with solid state switches representing the thyristor characteristics. A schematic representation of the model implemented on the TNA is given in Fig. 4.17.

Control system

The control system was represented using real components provided by the manufacturer. This procedure enables complete and real simulations of system components, thus avoiding simplifications which are usually required with general purpose models and which could affect the results.

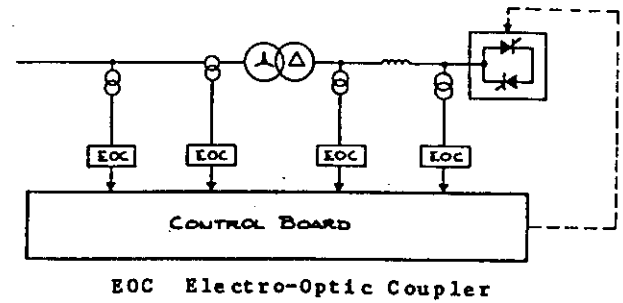


Fig. 4.17 : Interfaces between TNA and SVC control board

Sensing circuit for the actual value of the busbar voltage

This circuit, achieving a "three-phase control", consists of a section eliminating the zero sequence voltage component and a section which combines the measured three phase voltages to produce a single controlling voltage signal. This controlling signal is produced by a rectifier and an amplifier followed by an optocoupler. The optocoupler avoids the existence of a path to ground between the measuring and regulating circuits, and reduces the induced noise. All functions for this control section have been realized through suitable electronic circuits specifically designed for interfacing with the TNA.

Regulator

The TNA model used only the I (Integration) action of a PID controller to obtain an evaluation of the influence that this part of the regulator has on transient overvoltages. Different values of the integrator time constant, which is usually considered the most critical in the control design, have been considered in order to examine the effect of that parameter on overvoltages. Also this part of the control scheme has been specifically designed for the TNA interface.

Firing angle calculator and synchronization

The firing angle is simply calculated through a function generator block having as input the regulator output signal. This model was specifically developed for the TNA from the general principles outlined by the manufacturer of the SVC control system. The actual value of the angle is then transmitted to the synchronizing section of the control model which, in turn, provides the timing for the subsequent firing pulse generators. The synchronizing unit was constructed using the real components made available by the manufacturer.

Firing pulse generators and thyristors

Both of these models have been specifically designed for interfacing to the TNA; they are significantly different from, and considerably less complex than, the real components. These models replicate well the real

behaviour of such control sections.

SVC models for digital studies

The SVC power components have been simulated using the electrical network section of EMTP while the TACS control functions have been used for the simulation of the control board adopted for the TNA studies. The control functions have been constructed by a network composed of logical and algebraic blocks and by equivalent transfer functions. The control network accepts signals from the power system and drives the thyristors by generating timed firing pulses. Fig. 4.18 shows schematically the flow of signals between the power system and the control network, and illustrates the basic functions of control. The control functions implemented in the digital model are: the voltage transducer, the regulator (of the P.I.D type), the linearization function (creating the inverse function of reactive power vs. conduction angle), the synchronizing control, the balancing control (compensating dc components), the blanking control (inhibiting firing before the peak value of the voltage occurs) and the firing pulse generator.

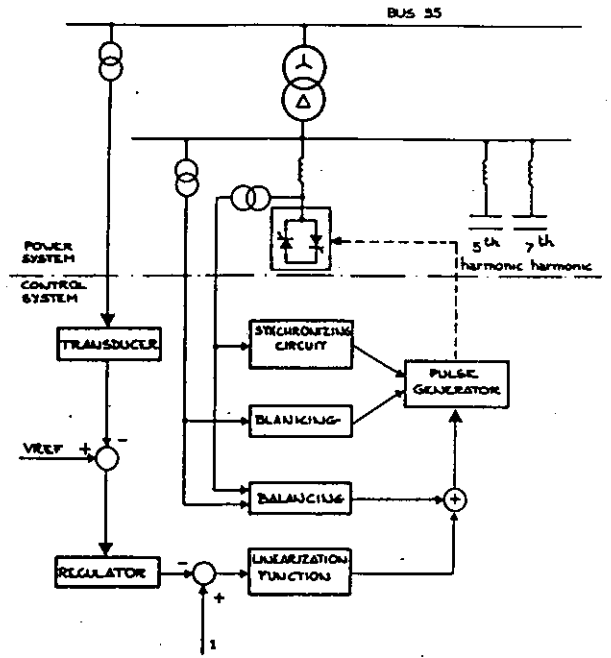


Fig. 4.18 : Scheme of the digital model of SVC control

CHAPTER 5

IMPROVING FIRST-SWING TRANSIENT STABILITY

by

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- 5.1 Introduction
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A study of a generic case
 - 5.3 Use of dispersed SVCs to enhance transient stability of a long EHV point-to-point transmission system
 - 5.4 Published works
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- Appendices

5.1 INTRODUCTION

Voltage control is the primary purpose of the majority of transmission SVCs. Some SVCs also provide improvement of transient stability by increasing synchronizing power margins and by providing damping of machine rotor oscillations subsequent to disturbances. There are, however, very few cases, if any, of existing long-distance transmission systems with a severe stability criterion applied, where an SVC has been installed primarily to ensure first-swing stability.

This chapter focuses on the use of SVCs to ensure first-swing transient stability in severe cases. Section 5.2, "The use of a single SVC versus other means: A study of a generic case", deals with an EHV long-distance radial transmission from a power station into a relatively large system. The use of a single SVC installation at a mid-point bus is compared with the use of an additional parallel line and with the use of series capacitors.

Section 5.3, "Use of dispersed SVCs to enhance transient stability of a long EHV point-to-point transmission system", treats an EHV transmission similar to that in section 5.2 but with dispersed SVCs at four stations.

Section 5.4, "Published works", gives some guidance for literature on the use of SVCs for improving first-swing stability. Finally section 5.5, "Conclusions", summarises the essential findings.

An endeavour has been made in the following to express quantities in per unit (p.u.) in order to make the results as generic as possible. The surge-impedance load (SIL), or natural load, of one transmission line has been chosen as p.u. power base.

5.2 THE USE OF A SINGLE SVC VERSUS OTHER MEANS: A STUDY OF A GENERIC CASE

A 50 Hz power system with two 600 km, 400 kV lines from a power station into a relatively large system was studied. This type of transmission was chosen because the problem of first-swing transient stability is pronounced in such cases, if a severe stability criterion is applied.

The use of SVC was compared with the use of an additional parallel line and with the use of series capacitors for increasing the stability limit.

The p.u. power base used in this section is the SIL of one line: 550 MW at 400 kV.

5.2.1 System Studied and Assumptions

Fig.5.1 and Appendix 5-I give the main characteristics of the power system studied.

It was assumed that a hydro power station is located at the sending end and thermal power stations are located in the larger receiving system. Further, it was assumed that there is an intermediate switching station in the 400 kV transmission system.

For each study case appropriate passive shunt compensation of the transmission system was assumed by using fixed shunt reactors or capacitors at bus C to obtain a pre-fault voltage profile of 1.03, 1.015 and 1.00 p.u. at buses A, B and C, respectively. The simplicity of this approach has no significant influence on the comparisons made.

The sending-end equivalent generator was equipped with a fast-acting excitation system, including a static exciter with a ceiling voltage of 5 p.u. An excitation system transient gain of 30 was assumed. A power system stabilizer (PSS) was also included.

The receiving-end equivalent generator was equipped with a slow-acting excitation system, including a rotating DC exciter. A slow-acting turbine governor system was also included.

Since the above control systems have only a second-order influence on the first-swing stability, the detailed

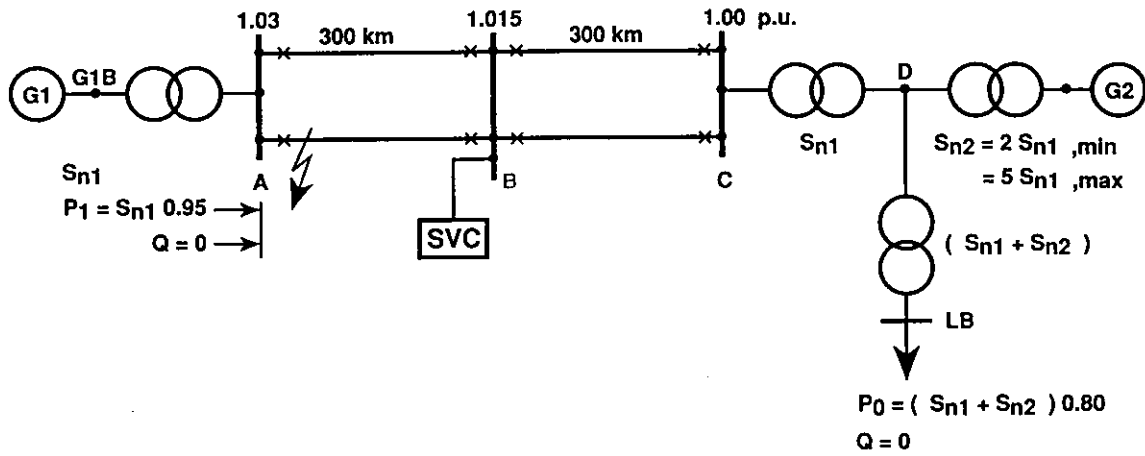


Fig. 5.1 : System studied, section 5.2

data for these systems are not included in this report.

The SVC alternative:

In the simulations one equivalent SVC was connected at the transmission midpoint. In practice two parallel-operating SVCs at the midpoint may be preferable to ensure availability. Fig.5.2 and Appendix 5-II provide the details of the SVC representation.

A straightforward voltage control, as in Fig.5.2, will cause the SVC to hit the limit B_{max} during the fault time, when a severe voltage depression appears. In order to minimize overvoltages during one power-frequency cycle, or so, after the fault clearing, it is usually advisable in applications like this to control the SVC to B is equal zero (no SVC current) or to B is less than zero (absorption) upon severe voltage depressions.

Furthermore, in order to take full advantage of the SVCs ability to increase the synchronizing power during the critical first swing, it is advisable for applications like this to endeavour to control the voltage to a higher than normal value during the first half of the first swing after the fault has been cleared. Damping action by the SVC was not included in this study; however, continued "bang-bang" control until the power oscillation has declined below a certain level, may provide improved system damping.

In this study both actions discussed above were simulated by changing the voltage reference. A bus voltage of 1.3 p.u. was allowed for 0.5 seconds.

The series capacitor alternative:

For real life series capacitor applications, the choice of location may require a special study with respect to overall economy and system security, taking into account voltage profile, compensation effectiveness, losses, fault currents, overvoltages, proximity to attended stations, etc.

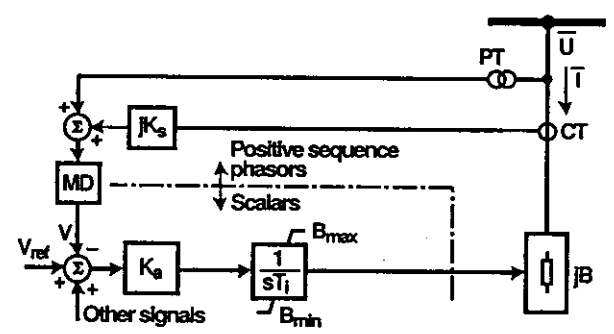


Fig. 5.2 : SVC representation (MD = measuring device)

In this study the series capacitors were located at the midpoints of the line sections. Other possible line locations would not significantly influence the results of this study.

Stability criterion applied:

The system shall be stable for a three-phase line short-circuit at the sending end, cleared after 0.1 seconds by permanently disconnecting the faulty line section.

Study technique and tools:

"Existing" system, two lines:

Find the stability limit, i.e. the maximum pre-fault real power, which can be transmitted stably after the disturbance.

Third line:

Find the stability limit.

SVC:

Find the required SVC size to match the stability limit with a third line.

Series capacitors:

Find the required degree of line series compensation to match the stability limit with a third line.

General purpose power flow and transient stability programs were used.

5.2.2 Simulation Results

The following results were found for a receiving-end to sending-end system MVA ratio (S_{n2}/S_{n1}) of 2.

“Existing” system, two lines:

The transmission stability limit was found to be approximately 0.80 p.u. (on SIL base of one line). The pre-fault voltage angle difference, i.e. the difference in voltage angles of the buses G1B and D, was 31 deg.

Third line:

Stability limit was 1.50 p.u. Pre-fault voltage angle difference was 35 deg.

SVC:

The required SVC capacitive range Q_{cmax} was found to be approximately 1.10 p.u. (on SIL base and as referred to 1.00 p.u. voltage). Pre-fault voltage angle difference was 45 deg.

The stability limit of 1.50 p.u. corresponds to a pre-fault individual line loading of 0.75 p.u. and a post-fault line loading of 1.50 p.u. for the retained single line section.

Fig.5.3 illustrates the SVC and power system performance for a case fairly close to the stability limit.

Series capacitors:

The required degree of line series compensation was found to be approximately 40 % of the line inductive reactance. Pre-fault voltage angle difference was 33 deg.

The studies for a receiving/sending system MVA ratio of 5 gave about the same results, but the required SVC capacitive range Q_{cmax} had to be increased from 1.10 to 1.18 p.u.

5.2.3 Cost Comparison

Basis for comparison:

“Existing” system, two lines:

The line losses (2 lines) at the transmission stability limit loading of 0.8 p.u. were 7 MW.

Third line:

A 600 km, 400 kV line plus switchyard bays etc.

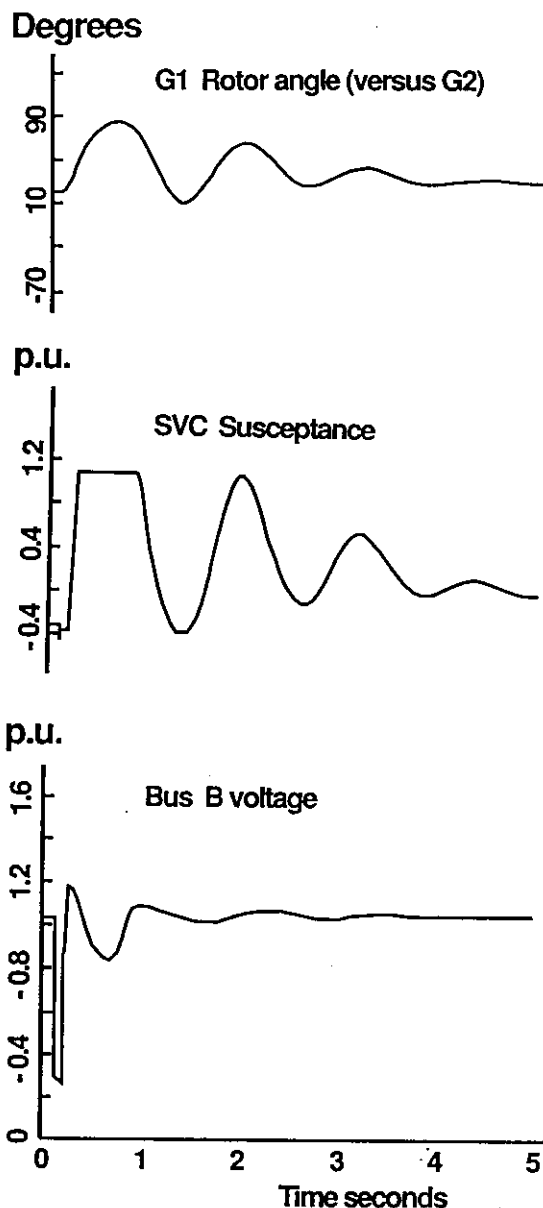


Fig. 5.3 : SVC and power system performance for a case close to the stability limit (4T33)

The line losses (3 lines) at the transmission stability limit loading of 1.5 p.u. were 17 MW.

SVC:

The required value $Q_{cmax} = 1.10$ p.u. corresponds to 600 Mvar capacitive capability at 400 kV. Considering the short time of operation at maximum current, the SVC capacitive rating has been set at 0.75 times 600 Mvar. The figure 0.75 is from a coarse estimate.

The SVCs have a total, 200 Mvar inductive to 450 Mvar capacitive capability at 400 kV.

The line losses (2 lines) at the transmission stability limit loading of 1.5 p.u. were 25 MW.

Series capacitors:

The power rating Q_n of each capacitor station was determined by

$$Q = 3I^2 X_c \quad (5.1)$$

where

I = Total transmission current at the stability limit divided by 1.35. The constant 1.35 is applied to take advantage of the short-time overload capability of series capacitors. (Cf. 1987 Revision of IEC Publ.143.) It was assumed that the disconnected line section will be reconnected within 30 minutes or the transmitted power reduced within that time. Despite the dividing by 1.35, the capacitor voltage, due to the so-called swing current during the first seconds after a line fault, will be below the protective level of the capacitor overvoltage protection, if the latter is properly designed.

X_c = Capacitor reactance per phase

There are 4 series capacitor stations installed, 100 Mvar each.

The line losses (2 lines) at the transmission stability limit loading of 1.5 p.u. were 25 MW.

A comparison:

It should be emphasized that it is difficult to make a generic cost comparison. Line costs may vary much, losses are evaluated differently by different utilities and equipment market prices are different from country to country. While this comparison should be considered as an example for an industrialized country, it provides a general indication of relative costs of the means studied.

Estimates of initial capital expenditure plus present worth values of increased losses, operation and maintenance were made for the three alternatives studied. The estimates gave the following cost relationship:

Third line/SVC/Series capacitors = 1.00/0.27/0.20

Both line investment cost and line loss cost are very influential on the cost comparison. The line cost calculations were based on the following 1990 main cost figures:

- Investment cost: 2.0 MSEK/km
- Loss cost: Loss factor 0.40, 225 SEK/MWh
- Interest: 8%
- Economic life: 30 years

(6 SEK was approximately equal to 1 US \$)

5.2.4 Discussion of Section 5.2

The study was limited to a 600 km, 400 kV transmission system. Two receiving/sending system MVA ratios and one SVC location were considered. A comprehensive study should, of course, consider other conditions and parameter values. However, the cost relationship would not change radically.

The third line alternative:

Adding a third line may not be feasible within the same time frame as installing the SVC or the series capacitors.

The SVC alternative:

Theoretically, the location for a single SVC should be at the electrical midpoint of the post-fault circuit. In practice, one is restricted to a few discrete buses only and has to consider different contingencies and fault locations. In real cases, the SVC location has to be determined from studies that balance all of these considerations.

The series capacitor alternative:

The four series capacitor installations in this study are very small, making the cost per rated kvar high. Transmission systems requiring larger stations would further decrease the relative cost figure of the series capacitor alternative.

If the sending-end power station were a thermal power station, possible subsynchronous resonance phenomenon might require countermeasures, increasing the series capacitor costs.

5.3 USE OF DISPERSED SVCs TO ENHANCE TRANSIENT STABILITY OF A LONG EHV POINT-TO-POINT TRANSMISSION SYSTEM

For the 1987 CIGRE Symposium on "AC/DC Transmission Interactions and Comparisons" [18], a study was carried out in order to focus on the factors affecting the overall AC and DC transmission system reliability. In the course of the study the behaviour of a long-distance point-to-point 50 Hz AC transmission system was examined.

This section describes the AC system studied and summarizes the criteria adopted and the calculations made to define the reactive compensation means needed to ensure steady-state and transient stability.

The p.u. power base used in this section is the SIL of

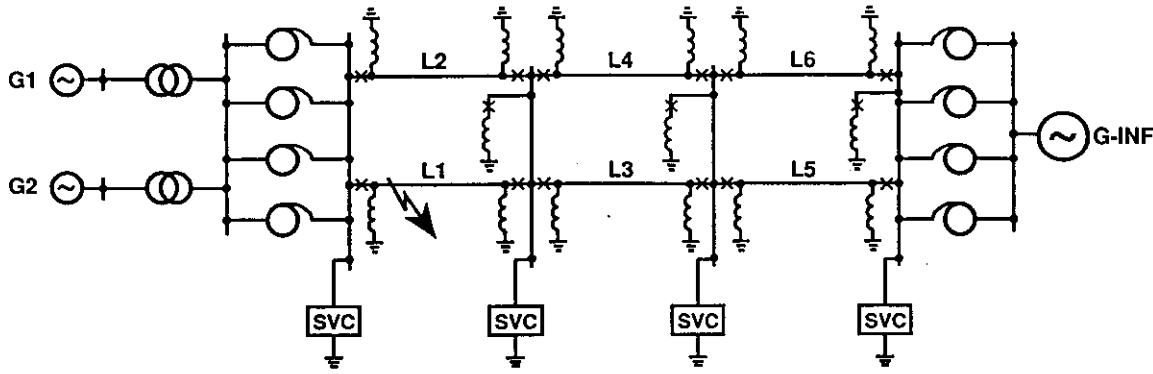


Fig. 5.4 : System studied, section 5.3

one line: 1070 MW at 500 kV (4 conductors/phase).

5.3.1 System Description

Fig.5.4 shows the power system studied. It is comprised of:

- A 1500 MW (1.4 p.u.) mine-mouth coal-fired generation plant with two thermal units.
- Two 900 km, 500 kV transmission lines, each divided into three sections of 300 km. The transmission system includes autotransformers at the sending and receiving ends.
- A large and strong receiving-end system, modeled as an infinite bus.

The representation of the generators included their AVR and PSS, the latter with frequency and electric power input signals.

5.3.2 Criteria

The reactive compensation means and ratings were determined using the following criteria:

- Transmission energization shall be accomplished through energization of one line section at a time, preferably starting from the receiving end. The second line shall not be energized until the first line is loaded.
- At no-load steady-state conditions, the transmission voltages shall be within +/- 10 % of the nominal voltage. At heavy-load conditions, the voltages shall be within +/- 5 % of the nominal voltage.
- During heavy-load conditions the generators shall be operated lightly overexcited.
- Dynamic shunt compensation by means of dispersed SVCs shall ensure transient stability for the following operating conditions:
 1. Peak continuous loading of 1.4 p.u. during normal (i.e., all facilities in service) conditions.

2. Reduced continuous loading for "n-1" and "n-2" outage (i.e. contingency) conditions. The system may have to be operated at a peak loading of 1.4 p.u. for a short time following a single contingency until the power transfer is reduced.

- The disturbance shall be:

1. A three-phase short-circuit fault on a line section closest to the generating plant.
2. Fault clearance by tripping the circuit breakers at the two ends of the faulted line section after 0.10 and 0.13 seconds, respectively.

5.3.3 Study Results

Steady-state conditions:

The study indicated the need for fixed, line-connected shunt reactors with a total power rating of 1.12 p.u. (on SIL base) and bus-connected, breaker-switched shunt reactors with a total power rating of 0.28 p.u., the latter being disconnected during heavy loading conditions.

Transient stability:

For the peak loading of 1.4 p.u. during normal conditions it was found that one SVC with a capacitive range $Q_{cmax} = 0.56$ p.u. (on SIL base and as referred to 1.00 p.u. voltage) is needed at each of the four buses.

For the peak loading of 1.4 p.u. during specified contingency conditions it was necessary to use $Q_{cmax} = 0.70$ p.u. Using SVCs with $Q_{cmax} = 0.56$ p.u. (rather than 0.70 p.u.) lowers the stability limit from 1.40 p.u. to 1.26 p.u. during contingency conditions.

The analysis evidenced the need for dynamic shunt reactive power injections to maintain the voltages at transmission substations during the critical first swing

after severe disturbances.

5.3.4 Concluding Remark of section 5.3

The study has shown that SVCs can improve transient stability of the system. A total short-time reactive power injection from the SVCs of 2.24 to 2.80 p.u. (on SIL base and as referred to 1.00 p.u. voltage) would be needed to provide a stability limit of 1.4 p.u. Series compensation could be much more cost effective in this application, however, if first-swing stability were the only concern.

5.4 PUBLISHED WORKS

Reference [19] discusses in its chapter 3 how first-swing stability can be improved by means of an SVC. References [20] to [23] deal with SVC applications in actual power systems. From the papers, it is understood that the SVCs give improvements of first-swing stability. However, no paper has been found on the use of SVCs as the sole means for enhancing first-swing stability in a severe case as discussed in the sections 5.2 and 5.3 above.

5.5 CONCLUSIONS

First-swing stability concerns can be grouped into cases of severe problems and other cases.

Cases of severe problems:

The typical case is a long-distance radial transmission system from one or more power stations into a relatively large system, subjected to a severe stability criterion, such as a three-phase short-circuit or a double line-to-ground fault.

Reactive compensation methods are usually much more cost effective for providing first-swing stability than introducing additional line(s).

Technically, dynamic shunt compensation by SVCs solely can be used to provide first-swing stability but usually at a much higher cost than for series compensation.

Other cases:

There are cases where one or more SVCs of reasonable size are sufficient to provide first-swing stability, i.e. cases of shorter distances than discussed in this chapter and/or where less stringent stability criteria are applied. In such cases, the use of SVCs may be especially attractive if there is also a need for either damping improvement during subsequent swings or voltage control with respect to load areas.

Furthermore, there are cases, where one or more SVCs

in combination with series capacitors are most beneficial in providing the desired improvements in transient stability and voltage control performance [22].

APPENDIX 5-I

Data used in the study of section 5.2:

400 kV Lines

| | | | |
|-------|---|------|---------|
| X | = | 0.33 | Ohm/km |
| R | = | 0.02 | Ohm/km |
| Q | = | 0.60 | Mvar/km |
| SIL | = | 550 | MW |

Transformers

$X = 0.15$ p.u. on transf. power rating

Load

$P = P_o(U/U_o)$ i.e. constant active current

Generators

| | G1 | G2 | |
|------------|---------------|------|-------|
| S | = See Fig.5.1 | | MVA |
| H | = 4 | 4 | Ws/VA |
| X_d | = 1.00 | 2.00 | p.u. |
| X_d' | = 0.30 | 0.25 | p.u. |
| X_d'' | = 0.20 | 0.20 | p.u. |
| X_q | = 0.60 | 1.90 | p.u. |
| X_q' | = - | 0.50 | p.u. |
| X_q'' | = 0.20 | 0.20 | p.u. |
| X_a | = 0.12 | 0.15 | p.u. |
| T_{do}' | = 5.00 | 6.00 | s |
| T_{do}'' | = 0.08 | 0.03 | s |
| T_{qo}' | = - | 0.60 | s |
| T_{qo}'' | = 0.12 | 0.06 | s |

APPENDIX 5-II

Choice of SVC control parameters in the study of section 5.2: See Fig. 5.2.

Variables:

| | | | |
|-------|---|--------------------|-------------|
| U | - | Bus voltage | (p.u., rad) |
| I | - | SVC current | (p.u., rad) |
| B | - | SVC susceptance | (p.u.) |
| V | - | Controlled voltage | (p.u.) |
| V_r | - | Reference voltage | (p.u.) |

Parameters:

- K_s - Control slope (p.u./p.u.)
- K_a - Control gain (p.u./p.u.)
- T_i - Integrator time constant (s)

K_s was set equal to 0.

K_a was set to the inverse of K .

K is here used for the "Power system gain" = $\Delta U / \Delta B$ as derived below.

T_i was set to 0.020 s, yielding a voltage control small-signal step-response time of about 50 ms at values of other parameters as below.

The following simplified analysis forms the basis for the choice of K_a and T_i .

If we assume the power system to be represented by an internal voltage E behind a reactance X_e and the SVC by a reactance X , as shown in Fig. 5.5, then

$$U = E \cdot X / (X + X_e) \quad (5.2)$$

$$= E / (1 - B \cdot X_e) \quad (5.3)$$

$$K = E \cdot X_e / (1 - B \cdot X_e)^2 \quad (5.4)$$

If K_a is set to the inverse of K , the small signal transfer function of the closed-loop voltage control system will be $1 / (1 + sT_i)$.

When determining K_a the following variable and parameter values should be used:

- $E = 1.0$
- $B = B_{max}$
- $X_e =$ Equivalent external transient reactance at minimum short-circuit MVA level.

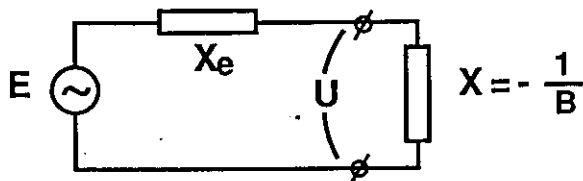


Fig. 5.5 : Equivalent circuit

CHAPTER 6

DAMPING OF POWER OSCILLATIONS

by

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- 6.2 Use of SVC's for Power System Damping Improvement
- 6.3 Methods of Damping Analysis in Power System
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6.1 THE POWER SYSTEM DAMPING PROBLEM

Problems with power system damping have increased due to:

- Faster controllers (normally giving improved system transient stability, but reduced system oscillatory stability).
- Greater system utilization and more complex systems (leading to an increased system sensitivity to control parameter settings and a higher probability of inadequate parameter settings).
- Larger variations in short circuit levels.
- Increased transmission loadings.

Power oscillations have been traditionally seen as a problem of long interconnected systems with a predominantly radial structure and of weak inerties between neighbouring systems. Nowadays these problems are of increasing interest to the planners of tightly interconnected systems with large units connected to the periphery of the system.

In order to improve system damping, three main strategies can be applied:

- control measures in the generation system
- measures affecting transfer impedance
- control measures at the load buses

The most commonly used methods of improving system damping so far have been:

- Adding power system stabilizers to generators.
- Utilizing Static Var Compensator with damping control.
- Providing HVDC links with similar supplementary damping control features.

6.2 USE OF SVC FOR POWER SYSTEM DAMPING IMPROVEMENT

Reactive power absorption or generation at a system busbar influences voltage profile of the system. As a result, active and reactive power flows within the system are changed, modifying system stability and system damping. By using a proper SVC control scheme, system stability and damping can be improved.

The influence of voltage control on system stability is described using the simple system shown in Figure 6.1:

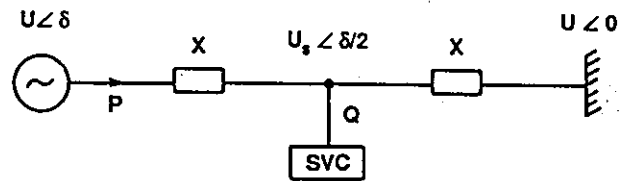


Fig. 6.1 : Generator connected to infinite bus via a SVC-compensated system

The SVC is connected at the electrical midpoint between the generator and the infinite bus. The dynamic behaviour of the system can be described by equation (6.1):

$$M \frac{d^2 \delta}{dt^2} + D \frac{d\delta}{dt} + \frac{U_G U_S}{X} \sin \frac{\delta}{2} = P_m \quad (6.1)$$

where

- M momentum
- D damping constant
- U_G generator voltage
- U_S SVC voltage
- δ machine angle
- $2X$ total system reactance between the generator internal voltage and the infinite bus voltage
- P_m mechanical power

For steady state stability analysis it is sufficient to consider small perturbations and constant mechanical power, giving:

$$M \frac{d^2(\Delta\delta)}{dt^2} + D \frac{d(\Delta\delta)}{dt} + \frac{U_{S0}}{X} \sin \frac{\delta_0}{2} \Delta U_G + \frac{U_{G0}}{X} \sin \frac{\delta_0}{2} \Delta U_S + \frac{U_{G0}U_{S0}}{2X} \cos \frac{\delta_0}{2} \Delta\delta = 0 \quad (6.2)$$

The fourth term shows the part dependent on the SVC bus voltage variations which could be influenced by proper damping control of the SVC.

If the SVC voltage U_S and the generator voltage U_G are kept constant by the voltage control system, then $\Delta U_S = 0$ and $\Delta U_G = 0$, giving:

$$M \frac{d^2(\Delta\delta)}{dt^2} + D \frac{d(\Delta\delta)}{dt} + \frac{U_{G0}U_{S0}}{2X} \cos \frac{\delta_0}{2} \Delta\delta = 0 \quad (6.3)$$

Figure 6.2 shows $\Delta\delta$ as a function of time after a system disturbance.

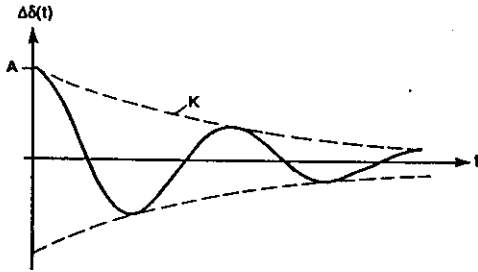


Fig. 6.2 : Rotor angular oscillation

The dotted envelope K in Figure 6.2 is given by

$$K = A \cdot e^{-\sigma t} = A \cdot e^{-\frac{D}{2M}t} \quad (6.4)$$

where A is determined from the initial condition. The damping of the power angle oscillation is increased by increasing the damping constant D and decreasing the momentum M .

With no SVC in the system the following description is obtained:

$$M \frac{d^2(\Delta\delta)}{dt^2} + D \frac{d(\Delta\delta)}{dt} + \frac{U_{G0}U_0}{2X} \cos \delta_0 \Delta\delta = 0 \quad (6.5)$$

Comparing equation (6.3) and equation (6.5) it is observed that the damping constant is the same while the synchronizing torque is larger in the case with SVC, giving an increase in oscillation frequency. Thus, it can be concluded that the applied SVC control strategy (constant voltage control) does not contribute to system damping directly. Indirectly, however, the damping of the system is slightly improved because the inherent damping of the generator is increased with the frequency of system oscillations.

In order to use the SVC efficiently for damping the power oscillations, the SVC voltage must be varied proportionally to $d(\Delta\delta)/dt$; this effect is obtained through the term

$$\frac{U_{G0}}{X} \sin \frac{\delta_0}{2} \Delta U_S \quad (6.6)$$

in equation (6.2). The device for such an additional control of the SVC is known as POD (power oscillation damper). This damping concept could be referred to as damping by influencing the transfer impedance.

Another concept is applicable where the structure of an interconnected power system involves strong electrical coupling between generation and load, but weak coupling to other systems; this concept is termed load modulation and is discussed below.

To use a mechanical analogy, the network can be considered as springs and the generation as inertia; the corresponding analogy for displacement is angle. To provide damping in such a mechanical system viscous damping applied at nodes would be appropriate. Viscous damping will provide forces proportional to the rate of change of displacement (analogous to the rate of change of angle).

Thus, if power system loads were to be varied according to variations in frequency, damping action would follow. SVC can be controlled to vary the voltage at major load centres so that this relation between load and frequency variations is achieved. We normally refer to this as load modulation.

If it is assumed that the load responds in phase with changes in voltage magnitude, then an appropriate control strategy is to vary the load voltage in phase with frequency changes.

In order to achieve damping control, additional signals have to be fed to the SVC controller such as:

1. Power flow in lines.
2. Current flow in lines.
3. Frequency of an AC voltage.
4. Rate of change of voltage magnitude (dV/dt).

Different control strategies will be further described in part 6.4.

The SVC power oscillation damping capability is strongly related to the ability of the SVC to influence the voltage at its bus, and is hence dependent on the SVC MVA rating relative to the short circuit strength at its point of connection.

The damping effect is counteracted by voltage control devices in the neighbourhood of the SVC and the usual constant voltage control function of the SVC itself. Conversely, the POD of the SVC reduces voltage quality (in terms of constancy of magnitude) during

system disturbances.

The fundamental behaviour of the SVC as a controlled susceptance can be derived from the resulting reactive power at the point of its connection. The injected or absorbed reactive power changes the voltage profile of the network and thus influences the synchronizing and damping torques, as well as the load to the extent that the latter is voltage dependent. Ref. [1].

6.3 METHODS OF DAMPING ANALYSIS IN POWER SYSTEMS

The main types of generally available analysis tool may be applied to investigate power system damping:

- Time domain (transient stability) analysis using non-linear description of the power system, see (6.1).
- Frequency domain (eigenvalue analysis) based upon a linearized description of the power system, see (6.2).
- Transient Network Analyser (TNA).

The first method is necessary when analysing large system disturbances, such as generator tripping, power system faults with subsequent relay operations, and abnormal load variations; the method is also applicable when studying oscillatory stability. The method has the disadvantage, compared to eigenvalue analysis, of being a sample inquiry. It can, however, be advantageous in terms of accuracy of some of its models.

The eigenvalue analysis gives information about system damping for any small disturbance, but has the disadvantage compared to transient stability programs of disregarding non-linearities, such as:

- saturation (in components and controllers)
- dead zones
- relay functions
- hysteresis

Digital and analogue nonlinear models (TNAs) are useful in confirming control performance if the transmission system studied is limited in size and complexity.

One possible strategy that is adopted for system studies is to combine the two main types of analytical tools:

- Step 1: Eigenvalue/sensitivity (frequency domain) analysis to determine optimum parameter settings of controllers.
- Step 2: Transient stability studies of severe system disturbances.

A more comprehensive approach in use is shown in figure 6.3.

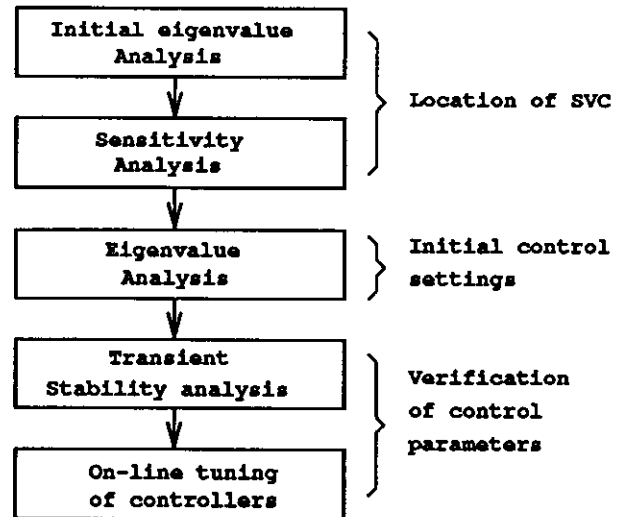


Fig. 6.3 : Strategy for SVC analysis

Location of SVCs is often determined by other factors than damping improvement. In such cases location is not a degree of freedom in the above process.

A generalized functional block diagram of the SVC model is shown in Figure 6.4.

SVC modelling for analysis of system damping includes:

- modelling of the part of the SVC which represents the controllable reactive power component,
- modelling of the applied control system with the implemented control signals, transfer functions and loops of the controller.

In general cases, an eigenvalue analysis along with a transient stability type program constitute suitable tools for studies of damping of electromechanical oscillations between generators and the network for the following reasons:

- Usually, a fairly extensive representation of the power system is needed, including network, generators etc. This can easily be done by means of a stability type program, but not with TNA or dedicated analogue simulator.
- The oscillation frequency is low in most cases where SVCs are used for damping improvement; it usually is in the range of 0,2 to 2,0 Hz (typically below 1 Hz). This means that a simple fundamental-frequency model is sufficient in such studies, neglecting saturation phenomenon of transformers and iron core shunt reactors. Such a model can easily be implemented in stability type programs.

Modelling the SVC reactive power component by stability programs may be based on a controlled susceptance or a controlled current (or voltage) source representing the same reactive power characteristic.

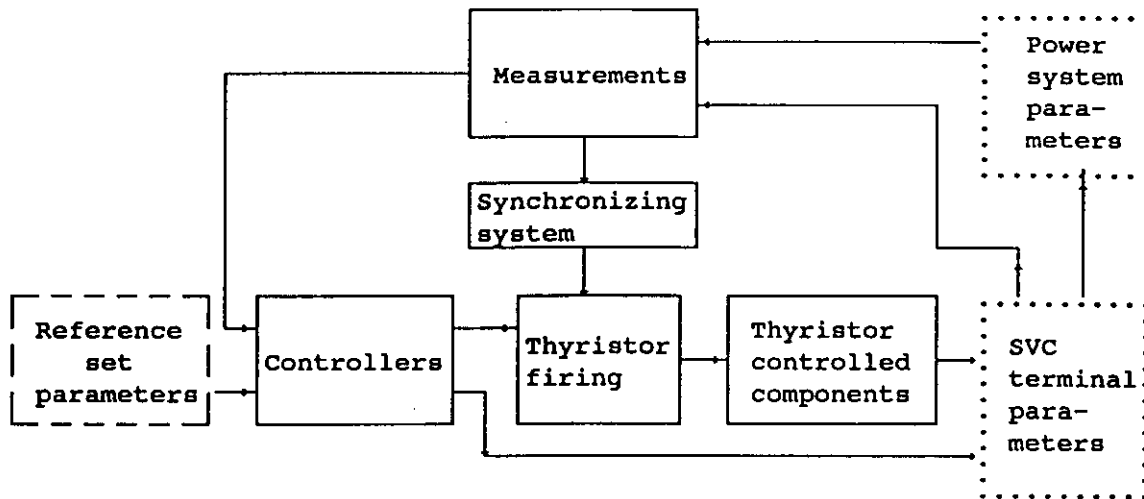


Fig. 6.4 : SVC Model, generalized functional block diagram.

The controlled susceptance model reflects the reality directly. On the other hand, the controlled current source model offers considerable computation time savings according to [52].

6.4 CONTROL STRATEGIES

6.4.1 Input Signal Choices

Several criteria can be applied in selecting an input signal or a set of input signals appropriate for damping power system swings. The signal must, of course, be responsive ("observable" [58]) to the swing modes to be damped.

A local signal is preferred to a communicated signal because communications add time delays and, more importantly, unreliability. The modulation control should provide a positive contribution to damping for any power system operating condition, i.e. the control should be "robust".

Interaction with other controlled devices in the system should be considered and will depend on the selected input signal. Selection of input signals can also be influenced by their impact on first-swing stability and subsequent voltage deviations or by their potential for localized control instability.

Furthermore, all measurements are distorted with noise. For a given damping contribution, the sensitivity to noise will be different with different input signals.

Possible input signals from local measurement are:

| | |
|----------------|---|
| P | active power transfer |
| f | SVC bus frequency |
| V | SVC bus voltage |
| dV/dt | bus voltage change |
| I_a | active component of line current(s) |
| dP/dt | active power gradient |
| θ | observed voltage angle across line impedance between source and SVC |
| $d\theta/dt$ | gradient of observed voltage angle across line impedance between source and SVC |
| $\Delta\delta$ | change of bus voltage vector angle (using washout functions). |

The term "observed" voltage angle means the angle across the line between generator voltage and SVC voltage as it can be "observed" by local measurements at the SVC bus. Figure 6.2 is used to explain how the voltage angle can be observed. It is assumed that the line impedance X is known and that the voltage U_G remains constant during the studied time interval despite power oscillations. The observer at the location of the SVC calculates the voltage angle across the impedance X using the equation

$$\theta = \delta_{Generator} - \delta_{SVC} = \arcsin \frac{P X}{U_G U_S} \quad (6.7)$$

This equation shows that the signal θ includes information from both power flow and SVC voltage.

Under steady state conditions θ must be smaller than 90 degrees; it may however exceed this limit during power oscillations. The derivative $d\theta/dt$ can be used to determine whether θ is smaller or larger than 90 degrees.

The required resolution of measurement depends on the choice of the input signals due to their specific variations during power oscillations. Typical variations of

selected signals for large oscillations are:

- about 1 % for frequency
- about 15 % for voltage
- about 100 % for active line current

It appears sufficient for the purpose of power oscillation damping to provide a measurement resolution of about 5 % of the maximum signal change during a large disturbance. When using the frequency as an input signal, appropriate attention has to be given to the design of frequency transducers and signal filtering.

The value of frequency with respect to observability depends strongly upon the point of connection of the SVC. Frequency variations are zero at the centre of the oscillation and are in phase opposition on the two sides of the centre. It might be difficult in a real network to be sure that a given measuring point can be used in all operating situations.

The use of frequency-based control signals is robust when the SVC is located near major load centres and the level of power transfer on weak interconnections is relatively small compared to the total load.

For both power and active current flow signals, the magnitude of observability decreases with the amount of power transfer and the sign is dependent on the power transfer direction [58].

In the special case with the SVC located midway between two areas, for both voltage and frequency, the sign of observability changes with the power transfer direction and the magnitude of observability increases with the amount of power transfer.

6.4.2 Control Strategies

Several aspects are of interest in evaluating the POD control strategy:

- availability of local and remote signals relevant for power oscillation damping,
- selection of input signals with respect to their contribution to damping,
- configuration of the power system and the availability of PSS (Power System Stabiliser) in the excitation systems of generating units,
- control path configuration,
- mode of operation (continuous or discrete) during small or large power oscillations, control system complexity that can be modelled in stability studies.

Controlling constant SVC voltage contributes to the synchronizing power. Contribution to damping can occur indirectly in the presence of loads [61].

No precision of the damping control signal with respect to magnitude is required; however, the correct

phase lead of the control signal is important. This characteristic must be maintained also when using combined voltage and power oscillation control. For the combined control, series or parallel arrangement of the controllers has been used. With the parallel arrangement, shown in Figure 6.5, it is easy to introduce a robust damping control for power stabilization independent from the voltage controller [57].

When using the series arrangement (Figure 6.6), care is needed to achieve the correct phase lead of the damping signal taking into account the frequency response of the voltage controller [56]. The effect of slope setting also has to be taken into consideration:

All damping controllers must include a filter circuit which provides the necessary phase lead of the input signal P , I_a or θ in the frequency region where damping is to be obtained. The circuits, such as high-pass filter, reset filter, lead-lag or smoother-differentiator provide this function and also help to reduce DC and extremely low-frequency signal components. The parameters of the filter circuit are chosen such that the frequency to be damped by the SVC is in the range A of the Bode diagram (Figure 6.7). This range belongs to the differentiation part of the filter. The cut-off frequency ω_0 has to be chosen sufficiently above the dominant mode of power fluctuations to avoid the influence of integral power error feedback. On the other hand, too large a value of ω_0 could cause problems with higher resonant modes of the power system. More information on choosing the right parameters of the filter circuit is given in [37].

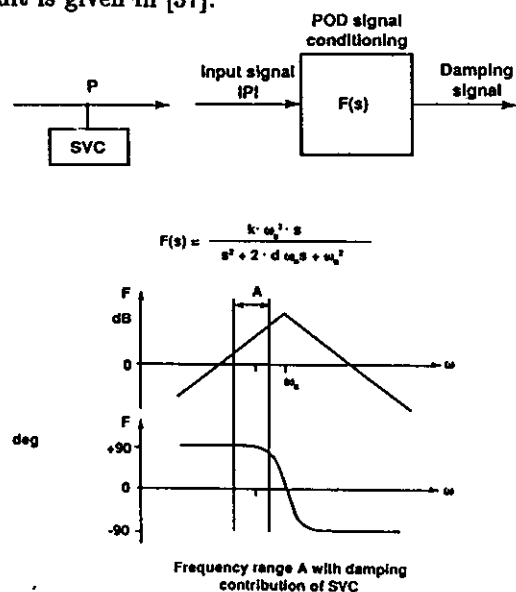


Fig. 6.7 : Transfer function of POD signal

Several authors have shown that the control signal, derived from the rate of change of either power P or voltage angle θ , must change sign if the direction of transmitted power is changed. With the input signal P , one can solve this problem by using only the absolute value of power as input for obtaining the rate of

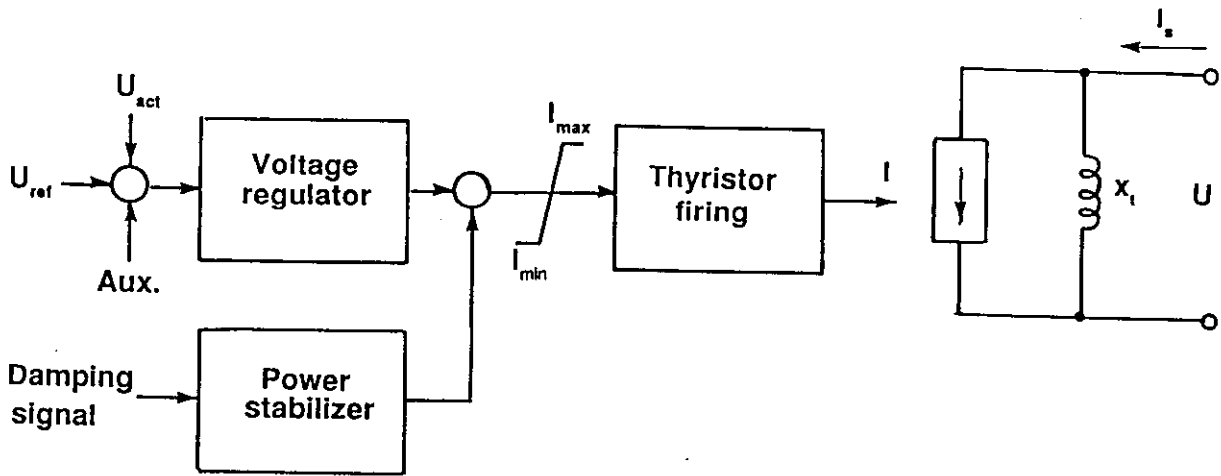


Fig. 6.5 : Configuration with parallel paths for voltage and power damping control.

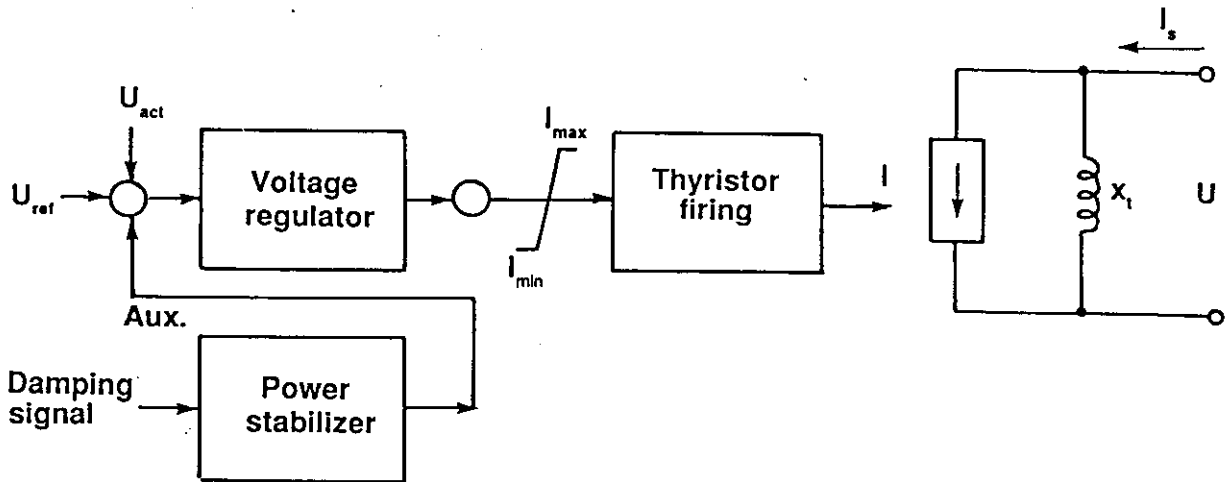


Fig. 6.6 : Configuration with series paths for voltage and power damping control.

change of power. Another practical rule for a robust control strategy is to follow Pontryagin's maximum principle which yields the optimal control parameters for the SVC [52].

A list of existing (status 1990) damper controller designs is shown in Table 6.1:

6.4.3 Bang-bang Control

While this control strategy is not presently being used (see Table 6.1), it has some interesting aspects of performance as described below.

For damping power oscillations, the available SVC capacitive or inductive capability can be switched fully to control the SVC bus voltage to permitted limit values, i.e. maximum reactive power or minimum during real power increases or decreases, respectively. This means that the SVC introduces voltage fluctuations shifted by 90 degrees and leading with respect to the power oscillations (Figure 6.8).

The mechanism of damping the power oscillations by introducing transient voltage fluctuations is discussed

in 6.2.

In order to damp oscillations it is important that the sign of the voltage change, ΔU_s , corresponds to the sign of power change, ΔP . This means

$$\text{for } \frac{\Delta P}{\Delta t} > 0 : \text{increase } U_s (Q_{SVC} = Q_{cap}) \quad (6.8)$$

$$\text{for } \frac{\Delta P}{\Delta t} < 0 : \text{decrease } U_s (Q_{SVC} = Q_{ind}) \quad (6.9)$$

Periodic voltage fluctuations could be amplified by the bang-bang control of SVC due to its high gain and fast response characteristics. In order to solve this problem, a so-called "reset filter" can be inserted into the voltage measurement path [48]. An SVC equipped with the reset filter does not respond to slow voltage oscillations. Under steady state, it acts on the SVC in such a way as to control the var output of the SVC to zero level ('float'). During disturbances, it shows a leading effect with respect to the synchronizing torque

Table 6.1 : POD Designs in Operation

| No. of SVCs with POD | Input Signal | Control Path ¹⁾ | | Mode of operation | | | | | Hardware | |
|----------------------|--------------|----------------------------|--------|-------------------|-----------|-----------------|-----------------|-----------|-------------------|-------------|
| | | Parallel | Series | Small Osc. | | Large Osc. | | | Operational Ampl. | Micro Proc. |
| | | | | Cont. | Dis-cont. | Cont. | Discont. | | | |
| | | | | | | | Large Step | Bang Bang | | |
| 2 | P | X | | | | | X ²⁾ | | | X |
| 4 | f | | X | X | | X | | | | X |
| 1 | f | | X | X | | X | | | X | |
| 2 | f | | X | | | | X | | | X |
| 2 | P | | X | X | | X | | | X | |
| 7 | P | | X | | | X ²⁾ | | | | X |
| 5 | θ | X | | X | | X | | | | X |

- ¹⁾ Signal parallel to the voltage controller or added to the voltage controller reference voltage.
²⁾ Incorporating a dead zone.

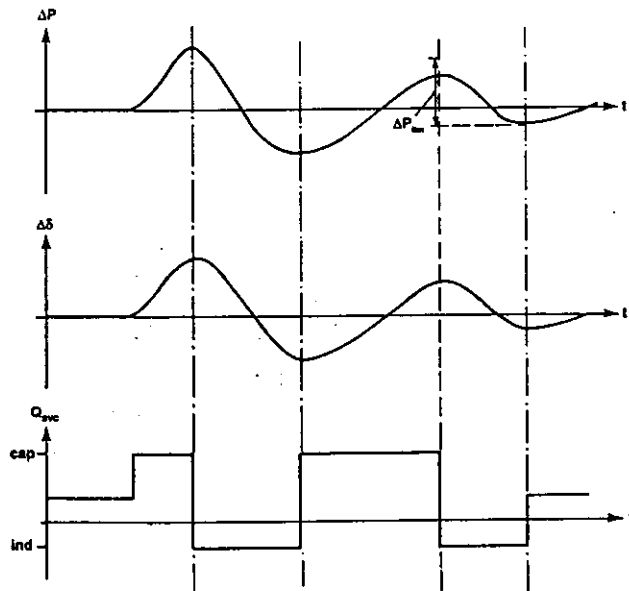


Fig. 6.8 : Power oscillation damping

in the power system and thus works to improve oscillatory stability.

Bang-bang control [55] becomes unstable when the voltage deviations caused by the SVC become greater than the magnitude of the network oscillation. To avoid this, a band ΔP_{lim} must be introduced within which the gain is small in order to give continuous regulation. An example is shown in Fig. 6.9.

6.5 CASE STUDIES

The study network, Figure 6.10, is comprised of two generators connected with a line, compensated by an SVC at the midpoint.

The p.u. power base is the SIL of the line: 350 MW at 300 kV.

The generator models are of 6th order and prime mover controllers and voltage controllers are included. PSS of generators are not included in the model. The load model is voltage independent (constant P, Q) which is the worst case model from the standpoint of oscillatory performance.

A block diagram of the SVC controller is shown in Figure 6.11 [1].

The SVC regulator (represented by transfer function G_1) is a PI-controller.

$$G_1 = K(1 + \frac{1}{T_i s}) \quad (6.10)$$

The additional control signal transfer function A_1 is represented by

$$A_1 = \frac{K_A s}{(1 + T_A s)^2} \quad (6.11)$$

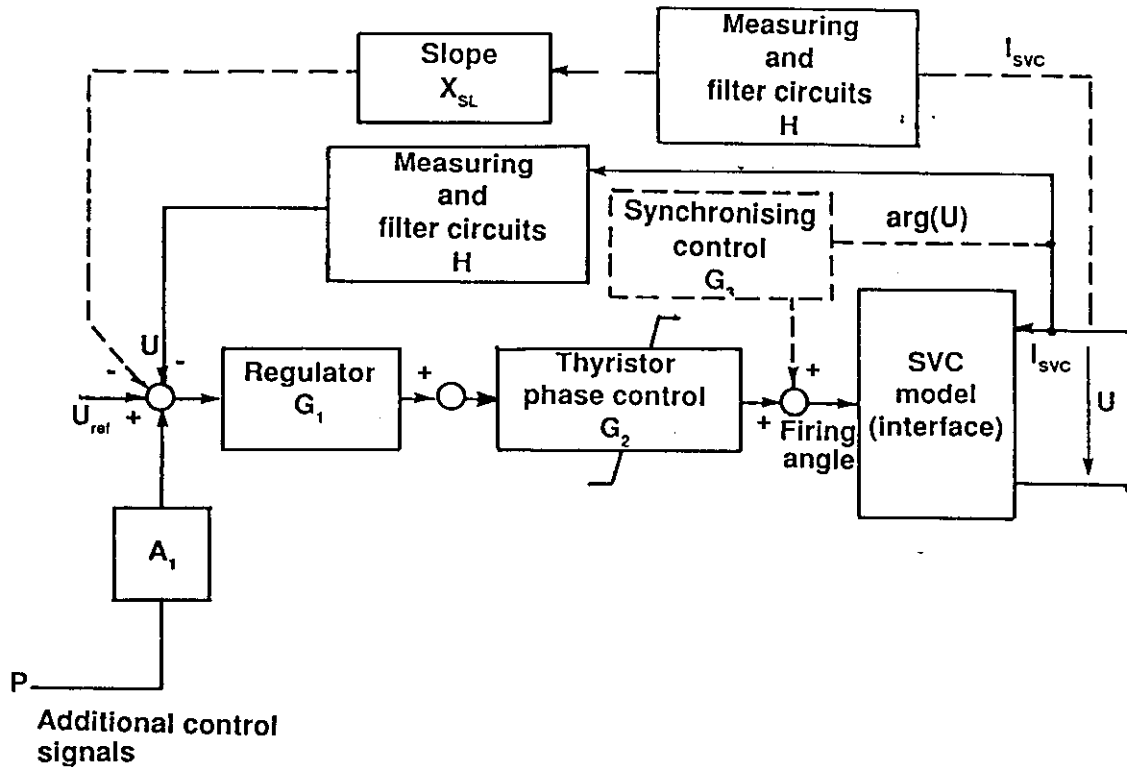


Fig. 6.11 : SVC controller model block diagram for the study case

Figure 6.12 shows the results of an eigenvalue analysis. Damping ratio for the inter-generator oscillation mode of approximately 0.9 Hz is presented as a function of power transfer between the two systems. Two different total line lengths were analyzed: 120 km and 240 km.

The following control parameters were applied:

$$\begin{aligned}
 K &= 10 \\
 T_i &= 0,02 \quad \text{sec} \\
 K_A &= 80 \cdot 10^{-2} \quad \text{p.u. (voltage/p.u.} \\
 &\quad \text{power (power base 350 MVA))} \\
 T_A &= 0,05 \quad \text{sec}
 \end{aligned}$$

The damping ratio for a complex pair ($\sigma \pm j\omega$) is given by:

$$\rho = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (6.12)$$

As a planning criterion, some utilities aim at a damping ratio higher than 0,03 to 0,05 which corresponds to approximately 5 to 3 periods of observable oscillations.

The increased transfer capability of the line with SVC POD is approximately 500 MW (1.43 p.u.) for the 120 km line, and 350 MW (1.0 p.u.) for 240 km line.

System performance without SVC, is not significantly different from that in Figure 6.13 (SVC without POD) which shows oscillograms from tests carried out in the Norwegian Power System.

In the Norwegian tests, power oscillations were triggered by switching out 250 MW of load. The POD was of the same type as that described earlier in Figure 6.11. Note that without POD, it takes more than 25 seconds to damp out the oscillations. With POD, the oscillations are well damped after 10 seconds. The oscillation period is about 2 seconds.

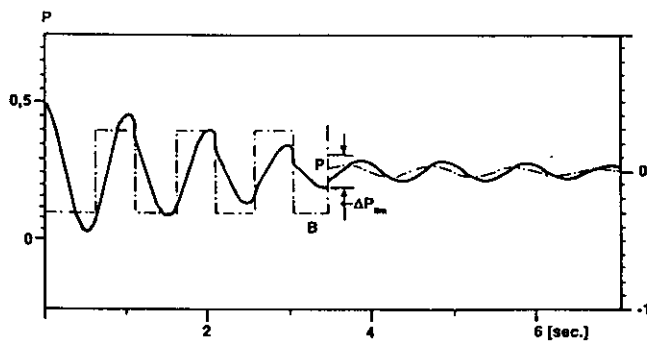
An example of reinforcing an AC interconnection between two large networks by the use of SVCs is published in Electra No. 132 October 1990 [64]. That example illustrates the use of SVCs to enhance stability performance when interconnecting the UCPTE and NORDEL systems.

6.6 CONCLUSIONS

SVC installations can influence system damping in two ways:

- 1) transfer impedances can be modulated and
- 2) load can be modulated.

The location and control of the SVC will depend on which of the two modulations will be most effective in damping power system oscillations. Often, both methods will have some merit which makes any optimization task complicated. It should be remembered that, in most cases, the primary function of the SVC is not to enhance system damping. SVC location and



$$X_1 = 0,5 ; X_2 = 0,5 ; U_1 = U_2 = 1$$

Controller: For large amplitudes ΔP :
Bang-bang using dP/dt ,
B-limits = $\pm 0,3$

For small amplitudes ΔP :
 $B = 0.2s / (1 + 0.05s)^2 P$

Fig. 6.9 : SVC with combination of Bang-bang control and continuous control

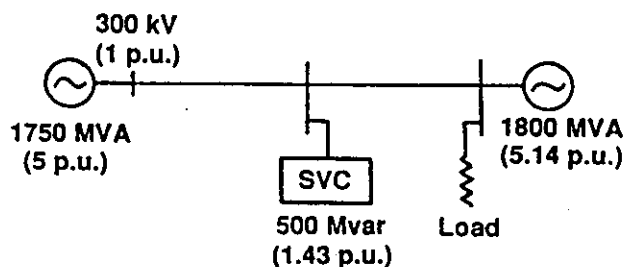


Fig. 6.10 : Two-machine system with SVC

size are hence often based on other criteria.

As input signal to the controller, local measurements are preferred because they are more reliable and avoid transmission time delays. The signal can be bus frequency, bus voltage, line active power, line current or a combination of these. Normally, a signal based on active power measurement will be most convenient to use; its effectiveness will depend on the magnitude of the power transfer. While a communicated signal is less reliable, it can result in a more robust control, especially if the actions of several SVCs are to be coordinated. (Remote control signals are being considered in some countries, but are not yet implemented.)

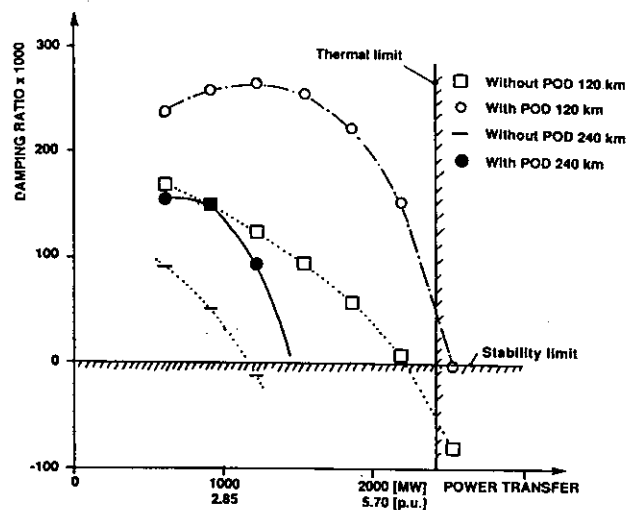


Fig. 6.12 : Damping ratio for different cases of intermachine oscillations

The choice of control input signal is dependent on the location of the SVC because it strongly influences the effectiveness of the control system, especially if local frequency is used as an input signal. Even with other signals, there will often exist SVC locations where the influence of the SVC on system damping can be improved. Detailed investigation is necessary in each case.

The SVC control should consist of a voltage regulator and a power oscillation damper (POD). The POD with a bang-bang control will normally be most effective for large system oscillations, but for small oscillations a continuous control will be necessary.

Simulations are essential to find the best location for the SVC and its optimal control. Eigenvalue analysis is an efficient method for determining both suitable locations for the SVC and initial settings for the control parameters. Additional time domain analysis is necessary to tune the controls and to size the SVC for severe disturbances. An ordinary transient stability program is well suited for this type of analysis.

To summarize, the advantages of SVCs for damping improvement include speed of action and easy controllability. While the SVCs can have a significant influence on system damping, they present a challenge for anyone planning to secure enough damping improvement for all operating situations.

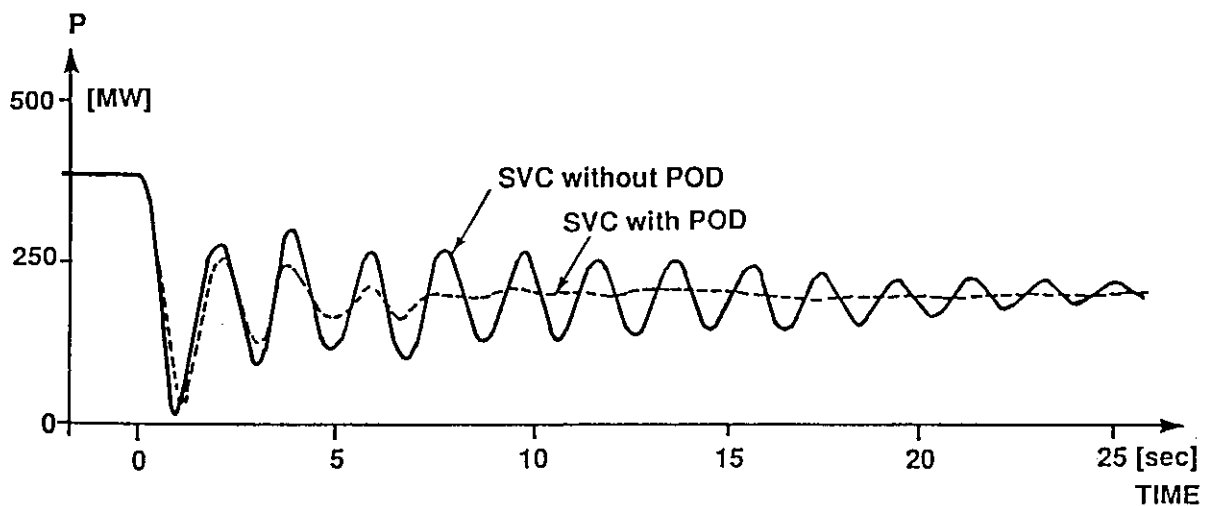
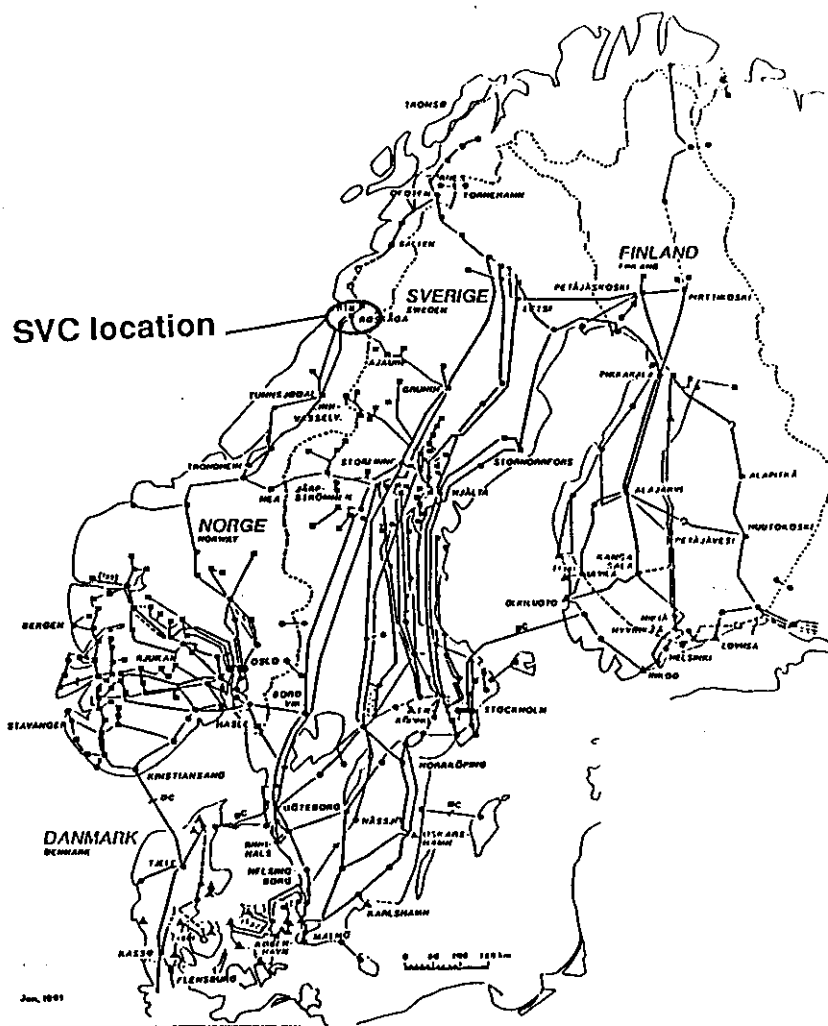


Fig. 6.13 : Example of POD test carried out in the Norwegian Power System

REFERENCES

Chapter 1

- [1] I.A. Erinmez et al. CIGRE SC 38, WG 01, TF2, *Static Var Compensators*
CIGRE Brochure No.25, 1986, CIGRE Central Office.
- [2] M.Erche et al. CIGRE SC 38, WG 01, TF3, *Reactive Power Compensation Analysis and Planning Procedure*
CIGRE Brochure No.30, 1989, CIGRE Central Office.
- [3] C.Barbier et al. CIGRE SC 32, WG 03. *Tentative Classification and Terminologies Relating to Stability Problems of Power Systems*
Electra, No. 56, Jan. 1978, pp. 57-67.
- [4] A.Bose et al. IEEE Committee *Proposed Terms and Definitions for Power System Stability*
IEEE Trans. on PAS, July 1982, pp. 1894-1898.

Chapter 2

- [5] W.B. Jervis, J.G. Scott, H.Griffiths *Future Application of Reactive Compensation Plant on the CEGB System to Improve Transmission Network Capability*
CIGRE Report 38-06, 1988.
- [6] G.Nicola *Reactive Power Compensation of a Long Radial HV Transmission System Lightly Loaded*
Report to CIGRE TF 38-01-04.
- [7] J.P.Paul, J.V.Leost, J.M.Tesseron *Survey of the Secondary Voltage Control in France: Present Realization and Investigations*
IEEE Trans. on Power Systems (PS), May 1987, pp. 505-511.
- [8] F.Illiceto, E.Cinieri *Comparative Analysis of Series and Shunt Compensation Schemes for AC Transmission Systems*
IEEE Trans. on PAS, Nov./Dec. 1977, pp. 1819-1830.
- [9] F.Illiceto, E.Cinieri, F.Gatta, A.Erkan *Optimal Use of Reactive Power Resources for Voltage Control in Long Distance EHV Transmission. Applications to the Turkish 420 kV System*
CIGRE Report 38-18, 1988.
- [10] N.Flatabø, A.Johannesen, T.Carlsen, L.Holten *Evaluation of Reactive Power Reserves in Transmission Systems*
Proc. IFAC Symposium on Planning and Operation of Electric Energy Systems, Rio de Janeiro, 1985.

[11] C.Lemaitre, J.P. Paul, J.M. Tesseron, Y. Harmand, Y.S. Zhao, *An Indicator of the Risk of Voltage Profile Instability for Real Time Control Applications*
IEEE Trans. on PS, Febr. 1990, pp. 154-161.

[12] N.Flatabø, R.Ognedal, T.Carlsen *Voltage Stability Conditions in a Power Transmission System Calculated by Sensitivity Methods*
IEEE Trans. on PS, Nov. 1990, pp. 1286-1293.

Chapter 3

- [13] A.-A. Edris *Controllable var Compensator: A Potential Solution to Loadability Problem of Low Capacity Power Systems*
IEEE Trans. on PS, Aug. 1987, pp. 561-567.
- [14] T.Østrup *The Influence from Reactive Power Control in Case of Load Shedding or Load Rejection*
Report to CIGRE TF 38-01-04.

Chapter 4

- [15] G.Borgonovo et al. *Five Years of Experience with the New CESI TNA. Modelling Techniques Used and Examples of Applications*
IEEE Can. Communication and Power Conf. Montreal, Nov. 1974.
- [16] E. Gaglioti, G. Santagostino, F.Leone, F. Profumo, R. Rosati, L. Valfre *Evaluation of Transient Performance of an SVC for Voltage Support in a Transmission System with Low Short-circuit Power*
CIGRE Report 38-12, 1984.
- [17] G.Moraw *The Use of a TCR for Higher Flexibility of the Austrian HVDC Back-to-Back Links*
EPE 89, Proc. Vol.1, 3rd European Conference on Power Electronics and Applications, Aachen 1989.

Chapter 5

- [18] O.Bertoldi, A. Invernizzi, G. Manzoni, S. Scalcino *Factors Affecting AC and DC Transmission System Reliability and Methods for Assessing their Influence*
CIGRE Symposium, Boston 1987, Paper 500-06.
- [19] T.J.E. Miller et al. *Reactive Power Control in Electric Systems*
John Wiley & Sons, N.Y., 1983.

- [20] R.Elsiger, Y.Hotte, J.C.Roy
Optimization of Hydro- Quebec's 735 kV Dynamic-Shunt- Compensated System Using Static Compensators on a Large Scale
IEEE Paper A78-107-5, 1978.
- [21] P.Czech, D.McGillis
Hydro-Quebec's Experience in Planning, Designing and Implementing Static Compensation Systems
EPRI Seminar, Duluth, Minnesota, 1978, EPRI Report EL-1047-SR.
- [22] F.Aboytes, G.Arroyo, G.Villa
Application of Static var Compensators in Longitudinal Power System
IEEE Trans. on PAS, Oct. 1983, pp. 3460-3466.
- [23] G.N. Allen, V.E. Henner, C.T. Popple
Optimisation of Static var Compensators and Switched Shunt Capacitors in a Long Distance Interconnection
CIGRE Report 38-07, 1988.
- ### Chapter 6
- [24] K.-E. Johanson, T.Petersson
Överföringslinje mellan Två Punkter i ett Växelströmsnät
Swedish Patent No. 42.45 S (363 938), 1972.
- [25] Å.Ölvegård, L.Ahlgren, H.Frank
Thyristor-Controlled Shunt Capacitors for Improving System Stability
CIGRE Report 32-20, 1976.
- [26] H.E. Schweickardt, G.Romegialli, K. Reichert
Closed Loop Control of Static var Sources (SVS) on EHV Transmission Lines
IEEE Paper A78 135-6, 1978.
- [27] H.Kinoshita
Improvement of Power System Dynamic Stability by Static Shunt var System
El. Eng. in Japan, No.6 1979, pp. 81-88.
- [28] W. Juling, H.Tyll
Effect of Static Compensators on the Dynamic Performance of AC Systems
HQ-EPRI International Symposium on Controlled Reactive Compensation, Varennes, Canada, Sept. 1979.
- [29] K.Engberg, S.Ivner
Static var Systems for Voltage Control During Steady-State and Transient Conditions
Ibid..
- [30] K.Reichert, H.E. Schweickardt
Application of Controllable Reactor Compensators in AC systems
BBC Publication No. CH-E 201 623 E.
- [31] L.X. Bui, D. Crevier
Dynamic System Stability Improvement with a Frequency Actuated Stabilizer Acting on Static Reactive Compensators
IEEE Paper A 80 078-6, 1980.
- [32] Å.Ölvegård, K. Walve, G. Våglund, H. Frank, S. Torseng
Improvement of Transmission Capacity by Thyristor-Controlled Reactive Power
IEEE Trans. on PAS, Aug. 1981, pp. 3930-3939.
- [33] D. Nelles, A. Wahi
Dämpfung von Netzpendelungen durch steuerbare Parallelkompensatoren
Wiss. Ber. AEG-Telefunken, 1983 3, pp. 141-146.
- [34] G. Romegialli, H. Beeler
Problems and Concepts of Static Compensator Control
IEE Proc. Vol. 128, No. 6, Nov. 1981.
- [35] G. Ledwich, T. Jordan
Placement of Shunt var Systems
El. Power Systems Research, 1982 5, pp. 299-306.
- [36] M. El-Sadek
Optimization of Static var System Parameters for Stabilizing Power System Oscillations
Ph.D. Thesis No. 446, Lausanne, Switzerland, 1982.
- [37] R.Baker, W.Egli, P.Eglin, G.Güth
Control Algorithm for a Static Phase-Shifting Transformer to Enhance Transient and Dynamic Stability of Large Power Systems
IEEE Trans. on PAS, Sept. 1982, pp. 3532-3542.
- [38] R.L. Hauth, S.A. Miske, F. Nozari
The Role and Benefits of Static var Systems in High Voltage Power System Applications
IEEE Trans. on PAS, Oct. 1982, pp. 3761-3770.
- [39] G. Ledwich
Control Algorithms for Shunt var Systems
El. Power Systems Research, 1983 6, pp. 141-146.
- [40] K. Kogai et al.
Improvement of Power System Dynamic Stability by Static var Compensator
IPEC, Tokyo 1983.
- [41] R.M. Mathur et al., CEA Committee
Static Compensators for Reactive Power Control
Cantext Publications 1984, Winnipeg, Canada.
- [42] K.R. Padiyar, M.H. Rajasekharam
Dynamic Stabilization of Power Systems Through Reactive Power Modulation
IEEE Paper 84 WM 060-0, 1984.

- [43] B.T. Ooi, M.H. Banakar
Coordination of Static var Compensators With Long Distance Radial Transmission System for Damping Improvement
IEEE Trans. on PAS, Febr. 1984, pp. 265-274.
- [44] T. Petersson
Power System Stability
ASEA Information NK 02-3006E, 1984.
- [45] C.-O. Lindström, K. Walve, G.Våglund, H.Frank, S.Ivner
The 200 Mvar Static Compensator in Hagby, Sweden
CIGRE Report 38-02, 1984.
- [46] M. O'Brien, G. Ledwich
Placement of Static Compensators for Stability Improvement
IEE Proc., Jan. 1985, pp. 30-35.
- [47] K. Hansson
Application Guide for Static var Compensators
El. Supply Board Ireland, 1985.
- [48] H.Suzuki, T.Ohyama, K.Yamashita, T.Maeda
Effective Application of Static var Compensators to Damp Oscillations
IEEE Trans. on PAS, June 1985, pp. 1405-1410.
- [49] A.E. Hammad
Analysis of Power System Stability Enhancement by Static var Compensators
Proc. PICA 1985, pp. 438-443.
- [50] R.L. Bolden
Use of Stabilizing Signals on Static Compensators to Enhance the Damping of Power Systems
Symposium on Static var Systems, Capricornia Institute, Australia, Nov. 1985.
- [51] O. Hauge, P. Meringdal, L. Vormedal, H. Frank, K. Engberg
5 Years Operational Experience with the 360 Mvar Hasle Static Compensator
IEE Conference Publication No. 255, 1985., pp. 287-291.
- [52] A.E. Hammad
Analysis of Power System Stability Enhancement by Static var Compensators
IEEE Trans. on PS, Nov. 1986, pp. 222-227.
- [53] M. O'Brien, G. Ledwich
Static Reactive-Power Compensator Controls for Improved System Stability
IEE Proc., Jan.1987, pp. 38-42.
- [54] A.E. Hammad, M.P. Häusler, P.A. Enstedt, B. Rösle
Static var Compensators for Maximizing Power Transfer and Stabilization of HVAC Interconnections
IEEE/CSEE Joint Conf., Beijing, China, Oct. 1987.
- [55] T. Østrup
Damping of System Oscillations by Modification of Transfer Impedance by Use of SVC. Investigations on a Two-Machine Model
Report to CIGRE TF 38-01-04.
- [56] L. Gyugyi
Fundamentals of Thyristor - Controlled Static var Compensators in Electric Power System Applications
IEEE Symposium Publication 87TH0187-5-PWR, 1987, pp. 8-27.
- [57] A. Hammad
Applications of Static var Compensators in Utility Power Systems
Ibid., pp. 31-35.
- [58] E.V. Larsen, J.H. Chow
SVC Control Design Concepts for System Dynamic Performance
Ibid., pp. 36-53.
- [59] A.J.P. Ramos
Dynamic Performance of a Radial Long Transmission System with Multiple Static var Compensators
EV-Bericht F227, Lehrstuhl für elektrische Energieversorgung der Universität Erlangen-Nürnberg, Germany, 1987.
- [60] K. Sand
Static var Compensators in Power Systems with Emphasis on the Use of SVCs to Enhance System Damping
Ph.D. Thesis, Trondheim, Norway, 1987.
- [61] W. Bayer
Dämpfung von Netzpendelungen durch Massnahmen im Netz
ETG Symposium Netzregelung, Baden-Baden, 1990.
- [62] W. Bayer, M. Erche, E. Lerch, D. Povh, L. Xu
Dynamic Reactive Power Compensation Using Advanced Control for Increasing Transmission System Capability
CIGRE Report 37-302, 1990.
- [63] N. Martins, L.T.G. Lima
Determination of Suitable Locations for Power System Stabilizers and Static var Compensators for Damping Electromechanical Oscillations in Large Scale Power Systems
IEEE Trans. on PS, Nov. 1990, pp. 1455-1469.

[64] J. Falck Christensen, T. Østrup
Example of Reinforcing an AC Interconnection between two Large Networks by Use of SVC
Electra No.132, Oct. 1990, pp. 163-169.

[65] E. Lerch, D. Povh, L. Xu
Advanced SVC Control for Damping Power Oscillations
IEEE Trans. on PS, May 1991, pp. 524-535.

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