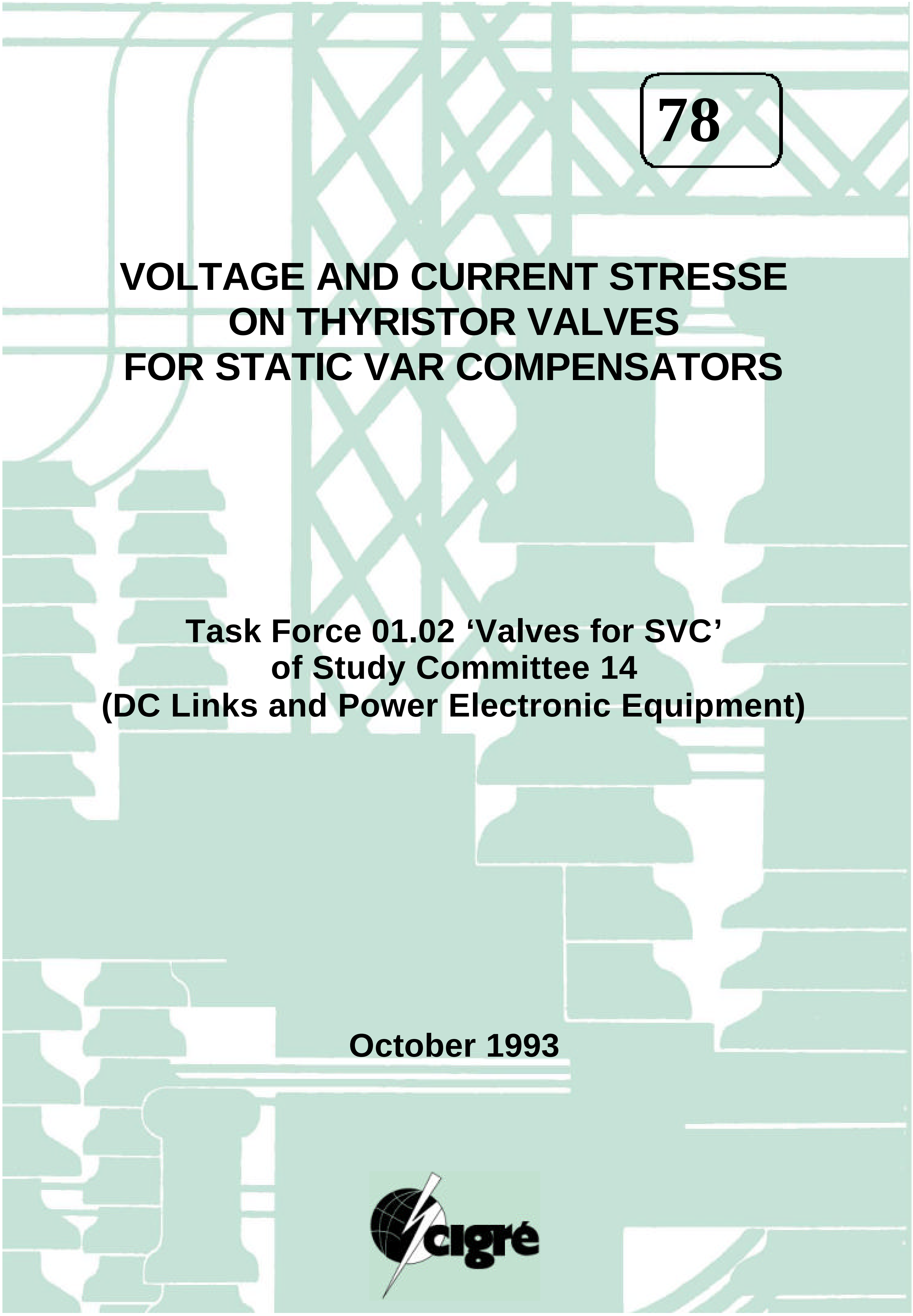

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VOLTAGE AND CURRENT STRESSE ON THYRISTOR VALVES FOR STATIC VAR COMPENSATORS

Task Force 01.02 ‘Valves for SVC’
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VOLTAGE AND CURRENT STRESSES ON THYRISTOR VALVES FOR STATIC VAR COMPENSATORS

Prepared by
CIGRÉ Working Group 14.01
Task Force 2
"Valves for SVC"

Edited by

MILAN CEPEK
Chairman
Task Force 14.01.02

CIGRÉ Working Group 14.01
Task Force 2: "Valves for SVC"
that prepared the Technical Brochure

Dr. P. C. S. Krishnayya	Convener, Working Group 14.01	Canada
Mr. P. Czech	Past Chairman, Task Force 2	Canada
Mr. M. Cepek	Chairman, Task Force 2	Canada
Mr. J. Bélanger		Canada
Mr. I. Bonfanti		Italy
Mr. P. Charles		France
Mr. B. Depommier		France
Mr. K. Engberg	Principal author of Part II	Sweden
Dr. M. Häusler	Principal author of Part I	Switzerland
Dr. K. Imai		Japan
Dr. S. Kobayashi		Japan
Mr. W. O. Kramer		United States
Dr. H. Mehta		United States
Mr. R. M. Middleton		United Kingdom
Mr. C. S. Miller		United States
Dr. C. A. O. Peixoto		Brazil
Mr. G. Thiele		Germany
Mr. M. L. Woodhouse		United Kingdom

CONTENTS

PART II VALVES FOR THYRISTOR SWITCHED CAPACITOR (TSC) TYPE STATIC VAR COMPENSATORS

FOREWORD

The application of Static Var Compensators (SVC) employing thyristor valves in power transmission systems has been rapidly increasing in the past decade. Nevertheless, there is no international standard for testing of thyristor valves for static var compensators. Study Committee 14: "DC Links and Power Electronic Equipment", responding to the request of its members, mandated Working Group 14.01 "Valves for HVDC and SVC", to produce a guide on the subject. Consequently, Task Force 2 "Valves for SVC" was formed with experts on SVC valves from power utilities, SVC manufacturers, research and test laboratories and consultants as members. The companies represented in the Task Force are: ABB, (Sweden), ABB (Switzerland), CANA (USA), National Grid Company (UK), CGEE Alsthom (France), CESI (Italy), EPRI (USA), FURNAS (Brazil), GEC Alsthom (UK), General Electric (USA), Hydro–Québec (Canada), Promon (Brazil), Siemens (Germany), Toshiba (Japan), Western Area Power Administration (USA) and Westinghouse (USA).

The scope of work was limited to SVCs for power transmission systems. SVCs for industrial applications (e.g. flicker control, control of voltage fluctuations caused by motor starting) are not in the scope.

As an essential initial step in developing a guide for testing of SVC valves, the Task Force undertook a thorough review of the electric stresses experienced by the thyristor valves in operation. The review was approved by Study Committee 14 in 1992 and is published as this Technical Brochure.

The Technical Brochure describes the stresses on valves for the two most common types of SVCs using thyristor valves, i.e. the Thyristor Controlled Reactor (TCR) type and the Thyristor Switched Capacitor (TSC) type. The two types are discussed in two separate parts of the document. The voltage and current stresses experienced by the valves of the two types are quite different from each other, due to the differences in their operational requirements and protection arrangements.

The electric stresses are discussed in considerable detail for various operating conditions and different SVC designs. Both steady–state and transient conditions caused by internal and external faults are addressed. SVC designs incorporating different types of overcurrent and overvoltage protection schemes are discussed.

The Task Force is in the final stage of completing the "Guidelines for testing of SVC valves" which is expected to be available as a CIGRÉ Technical Brochure in due course.

This Technical Brochure on electric stresses is envisaged to help in understanding the basis for the tests and interpreting the test procedures discussed in the "Guidelines for testing of SVC valves". The information will also serve as a basis for comparison of stresses on valves in any new or innovative SVC designs, to determine whether new or modified test procedures will be required.

PART I

VALVES
FOR
THYRISTOR CONTROLLED REACTOR (TCR) TYPE
STATIC VAR COMPENSATORS

Principal Author

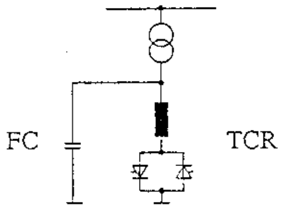
MICHAEL HÄUSLER

1. INTRODUCTION

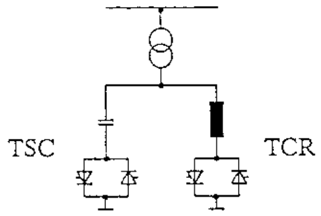
Part I of this CIGRE Technical Brochure deals with the steady-state and transient electric stresses experienced by the thyristor valves in static var compensators employing controlled reactors. The aim of this Technical Brochure is to provide the technical basis needed for defining meaningful test conditions for the thyristor valves. Special consideration is given to the stresses and protection of the thyristors, which are the most sensitive components of the valve. Strategies for protecting the SVC are considered while taking into account the system requirements, which will be different in different cases.

2. BASIC CONFIGURATIONS

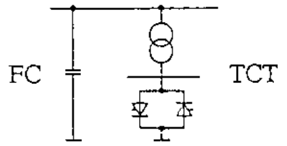
Figure 1 shows some arrangements of static compensators for reactive power control. The controlling element is the thyristor valve. For application in HV networks a stepdown transformer is connected between the point of common coupling and the thyristor valve. Thyristor-controlled reactors (TCR) are often combined either with fixed capacitor banks (FC) shown in Fig. 1a or with thyristor-switched capacitor banks (TSC) shown in Fig. 1b.



a) Thyristor controlled reactor (TCR) with fixed capacitor (FC)



b) Thyristor controlled reactor (TCR) and thyristor switched capacitor (TSC)



c) Thyristor controlled high reactance transformer (TCT) with fixed capacitor (FC)

Fig. 1 Basic Static Compensator Schemes

If the reactor has only to be switched on or off by the thyristor valve, the device is called a TSR (thyristor switched reactor). The TSR valve is either fired at a fixed firing angle of 90° for continuous conduction or it is blocked. The stresses of a TSR valve are identical to those of a TCR valve when operating fully conducting or when blocked.

Another type of TCR, shown in Fig. 1c, is the thyristor-controlled high reactance transformer (TCT) whose leakage reactance is equal to 1 p.u. and which is designed to saturate at a rather high voltage level [1, 2]. A comparison of these SVC types can be found in [3].

A six pulse TCR is normally formed of three delta-connected single phase units as as shown in Fig. 2. The reactors may be split or not. The typical split arrangement with the valve connected in between provides extra protection of the thyristor valve in the event of earth faults or faults in the reactor. In most cases, the system on the valve side of the stepdown transformer is unearthed which avoids high fault currents in the event of a single earth fault.

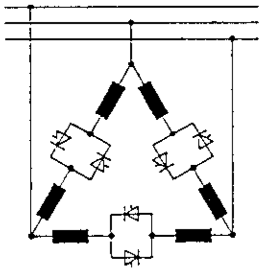


Fig. 2 Three phase TCR connection

3. FUNCTIONS OF THE VALVE

3.1 General

The main function of the valve is to act as a switch. In steady-state operation the thyristor valve is fired periodically each half cycle with a firing angle α between 90° and 180° (Fig. 3). Thus the reactor current can be controlled from maximum to zero continuously. At a firing angle of 90° the valve current is sinusoidal. For firing angles between 90° and 180° harmonic currents are generated.

Firing angles below 90° cause a pronounced d.c. current and an unbalanced loading of the valve (Fig. 12a). Except for the action of voltage breakover protection (VBO) against temporary overvoltage (see section 3.2.4), firing angles below 90° are considered as false firing.

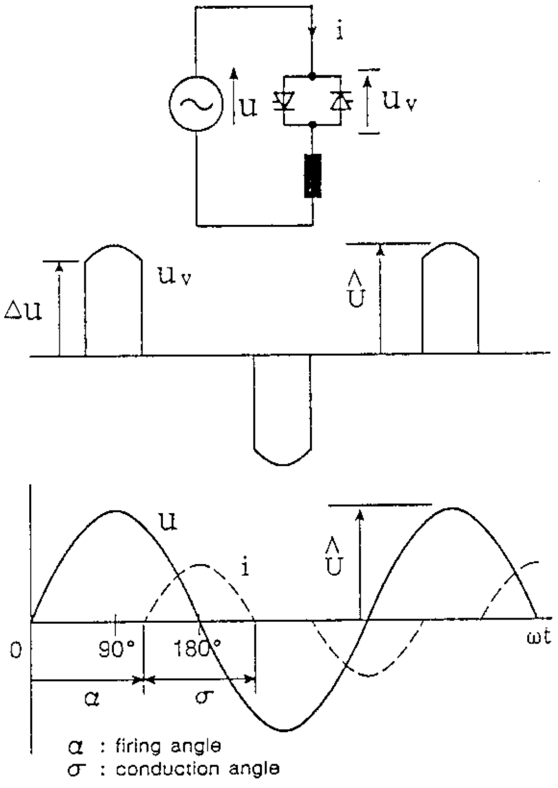
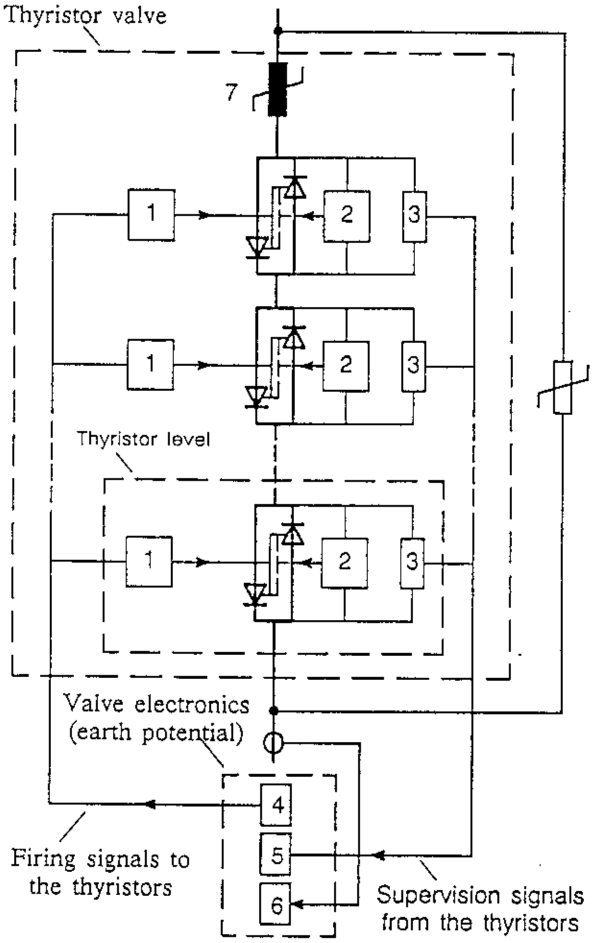


Fig. 3 Current i and Voltage u_v of TCR Valve (Simplified Waveforms)

3.2 Functional Structure of a Valve

Descriptions of typical TCR valves can be found in the literature e.g. [1], [2]. Fig. 4 shows the functional structure of the valve with series-connected thyristor levels. A thyristor level is the term for the assembly of a bidirectional thyristor pair and its auxiliary equipment for gating, monitoring and grading. By adequate series connection of thyristor pairs, the valve is matched to the design dependent voltage rating of the SVC (up to about 40 kV). Typical valve current ratings are 2 to 3 kA.

The high current rating requires forced cooling of the thyristors which are therefore mounted on heatsinks designed for an appropriate cooling medium that also has adequate dielectric withstand capability.



1. Gating device
2. Grading and local overvoltage protection
3. Thyristor monitoring
4. Firing impulse generator
5. Valve supervision
6. Valve protection
7. Valve reactor (if fitted) usually saturable
8. Valve surge arrester (if provided)

Fig. 4. **Functional structure of a TCR valve**

3.2.1 Grading Network

A series resistor-capacitor (RC) circuit (also called damping or snubber circuit), is connected in parallel with each thyristor pair to ensure uniform a.c. voltage distribution between the thyristors for power frequency as well as for high frequency voltages appearing at turn-on or turn-off, or caused by switching transients. This RC network is also designed to damp the extinction voltage overshoot.

The steady-state voltage across a TCR valve has no d.c. component. However, if a TCR (or TSR) valve remains in a continuously blocked state, internal d.c. voltages can arise in part of the valve due to differences in thyristor leakage currents. A d.c. grading network may therefore be required to limit such voltages. The peak voltage stress across a thyristor level when blocked is given by the sum of the crest value of the fundamental a.c. voltage and the remaining d.c. voltage.

When deblocked in phase control (i.e. as a TCR), each thyristor level is subjected to stresses which depend upon the operating voltage, the firing angle and the special protective actions particular to the design (see section 5.7.2). Maximum stresses of different components may occur at different operating conditions. DC grading components are, for example, stressed at their limits by high voltage applied without firing. Extreme load conditions for such components may result from high voltage applied for testing purposes, for a time longer than under actual power system conditions.

Maximum repetitive damping capacitor voltage and maximum damping resistor dissipation occur normally when the TCR valve is fired near 90°. The current in the RC network consists of a sequence of pulses. To reproduce stresses for testing purposes correctly, it may be important to simulate the total dissipation using the true shape of the current in the grading circuit

3.2.2 Valve Reactor

Valve reactors may be connected in series with the valve for the following purposes:

- To reduce the thyristor current stresses immediately after turn-on resulting from commutation of arrester current (where arresters are provided) and from the discharge of stray capacitances in parallel with the valve.
- To limit the du/dt appearing across the thyristors during fast front voltage surges.
- To reduce radio interference.

3.2.3 Firing and Monitoring Systems

Firing of the thyristors is initiated by control signals from circuits at earth potential. To insulate the signal transmission paths for the different potentials to earth of the thyristors, one of two solutions is normally utilized [12]:

- Magnetic coupling via pulse transformers
- Optical coupling via light guides.

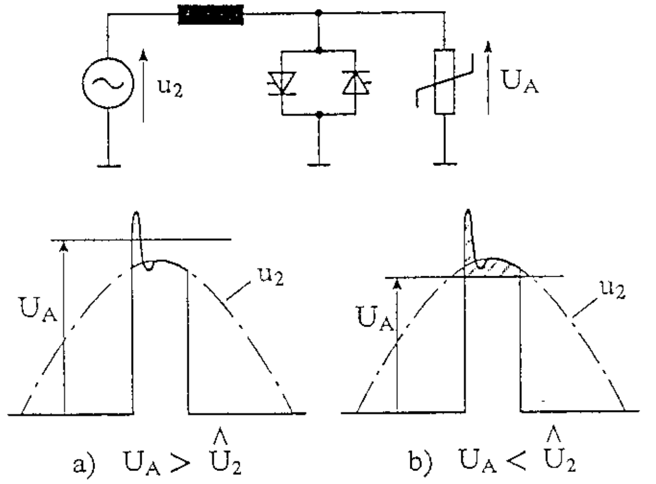
Usually, redundant thyristor levels are provided to allow for uninterrupted operation in the event of an outage of a thyristor level. In order to make the best use of built-in redundancy and thus improve the availability of the valve, monitoring of the thyristor status can be provided. If more levels than permitted fail during operation, the monitoring system can be used to trip the SVC. Similarly, monitoring of repetitive firing by voltage breakover (VBO) action can be provided.

As described above, the valves can contain electronic equipment for firing and monitoring of thyristor levels. The operating environment for these circuits is hostile, particularly with regard to interference arising from the rapidly varying electromagnetic fields that can be present. Great care is required to ensure that the circuits are designed in such a way that they do not malfunction [9].

3.2.4 Overvoltage Protection

Overvoltage protection is provided to protect the valve or thyristor levels against high voltage stresses which may transiently occur. This can be achieved by voltage limiting devices such as arresters or by protective firing initiated at a predetermined voltage across the valve or across each individual thyristor. The latter is commonly referred to as voltage breakover protection (VBO).

When arresters are used for valve overvoltage protection, they are connected directly in parallel with the valve [5]. If firing can occur during arrester operation, the thyristor valve must be designed to commutate the maximum arrester current prevailing at turn-on of the valve. The corresponding arrester current is determined from studies, taking into account the worst overvoltage at the instant the valve is fired. The choice of the overvoltage protection level of the arrester determines both the stresses of the valve and of the arrester. This is shown in Fig. 5, in a simplified circuit, with a fundamental frequency power source. Both cases illustrate overvoltages during which the arrester limits the valve voltage. For case b the protection level U_A is lower than in case a, resulting in a lower voltage stress for the valve. On the other hand a higher arrester current will be commutated to the valve if firing occurs during arrester conduction.



a) $U_A > \hat{U}_2$ b) $U_A < \hat{U}_2$

U_A: Protection level of arrester

(dashed area = voltage time area resulting from valve prospective voltages above protection level)

Fig. 5. **Arrester stress resulting from different protection levels**

Due to the phenomenon of partial blocking (see section 4.2 and Appendix 1) or after failure of thyristor levels, the voltage across individual thyristor levels may exceed the permitted limit, even if the total valve voltage does not exceed the design value. In order to limit the thyristor voltage under these conditions, metal oxide varistors (MOV) or similar voltage limiting devices can be connected across the individual thyristor levels. If this technique is chosen, special measures are necessary to avoid overloading the protection devices if the firing pulse to one leve; fails (see section 5.7.2). On the other hand, protective overvoltage firing of the thyristors at each thyristor level (e.g. by means of breakover diodes) changes a detrimental overvoltage stress, into a current stress which the thyristor must withstand [10]. Since the voltage across this protecting device collapses, the resulting power developed in it is negligible. Therefore this protection device can operate repetitively without being overloaded. Repetitive protective firing increases, however, the stresses on other components (see section 5.7.2).

Protective firing of the whole valve can be coordinated with the surge arrester of the valve according to different strategies. In one strategy, the surge arrester is the main protection of the valve against overvoltages. Out-of-sequence firing caused by protective firing is minimized by setting the minimum protective firing voltage of the valve sufficiently above the protective level of the surge arrester, taking into account uneven voltage sharing among series-connected thyristors under the worst operating conditions (see Appendix 3). The benefit of this strategy is that it decreases the possibility of thyristor stresses caused by overvoltage protective firing operation when the arrester is carrying current, since firing under this condition would mean that the arrester current has to be commutated to the valve. With this strategy, the valve must be designed to withstand a voltage with a sufficient margin above the arrester protective level. In addition, special measures are required to avoid ordinary firing during arrester conduction which could still damage the valve.

A second strategy accepts protective firing operation due to overvoltages. In this case, a surge arrester is normally not required. The overvoltage firing threshold must be set high enough so as not to interfere with the norml operation of the TCR. Hence repetitive firing due, for example, to the effect of valve extinction overshoot, coincident with the worst case system temporary overvoltage must be avoided under conditions during which the valve must remain controllable. Protective firing of the valve is permitted at a voltage which is usually 5% above the limit of controllability, including extinction overshoot.

Protective firing of the valve may be achieved either as a result of the sum of individual thyristor level protections or by firing of the complete valve in response to a voltage measurement across the valve. The method chosen will be design dependent. Sometimes, both valve overvoltage protection and individual thyristor protection may be employed.

3.2.5 Overcurrent Protection

If overcurrent exceeds the design value, the valve is protected by tripping the static compensator. Until the SVC is tripped, the thyristors may, in addition, be continuously fired in order to avoid voltage stress critical for them at elevated junction temperature. If a TCR is connected in parallel with capacitor banks, continuous firing may be maintained for some time, even after tripping, in order to avoid detrimental voltage stress from the charged capacitor banks. In this case, the frequency of operation will be the resonant frequency, which may be different from the power system frequency. This has to be considered in the design of the firing circuit.

It should be recognized that overcurrents typically encountered in TCR valves cannot, in themselves, damage the thyristors. The overcurrent causes an increase in temperature of the thyristor, taking it into a region where its voltage withstand capability may be impaired. Failure of the thyristor following overcurrent is essentially a voltage withstand failure brought about either by intense local heating induced by the passage of excessive leakage current at high temperature or by weak triggering initiated by reduced forward voltage blocking capability at high temperature. Thus it is the voltage that is the damaging agent [9]. If voltage stress is avoided, e.g. by continuous firing, the thyristor is able to withstand higher current without damage [5].

The time-dependent setting of the tripping level of the overcurrent protection is adjusted according to the overcurrent capability of the thyristors, taking into account the possibility of increased stress due to asymmetrical current loading described in section 5.1 (see also Fig. 8). An overcurrent protection based solely on time and magnitude of fault current will trip for some incidents which the valve would be able to withstand. A more sophisticated overcurrent protection considers the true current waveshape for both conduction polarities and cooling conditions. For that purpose a thermal model of the thyristor described in the next paragraph may be useful.

3.2.6 Thermal Overload Protection

As with other heavy electrical current equipment (transformers, motors), a thermal model can be provided for a thyristor valve. With regard to overload capability, the critical component of a valve is the thyristor. One way to model its thermal response is to use a microprocessor containing an equivalent circuit of the thyristor, its heatsink and cooling medium. The algorithm for calculating the junction temperature as a function of the true thyristor current is explained in [11]. The data needed for the representation of the equivalent circuit can be obtained from the thyristor data sheet and the characteristics of the heatsink. The thyristor junction temperature which is the output from the thermal model can then be used to detect when the permitted upper limit of the junction temperature has been reached. The initiated protective action is design dependent and can be one of the following:

- Limit the valve current such that the junction temperature does not rise further.

  This is a safe operating mode providing the valve is still controllable under the prevailing a.c. voltage. Where active overvoltage protection is provided, it must be coordinated with current limitation control.

- Apply continuous firing ($\alpha = 90°$).

  Continuous firing as a protective action requires the controlled reactor impedance to be high enough that the circuit current does not exceed the rated continuous current of the valve when it is operated under full conduction at maximum continuous voltage. Continuous firing avoids voltage stress on the thyristor at times when the junction temperature may exceed the limit for full voltage blocking capability. This mode is a temporary action, which may cause transiently further temperature increase during overvoltage conditions. The resulting temperature should remain below the value above which the thyristors can be damaged by the thermal effect of current alone. Controllability is regained after operating for some time at normal a.c. voltage levels during which the current as well as the thyristor temperatures return to normal.

- Trip (same as described earlier under "Overcurrent Protection").

  Tripping is the ultimate action for protecting the valve against overload conditions exceeding the design value.

4. STRESSES UNDER STEADY-STATE OPERATING CONDITIONS

Figure 3 shows the principal waveforms of valve voltage (u_v) and valve current (i) for a given firing angle (α) and power source voltage (u) where

$$u = \sqrt{2} U_{20} \sin \omega t \qquad (1)$$

and U_{20} is the line-to-line voltage on the valve side of the stepdown transformer (rms value at no-load operation).

The simplified circuit does not include the reactances of the stepdown transformer and the a.c. system. For a practical design, both reactances have to be taken into consideration (see also section 4.1.1). Using the simplified circuit, the instantaneous valve current in one polarity is given by:

$$i = \frac{\sqrt{2} U_{20}}{\omega L} \{\cos a - \cos \omega t\} \qquad (2)$$

for $\alpha < \omega t < 2\pi - \alpha$

Except when $\alpha = \pi/4$ (90°), the valve current in each polarity is separated by a blocking interval which is symmetrical about voltage peak and of duration ($2\alpha - \pi$). During this interval, the valve voltage recovers to and fires from the instantaneous line-to-line voltage, u (see Fig. 6).

Due to the thyristor reverse recovery current I_{rr} (shown in Fig. 6) and the presence of stray capacitances and the inductance L in the circuit, the valve voltage at turn-off overshoots the ideal (prospective) voltage. The rate-of-rise (du/dt) of the valve voltage is mainly determined by the decay of the reverse recovery current and the size of the damping resistor. For more information on turn-off behaviour see [9].

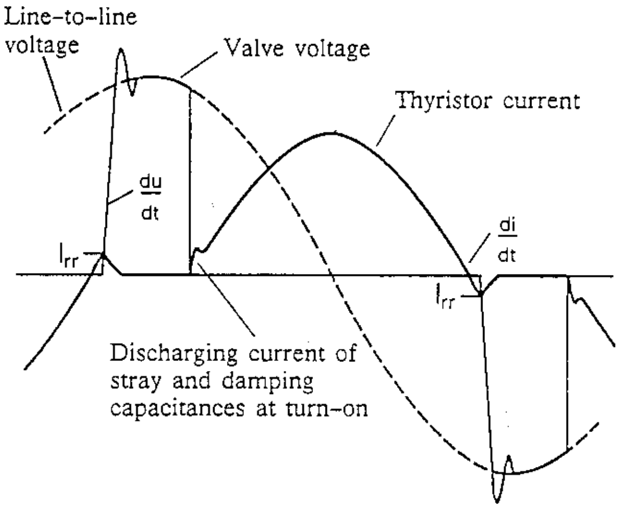


Fig. 6. Voltage and current in a TCR valve (Steady-state operation)

The extinction overshoot factor k_c is defined by

$$k_C = \frac{U_{OS}}{\sqrt{2} U_{20} \sin a} \qquad (3)$$

where U_{os} is the valve voltage peak following turn-off and the expression in the denominator is the ideal (prospective) value of the voltage at current zero during steady-state.

Fig. 7a shows the effect of varying the firing angle on the valve voltage. Depending on the firing angle, the maximum periodic valve voltage is either the peak of the power frequency voltage $\hat{U}_2$ or the extinction overshoot voltage U_{os}, whichever is greater.

The voltage stress of the individual thyristor is increased by the voltage distribution error arising from several independent sources:

- tolerances of the valve grading components,
- differences in reverse recovery charge of the thyristors,
- effect of stray capacitances and stray inductances (for fast transients).

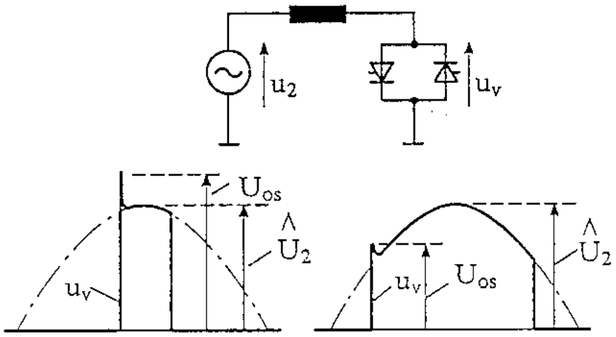
The magnitudes of the thyristor reverse current at turn-off and the current-time area ($\int idt$) connected with it are called:

- Reverse recovery current I_{rr},
- Reverse recovery charge Q_{rr}.

I_{rr} and Q_{rr} depend mainly on the junction temperature and the di/dt prior to the recovery (see Fig. 6). They are also slightly influenced by the voltage during turn-off.

The I_{rr} is mainly responsible for the extinction overshoot. The Q_{rr} and especially the differences of the maximum recovery charge Q_{rrmax} minus the mean value $\overline{Q}_{rr}$ ($Q_{rrmax} - \overline{Q}_{rr}$) and the difference of the mean value $\overline{Q}_{rr}$ minus the minimum value Q_{rrmin} ($\overline{Q}_{rr} - Q_{rrmin}$) are responsible for the off-set voltage distribution errors for positive and negative polarities respectively (see Fig. 12a and 12b).

Neither the extinction overshoot nor the voltage distribution error are constants. They depend on the operating conditions. When performing tests they can be reproduced and verified for defined turn-off conditions.



$U_{os} > \hat{U}_2$
α approaching 90°

$U_{os} < \hat{U}_2$
α approaching 180°

Fig. 7a Valve voltage in a TCR without capacitive load (at different operating points)

4.1 Effect of A.C. System and SVC Components on TCR Valve Stresses

The stresses imposed on the TCR (or TSR) valves are influenced by the a.c. system and the main components of a SVC such as FC and TSC. Stresses resulting from switching or system faults are considered in section 5.3. Influences on steady-state operation are given below.

4.1.1 Impedance of Transformer and A.C. System

Fig. 2 shows only the TCR valves and the controlled reactors. The usual circuit also includes a transformer for connection to the a.c. system. Both the reactances of the transformer and the a.c. system impedance have to be added to the controlled TCR reactor. An extreme case for a TCR is the TCT (Thyristor Controlled Transformer) in which no reactor exists, only the leakage reactance of the transformer (Fig. 1c).

The impedance of the transformer and the a.c. system is taken into account for steady-state conditions, by the load (or regulation) factor k_{ld} (see 4.1.2).

The main difference between an idealized delta TCR connection without transformer and a combined delta TCR with transformer (reactance) can be seen in the interdependence of individual phases during operation. For an idealized delta TCR there is no interaction between phases at any firing angle. For a combined delta TCR with transformer and symmetrical operation, three distinct ranges can be distinguished:

a) firing angle larger than 150°

b) firing angle between 120° and 150°

c) firing angle smaller than 120°

In the following, for the sake of simplicity, no FC is assumed at the secondary of the transformer. Within the range (a), the three phases are independent. The equivalent inductance to be controlled is

$$L = 2\,L_1 + L_2 \qquad (4)$$

where L_2 is the inductance of the reactor within the delta connection

L_1 corresponds to transformer leakage inductance per phase (wye equivalent)

Within the range (b), two TCR phases influence each other. If U is the phase-to-phase voltage (rms value) and ω is angular frequency, the instantaneous TCR current in one polarity within the delta connection becomes:

$$i = \frac{U\sqrt{2}}{\omega(2L_1 + L_2)}\left[1 + \frac{L_1^2}{L_2^2 + 4L_2L_1 + 3L_1^2}\right](\cos\alpha - \cos\omega t) \qquad (5a)$$

for $\alpha < \omega t < (300° - \alpha)$
and for $(\alpha + 60°) < \omega t < (360° - \alpha)$

alternatively

$$i = \frac{U\sqrt{2}}{\omega(2L_1 + L_2)}\left[\cos(300° - \alpha) - \cos\omega t + \left[1 + \frac{L_1^2}{L_2^2 + 4L_2L_1 + 3L_1^2}\right] \cdot (\cos\alpha - \cos(300° - \alpha))\right] \qquad (5b)$$

for $(300° - \alpha) < \omega t < (\alpha + 60°)$

This applies to each polarity of the TCR current.

Within the range (c), all three TCR phases interfere with each other. At full conduction of the valves, the current becomes:

$$i = \frac{U\sqrt{2}}{\omega(3L_1 + L_2)}\,(\sin\omega t - 90°) \qquad (6)$$

The equations for TCT current can be derived from the above given equations (5a), (5b) and (6), by setting L_2 to zero.

4.1.2 TCR with Fixed Capacitor Banks (FC)

When filters are connected at the line side of the step-down transformer, their influence upon the TCR valve can be included as part of the a.c. system. When connected at the valve side of the transformer (Figure 7.b), the filters influence the valve voltage, especially during turn-off of the valve. It can be seen from the U/I_{SVC} diagram in Fig.7.b that the secondary bus voltage U_2 follows a slope in proportion to the short circuit impedance of the transformer, assuming constant primary bus voltage (U_1). At turn-off of the valve, the capacitor banks smooth the bus voltage, depending on their size. The capacitor banks are often designed as filters. Filters provide a similar smoothing effect as pure capacitor banks.

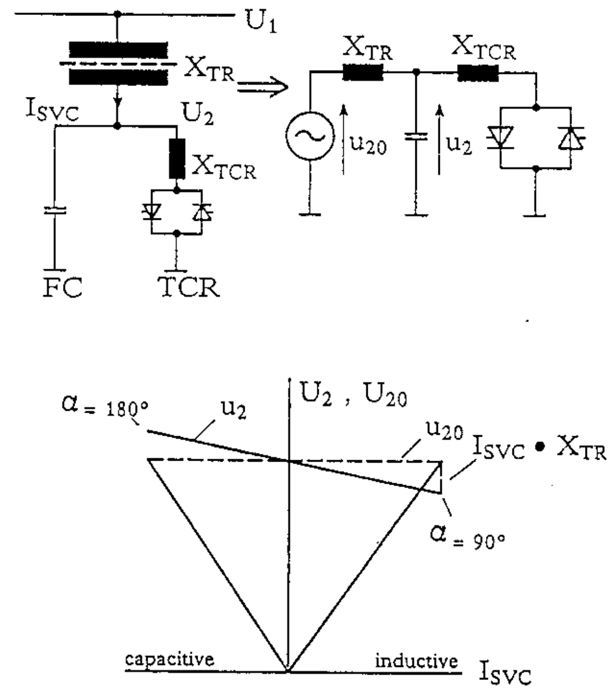
Assuming ideal filtering to sinusoidal waveshape of the secondary voltage, the maximum valve voltage is determined by the actual bus voltage U_2 rather than by the no-load voltage U_{20}. This influence can be allowed for by introducing the regulation factor k_{1d} into equation (3)

$$U_{OS} = k_C \, k_{1d} \, \sqrt{2} \, U_{20} \sin \alpha \qquad (3a)$$

where $k_{1d} = U_2/U_{20}$

The values of k_{1d} as well as k_c are both functions of the firing angle. It can be shown that the maximum valve voltage reaches its maximum at a firing angle slightly larger than 90°. The load factor k_{1d} for maximum valve voltage can be smaller or larger than 1.0 depending upon the design of the SVC.

Careful design of the filter(s) is needed in order to avoid a parallel resonance at a frequency where the TCR generates harmonic currents. If parallel resonance occurs, the valve side voltage can be distorted considerably, leading to additional stress of all major components of the SVC connected to the low voltage bus.



(a.c. system impedance included in X_{TR})

Fig. 7b. **Load Voltage U_2 for a TCR with FC**

4.1.3 TCR with Thyristor Switched Capacitor Banks (TSC)

When a TCR is operated in parallel with a single TSC (Fig.1b) it can be treated in the same way as the combination FC/TCR with regard to the on-state of the TSC. With the TSC turned off and with no FC present, the load factor k_{1d} becomes 1. The load factor k_{1d} is therefore different depending on the status of the TSC. Similarly, the case of parallel operation with more than one TSC or a combination of TSC and FC can be considered.

4.2 Switching Stresses

During the transition from the valve's off-state to the on-state, additional stresses must be considered for the thyristors, particularly for the last level turning on. These stresses are caused by the following effects:

- initial current conduction in a small area of the silicon wafer,
- initial step-like thyristor current due to the discharge current from parasitic capacitances in parallel with the valve and from the damping circuits (Figures 6 and 11),
- unequal voltage sharing resulting from deviations from perfectly coherent turn-on.

The dynamic behavior of the thyristors influences their stresses immediately after turn-off as well. The stresses related to the extinction overshoot have already been described earlier (section 4). Following the interruption of current, the thyristors gradually acquire forward blocking capability but their ability to withstand forward du/dt is severely limited [9]. The situation is further complicated by the fact that, due to the differences in Q_{rr}, some thyristors start recovering earlier than others. If forward voltage transients, e.g. due to capacitor bank switching, occur during the recovery period, then spontaneous turn-on of some thyristors may occur. This phenomenon causes partial blocking (Appendix 1). Without a firing pulse, the turning-on thyristors are vulnerable to di/dt failure. For this reason it may be vital that a properly co-ordinated protection scheme is employed to ensure that, if conditions for satisfactory recovery are not met, the thyristors are safely fired before destructive turn-on can occur. Partial blocking means that some thyristors are forced to withstand the total valve voltage and, without appropriate overvoltage protection, they can be damaged.

Partial blocking may also occur if, due to disturbances of the system voltage, the valve current is distorted in the way shown in Fig. 8b. Sometimes when the current reaches zero, the thyristors coming out of conduction block reverse voltage for an interval of time (hold-off) which is too short for their recovery. In this case the fastest thyristors may turn off while the other thyristors remain conducting.

Another possible cause of partial blocking is ordering the valve to block in the middle of a gate pulse, leaving a very short pulse sufficient to fire some but not all thyristors of a string. Without individual overvoltage protection of the thyristors (VBO), it is clearly necessary to design the thyristor firing devices in such a way that this event cannot happen.

4.3 Thermal Stresses

Some valve components are subjected to thermal stresses which affect their operating characteristics. Valve components contributing to valve losses are considered as heat sources. These are in the order of importance:

- the thyristors
- the damping resistors
- current carrying connections within the valve including the terminals
- valve reactors (when provided)
- DC grading components (when provided)
- gating circuits.

Maximum losses of the different heat sources occur at different operating conditions. Proper design of the valve including the provision of sufficient cooling and proper arrangement of those components which are sensitive to thermal stresses, is needed in order to withstand the operating conditions for specified operation of the valve.

4.3.1 Thyristors

As described in section 3.2.6, the most sensitive part of the thyristor is the silicon wafer. The junction temperature of the thyristors depends on the valve current (the losses due to voltage blocking are much smaller) and on the cooling conditions. Following a change in operating conditions and with constant inlet coolant temperature, thermal equilibrium is typically reached in seconds to minutes of operation, depending on the thermal time constant of the thyristor and its heatsink. Due to tolerances in their forward voltage drop, individual thyristors are heated differently which leads to differences in their junction temperatures.

Most of the thyristor characteristics are very sensitive to its junction temperature. Especially important is the voltage blocking capability, together with the corresponding leakage current and the reverse recovery charge which affects the behavior of the thyristor during the turn-off process. Practical voltage limits of the thyristor in the off-state are influenced by the energy absorption capability of the thyristor stressed in the reverse direction and by the forward leakage current threshold for spontaneous turn-on [9].

As stated in section 3.2.1, differences in thyristor leakage currents may cause internal d.c. voltage stress of the valve. The most important parameter for differences of leakage current is the spread in junction temperature which therefore must be considered for the proper design of the voltage grading network.

4.3.2 Damping Resistors

Losses in the damping resistors depend on the firing angle and on the secondary bus voltage (see formula 9 in section 5.7.2). At $\alpha = 90°$, which corresponds to full conduction for a TCR and normal operation for TSC, the damping losses are zero because no voltage is blocked. Maximum losses occur if the valve is fired at an angle which slightly exceeds 90° because there the voltage jumps will be the largest. As the firing angle is increased, the damping losses decrease because the voltage jumps become smaller, reaching zero at 180° where the valve stops conducting.

In valves where overvoltage firing protection of thyristors is employed, this protection can operate repetitively in the absence of the normal firing signal to the affected thyristor. Section 5.7.2 explains why the damping resistor is subjected to higher losses in such a case as compared to normal operation. If the valve is designed for continuous operation under this condition, the damping resistors must be rated for it.

4.3.3 Other Components

Other components may be exposed to thermal stresses if they are located near heat sources. Special attention is required for valve electronics which should be located in such a way that their operating ambient temperature is not significantly above the maximum valve hall air temperature.

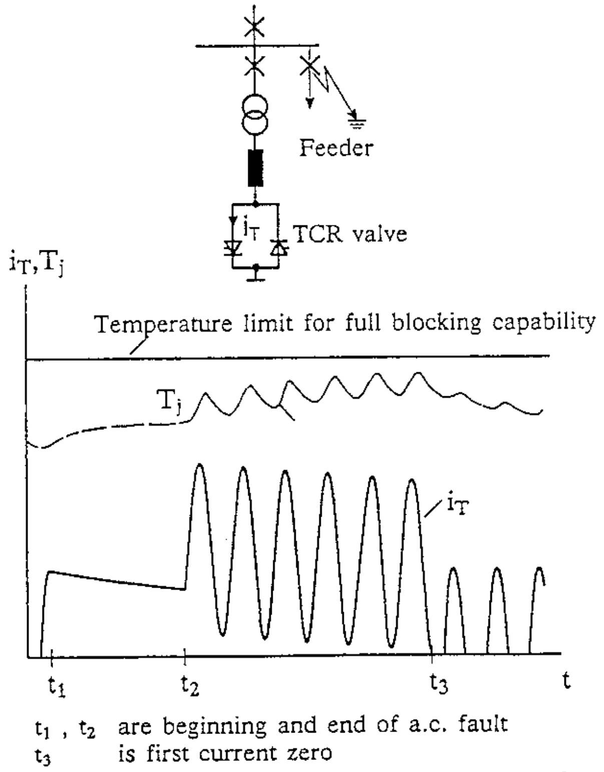
5. STRESSES UNDER TRANSIENT CONDITIONS

In this section the stresses on TCR valves are described under various system disturbance conditions. Since the characteristics of the valve depend on the protection chosen, many scenarios are possible. Only some typical cases will be discussed:

- A. C. system faults,
- temporary overvoltages in the a.c. network,
- switching overvoltages,
- insulation failures within the SVC,
- malfunction of the control.

5.1 A.C. System Faults

A.C. system faults may cause a combined stress of overcurrent followed by temporary overvoltage after fault clearing. During a low impedance fault, the a.c. content of the valve current becomes virtually zero. The d.c. component of the valve current decays according to the time constant L/R where L is mainly the inductance of the TCR reactor and R is given by the quality factor of the circuit, including the controlled reactor and the thyristor valve. The value of R of the valve can be calculated with sufficient accuracy from its conduction losses (Fig. 8a). As a consequence, the valve conducts asymmetrical current for some time. The heating effect on the thyristors in the direction which carries the larger portion of this current may be more than twice the heating effect which would occur under symmetrical loading.



t_1 , t_2 are beginning and end of a.c. fault
t_3 is first current zero
T_j is instantaneous junction temperature of the worst thyristor

Fig. 8a. Thyristor current i_T and junction temperature T_j for a three phase a.c. system fault

After fault clearing, depending on the polarity and magnitude of the recovery voltage, the valve current may be chopped or may be maintained for some time without current zero crossings, as shown in Fig. 8a. The first current zero crossing (t_3 in Fig. 8a) is especially late if there is a.c. system undervoltage at recovery. Field tests have principally confirmed this behaviour [6]. Control action is possible only after the first current zero crossing. Several strategies are considered:

- blocking of firing pulses,
- resumption of phase control,
- continuous firing.

For blocking, it is required that the junction temperature at current zero be below the maximum permitted value. Successful blocking is shown in Fig. 13, cases c and d. This depends upon the hold-off interval available. An insufficient hold-off interval leads to refiring of the thyristors (Fig. 13, case b). The design has to take account of this characteristic of the valve voltage. Reduced hold-off conditions may arise also after false firing (see Appendix 2).

Figure 8b shows the effect of an a.c. system fault on valve operation with immediate resumption of phase control with alpha close to 90°. The voltage shape across the valve during about a quarter of a period after the first current zero is the same as in case of blocking. Therefore critical voltage stresses are similar to those for blocking. With continuous firing, voltage stresses of the thyristors are avoided (see Fig. 13, case a).

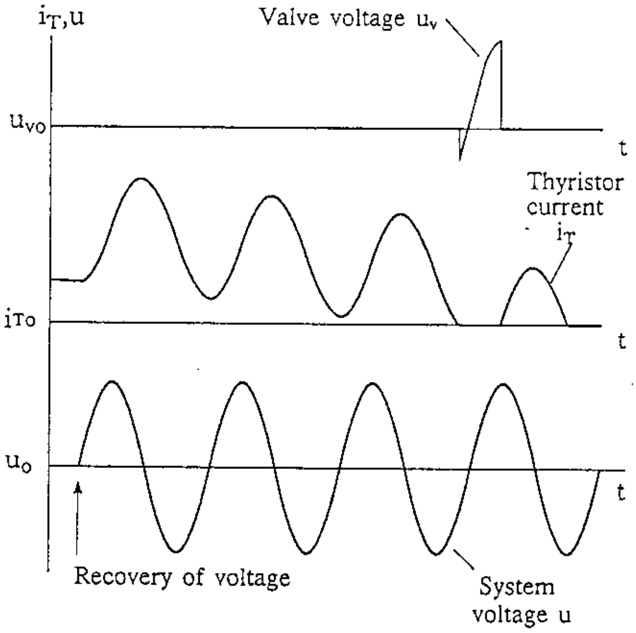


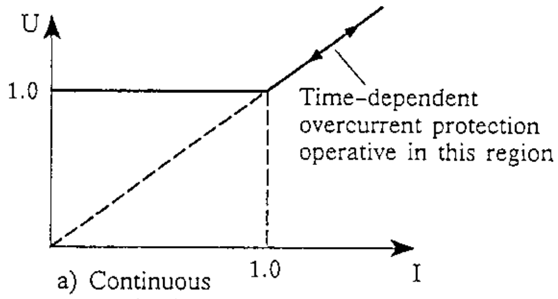
Fig. 8b. Valve voltage u_v and thyristor current i_T for a three phase a.c. system fault

For the design of the TCR valve with respect to stresses resulting from a.c. system faults, the following system conditions have to be considered:

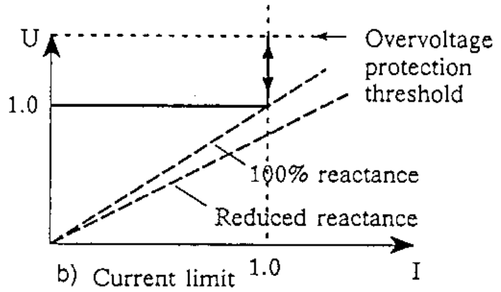
- type of fault,
- fault distance,
- point-on-wave of fault application,
- duration of fault,
- repetition rate of successive faults,
- single phase or three phase operation of fault clearing breaker,
- angle of recovery voltage at instant of fault clearance,
- temporary overvoltage factor,
- prefault current in the TCR and the initial thyristor junction temperature,
- Presence of FCs, TSCs or other TCRs at the same location and the effect these have on the fault recovery waveshapes for both the "on" and "off" states (see section 5.3)
- protective actions of the valve and /or the valve firing system.

5.2 Temporary Overvoltages

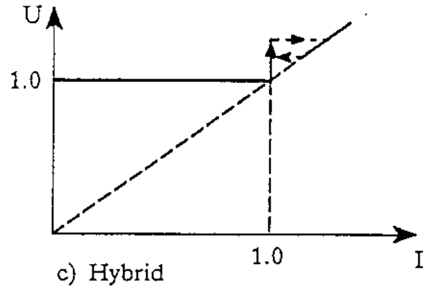
During operation, the TCR can be exposed to system temporary overvoltages. System studies are required to specify the voltage–time profile, for which TCR control must be maintained. Two basic TCR strategies are available for dealing with temporary overvoltages.



a) Continuous conduction



b) Current limit



c) Hybrid

Fig. 9. **TCR control characteristics at temporary overvoltage**

In the first strategy, temporary overvoltage stresses on the valves are converted into current stresses by ordering continuous conduction of the thyristors (Figure 9a). In normal circumstances this would be the natural response of the TCR controller, since full conduction corresponds to maximum var absorption. A consequence of this approach is that the valves then experience an overcurrent for which they must be designed. On clearance of a temporary overvoltage within the specified voltage-time profile, phase control action is immediately available. If the temporary overvoltage exceeds the specified value, the valves may experience excessive overcurrent heating of the thyristors. In this case, overcurrent protection may be invoked (see section 3.2.5). As an alternative to tripping, and within certain limits, the valves can be kept in continuous conduction without damage. On clearance of the temporary overvoltage, the TCR current will return to normal but the thyristors may now be too hot to withstand the voltages arising from resumption of phase control. If this is the case, then additional protective circuits are required which will temporarily inhibit phase control action until the thyristors have cooled down to a safe level.

In the second strategy, continuous conduction is not employed. Instead, at a specified current level, the TCR controller acts to limit the maximum current in the TCR, thereby preventing further temperature rise of the thyristors (Figure 9b). Since the valves are still in phase control, they must be designed to withstand the specified temporary overvoltages including extinction overshoot.

A valve surge arrester, when provided, would limit the peak voltage across the valve under these conditions (see section 3.2.4). If the valve incorporates overvoltage protection, the protection must be coordinated so that it does not operate at the maximum specified temporary overvoltage. If the specified overvoltage is exceeded, then protective shutdown of the compensator is required. This second strategy requires more thyristors in series than the first, but allows economies to be made elsewhere, e.g. adoption of a transformer/reactor combined reactance of less than 100 %. If continuous firing is employed in this case, then an overcurrent exists even at 1 p.u. voltage.

Combinations of both strategies may be employed to meet specific cost or performance objectives (Figure 9c).

5.3 Switching Surges

In static compensators, the load is purely reactive or capacitive and consists of components with low losses. Where a TCR is operating in combination with capacitor banks, filter banks or a TSC, resonant circuits with low natural frequency are formed. System disturbances such as fault application and clearing, or disturbance on the low voltage side of the compensator, excite these resonant circuits. The resulting transient voltages including TSC switching transients have rise times in the range of a switching surge.

As an effective means of evaluating the resulting voltage stress of the valve, digital computer simulation and transient network analyzers have been used (see [2], chapter 9). Experience shows that transfer of switching surges from the a.c. system to the low voltage side of the SVC is important for the arresters, but it is not design limiting for the thyristor valve. However, attention is called to the possibility that a switching surge may distort the waveform of the valve voltage during recovery in such a way that the thyristors are turned on unintentionally (Appendix 1 and Fig. 14).

5.4 Fast Surges Transferred from the A.C. System

For SVC substations with suitable overhead earth wires, the possibility of a direct lightning stroke on the low voltage side need not normally be considered. Lightning surges from the a.c.system are transferred to the valve through the stepdown transformer [7]. The magnitude of the voltage appearing at the valve terminals is reduced considerably by the voltage dividing action between stray capacitances of the controlled reactor and of the thyristor valve (Fig. 11). Where the controlled reactor is air insulated, the magnitude of the surge voltage appearing at the valve terminals is small, particularly for TCR valves placed between split reactors.

Another source for high frequency overvoltage from the a.c. system might be switching operations of disconnectors and circuit breakers. However, there is little information on the transfer of this kind of overvoltage. Field measurements have shown that, with damping resistors used for breakers on the a.c. system, and with properly located surge capacitors on the LV side, this kind of overvoltage can be avoided [8].

5.5 Effect of Insulation Failure on Off-State Valves

Valve stresses due to insulation failures to earth depend on the earthing conditions. For a single phase to earth fault on a SVC which is high impedance earthed on the LV side, the voltage to earth is reduced to zero in the faulted line, whereas the voltage to earth of the healthy lines is increased by a factor of $\sqrt{3}$. The increased voltage stress during the fault time has to be considered for the valve design. If the SVC is solidly earthed on the low voltage side of the step down transformer, the voltage to earth of the healthy phases remains practically unchanged in the event of an earth fault.

Earth faults may cause steep front surges between the terminals of the blocked valve, especially if the valve terminals had been charged to high potential by a preceding switching surge (Fig. 10).

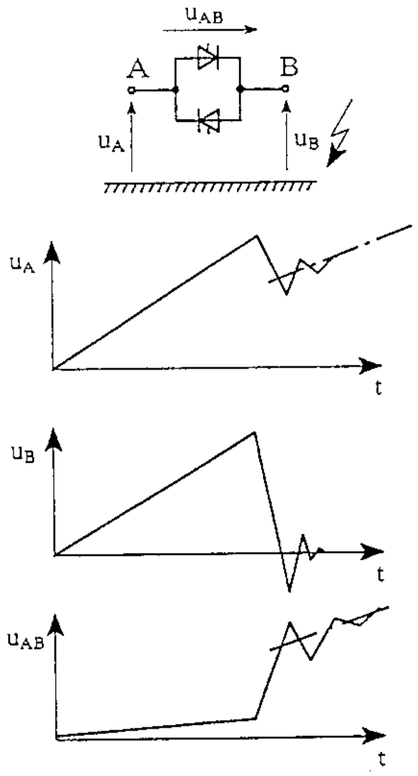
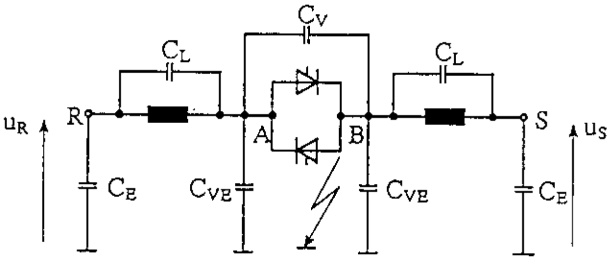


Fig. 10.. Insulation failure to ground (following a common mode switching surge)

The du/dt and magnitude of the steep front valve voltage depend on the stray capacitances and inductances of the actual design. To estimate the prospective magnitude of this voltage, the simplified high frequency scheme of one TCR branch with split reactors, shown in Fig. 11 can be used.



C_L	Winding capacitance	R,S	Bus bar connections
C_V	Stray capacitance of valve and reactor halves between terminals	A,B	Valve terminals
		C_{VE},C_E	Stray capacitance to ground

Fig. 11. **Simplified high frequency equivalent circuit of a TCR branch for analysis of insulation failure to ground**

The surge capacitors keep the busbar potentials u_R and u_S almost constant for the first few microseconds after an insulation failure. For a fault on terminal B to earth, the prospective voltage step across the valve becomes

$$\Delta u_{AB} = U_B\left[\frac{C_{VE} + C_L}{C_V + C_{VE} + C_L}\right] \qquad (7)$$

where U_B is the initial voltage on terminal B to earth prior to the fault and C_L, C_{VE}, C_V are the stray capacitances. The amplitude, rate of rise and natural frequency of the actual voltage transient at the valve depends on the magnitude and distribution of the circuit stray capacitances and stray inductances.

It is known that indoor insulation failures have become rare. For outdoor insulation failures, the effective stray inductance (not shown in Fig. 11) exceeds several micro Henries, thus reducing sensibly the voltage steepness.

Note: When evaluating the need for impulse voltage tests it is necessary to take into account the temperature and voltage dependent characteristics of the thyristors (see Appendix 4).

5.6 Effect of Insulation Failure on Conducting Valves

If an earth fault occurs while the valve is conducting, the valve current may be increased by a factor of two in the case of multiple earth faults for valves connected between split reactor halves. Higher fault currents can be caused, if the reactor is built as one unit per phase.

A case which could occur is a developing short circuit in one half of the controlled reactor in split arrangement. Usually, symmetrical firing of all phases is provided. With a short circuit in one half of the reactor, a considerable asymmetry in impedance between the three phases is present and the current in the faulted phase can prospectively reach twice the rated value. However, the SVC controller normally acts to limit the current to a lower value as required by the function of the SVC with regard to the a.c. system. Therefore the fault may remain undetected by the overcurrent protection. To detect this condition a current negative sequence relay can be provided. However, some time may be needed to distinguish negative sequence current due to a reactor fault from negative sequence current caused by a.c. system faults.

In the typical case of vertically stacked half reactors, with the valve electrically connected between them, it is possible that, during the fault time, the short circuit reaches both halves of the controlled reactor. This means, that the valve is bypassed by the arc which prevents further stress on the thyristors at the expense of a totally affected reactor.

In an arrangement with only one reactor per phase, the valve stresses in the case of a short circuit of the reactor are much more severe. The thyristors can be destroyed immediately by discharging capacitors connected to the low voltage bus (transformer stray capacitances, surge capacitors, TSC etc.), if no special countermeasures are provided (see section 3.2.2). Since the fault current reaches high values, being limited mainly by the short circuit impedance of the step-down transformer, the SVC is tripped by instantaneous overcurrent while the valve is free fired.

5.7 Control Malfunction

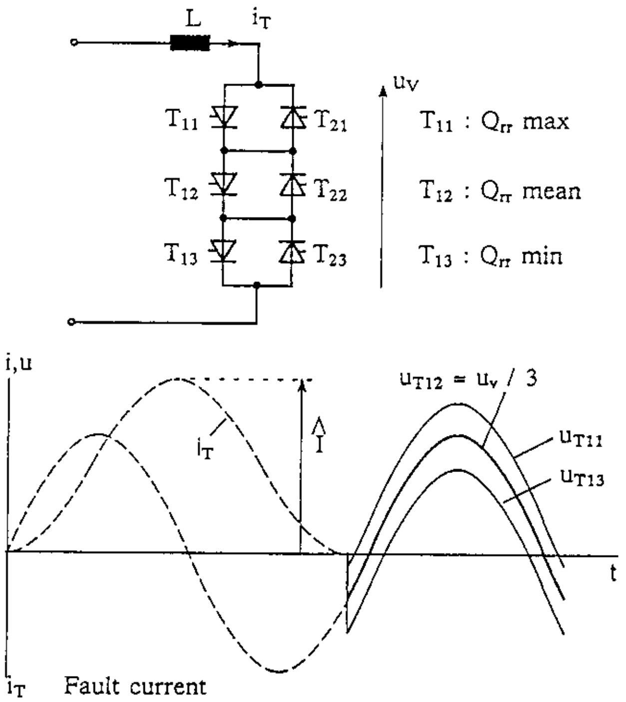
Many anomalies of operation can arise due to the malfunction of controls. Some examples will now be discussed:

- false firing of the valve,
- firing failure,
- malfunction of the closed loop control.

The valve protection should cover all these control malfunctions. Where it represents a limiting condition, the design should take care of it.

5.7.1 False Firing

In Fig. 12a the voltage and valve current waveshapes are shown in a very simplified manner for a TCR valve firing at α = 0°.



i_T Fault current
u_V Subsequent valve voltage
u_{T11}, u_{T12}, u_{T13} Thyristor voltages

Fig. 12a. **False Firing at α = 0°**

Due to the asymmetrical current waveshape, the valve is stressed by overcurrent in one direction, followed by a short hold-off interval for the last conducting thyristors.

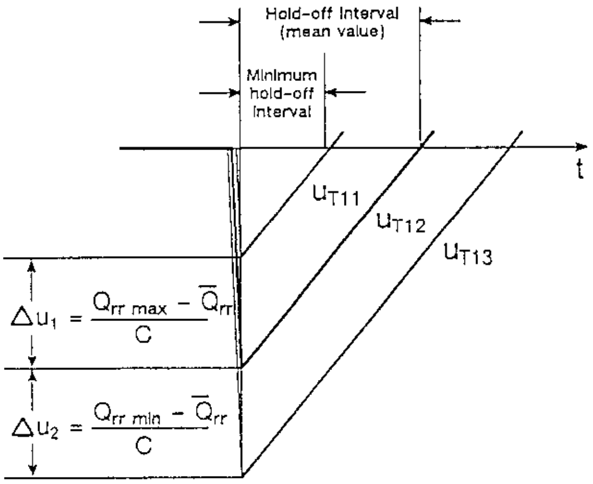


Fig. 12b. Deviations of thyristor voltages and hold-off intervals due to the spread of reverse recovery charge

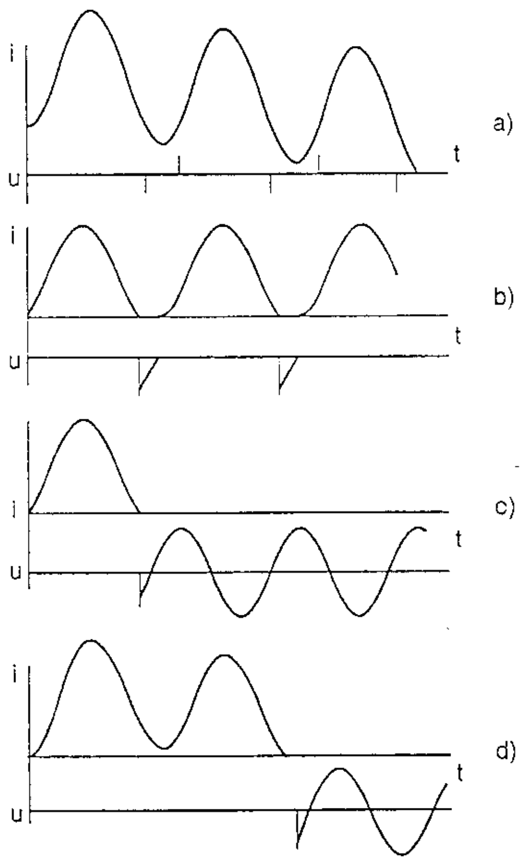


Fig. 13. Possible valve currents and voltages following system faults or false firing (shown for the worst case α = 0°)

The duration of the reverse voltage, i.e. the hold-off interval depends on the quality factor of the TCR circuit. For high quality factors, the hold-off interval can be rather short. Periodic firing with α = 0° may follow because of insufficient hold-off intervals. In addition, the spread of the reverse recovery charge establishes voltage deviations within the valve which are shown also in Fig. 12a. These further reduce the hold-off interval for some thyristors. If the valve is blocked, these voltage deviations can only decay through parallel paths e.g. parallel resistors or the leakage current of the parallel thyristors. The decay time constant may be rather long (a few 100 ms)

For firing at α = 0, Fig. 12a gives the blocking voltage of three thyristors with different reverse recovery charges. The curve (u_{T12}) is the voltage of a thyristor with the mean value of Q_{rr}. This trace also represents the voltage waveshape appearing across the complete thyristor string (u_v). The curve (u_{T11}) is the voltage of the thyristor with the highest reverse recovery charge Q_{rrmax} and the other curve (u_{T13}) represents the thyristor with the smallest, Q_{rrmin}. In Fig. 12a the voltage overshoot due to the decay of the reverse recovery current has been neglected.

Fig. 12b shows, in more detail, how the spread in recovery charge affects the available hold-off intervals for different thyristors in the valve. It is important that the minimum hold-off interval is greater than the turn-off time of the thyristors, otherwise a thyristor can turn on without a firing pulse.

A special case of a current waveshape following a false firing can occur if, during the current flow, the busbar voltage is reduced (Fig. 13, case d). In this case the current does not reach zero until the d.c. component becomes sufficiently low, depending upon the quality factor.

Current and voltage waveshapes of the valve after false firing are influenced by protective measures. Different possibilities are explained in Appendix 2

5.7.2 Firing Failures

If all but a few thyristors in a string of the valve are fired, the blocked thyristors will attempt to support the whole voltage across the valve. The blocked thyristors may be destroyed subsequently by overvoltage unless individual overvoltage protection (VBO) is used. Some valve designs rely upon the ability of thyristors to protect themselves by built-in protective firing in the event of high voltage. Other designs compensate for the risk of increased thyristor failure rate by increased redundancy of thyristors or provision of redundant firing circuitry.

To protect the thyristors, metal oxide (MO) based voltage limiting devices, connected at each thyristor level, or other equivalent voltage limiting protection can be used. However, if this strategy is employed, the protection device may be exposed to excessive duty if the firing pulse to one level fails. Therefore it may be necessary to trip the SVC or take other protective action to relieve this duty.

Where individual overvoltage protection firing is used, the voltage response of the protected thyristor level is generally as shown in Fig. 14.

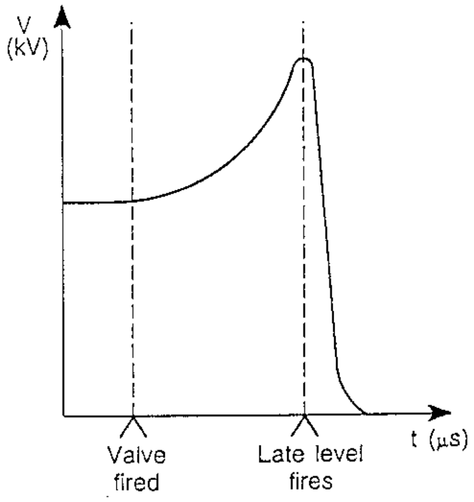


Fig. 14 Voltage on late firing thyristor level

Repetitive operation in this mode determines the continuous repetitive rating of the thyristor and its associated components. Maximum damping resistor dissipation and maximum thyristor voltage do not occur at the same operating condition as can be derived from the following equations. The voltage across a thyristor which fails to turn on when the rest of the valve is fired, will follow the equation (8) until its value reaches the VBO level, at which protective firing takes place.

$$u_T = i R + 1/C \int i \, dt + U_{co} \qquad (8)$$

where R is the damping resistor
i is the valve current
C is the damping capacitor
U_{co} is the initial voltage on the capacitor C

The power dissipated in the damping resistor due to voltage jumps can be approximated by the following formula:

$$P = \sum_{k=1}^{k=N} f \frac{1}{2} C \Delta U_k^2 \qquad (9)$$

Where
f is the power system frequency
ΔU is the voltage jump at firing or at extinction
N is the number of voltage jumps per cycle (usually one during turn-on and one during turn-off for each direction as per Fig. 3)

If periodic operation of active overvoltage protection (either by VBO, or by the thyristor itself) is allowed by the design, then the components must be rated for it. In such cases, one or both voltage jumps per cycle which are associated with the turn-on will attain the protective voltage threshold repetitively. As the regularly fired thyristors start conducting, the voltage across the unfired level rises and the resulting current charges its damping capacitor via its damping resistor. When the voltage across the unfired level reaches the threshold of the protective device, the thyristor is fired as shown in Fig.14. Maximum voltage jumps at firing and at extinction occur in normal operation near $\alpha = 90°$ where the thyristors are fired near the crest of the blocked power frequency voltage (see Fig. 3). Protective firing at this condition causes only slightly increased losses in the damping resistor because the voltage across the unfired level rises so quickly that the damping capacitor does not have time to be charged appreciably before the protective firing takes place. Maximum damping resistor losses are obtained with firing angles near 180° which allows charging of the damping capacitor up to a value very near to the threshold of the protective firing device. Note that in this case the voltage jumps at turn-off are very small.

If the valve is operated at high firing angles (near 180°), a failure to fire a thyristor might cause valve blocking in one conducting polarity only, while the valve operates as usual in the other polarity. In order to avoid a significant d.c. component of the valve current, the maximum firing angle for the healthy polarity must be limited if periodic overvoltage protective firing is allowed. The maximum firing angle should be limited to:

$$a = \arcsin \frac{nU_P}{\sqrt{2}\, U_2} \qquad (10)$$

where n is the number of protective fired levels
U_P is the protection voltage
U_2 is the rms value of the fundamental of the valve side voltage

5.7.3 Control Interactions with the Power System

Ideally, normal closed loop operation of the TCR produces no d.c. current. D.C. current is, however, possible due to control interaction with the power system. This can lead to saturation of the stepdown transformer creating harmonic currents which may distort the power system voltage further [4]. The result may be unstable operation with asymmetrical valve current, if the controller is not designed correctly.

Control or protection interaction with the system can also be caused by a failure of electronic control. For example, the loss of all firing signals, due to a power supply failure in the controls, could cause sudden blocking of the TCR. If the a.c. system is weak, this could cause high overvoltages which have to be considered for valve design and control.

Care must be taken with the design of the SVC protection to avoid incorrect interaction with the power system

6. CONCLUSIONS

The electrical stresses on TCR thyristor valves for SVC depend greatly on the particular SVC system chosen, the specific protection philosophy and the contingencies of the SVC and the power system to which it is connected.

Consideration of a typical valve and its main components with regard to stresses under different system operating conditions should serve as a basis for understanding the interdependence of specification, design and protection of TCR valves for SVC. Knowledge of valve stresses and relevant thyristor parameters is needed to determine necessary and sufficient testing conditions.

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[11] IEC - Semiconductor Convertors, Publ. No. 146, Part II: Application Guide, Section 5.1/5.2, Revision May 1985

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APPENDIX 1

DEFINITION OF PARTIAL BLOCKING

Partial blocking of a thyristor valve with series-connected thyristors means that only some of the thyristors are in the blocked state, while others are turned on for reasons other than the normal valve firing. Possible causes of partial blocking can be

- improper firing,
- du/dt firing following an insufficient hold-off interval or,
- protective overvoltage firing of individual thyristors.

To consider one specific case of partial blocking, assume that, under abnormal transient conditions, a forward current was extinguished by the application of a reverse blocking voltage to the valve and that a forward blocking voltage reappears with a certain positive du/dt within a short time.

Depending upon the individual turn-off times of the series-connected thyristors, some thyristors may turn-on without any firing pulse while the other thyristors have to block the complete valve voltage. The forward current of the conducting thyristors is mainly given by the displacement current via the damping circuits of the blocked thyristors. This effect, called partial blocking, means that, for forward blocking voltage, the initially blocked thyristors may be overstressed while, for an immediately following reverse blocking voltage, the originally conducting thyristors may be overstressed (see Fig. 15).

APPENDIX 2

FALSE FIRING OF A TCR THYRISTOR VALVE

The waveshapes of valve current and voltage after false firing depend on the protective measures adopted. Other important parameters are the quality factor of the circuit and the magnitude of the a.c. voltage source during the critical period after false firing. Fig. 13 shows several possible current and voltage waveshapes for the worst case of false firing at $\alpha = 0°$. Cases a through c assume constant a.c. voltage.

Case a

Continuous firing is applied for both current directions. As a consequence, voltage stress is avoided while the initial d.c. component of the valve current decreases. After some time, normal a.c. current is reestablished which allows normal operation.

Case b

In this case, continuous firing is generated for the thyristor string which experiences the initial firing at $\alpha = 0°$. Such protection may be provided to prevent the overheated thyristors from getting into the conducting state in a dangerous way. Hereafter the TCR has to be tripped or continuous firing for both directions (case a) is required to reach normal operation.

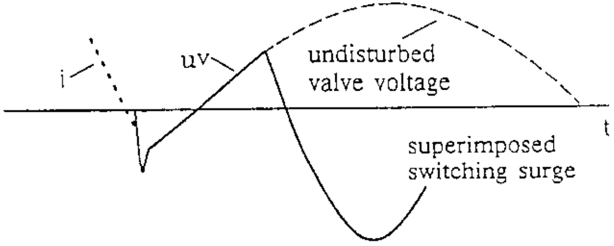
Case c

The traces show successful blocking of the valve after the first current zero crossing. Successful blocking requires a sufficient hold-off interval for the thyristors to regain their off-state blocking capabilities. Normal operation is possible immediately after the blocking as shown in Fig. 8a in a similar condition following an a.c. system fault.

Case d

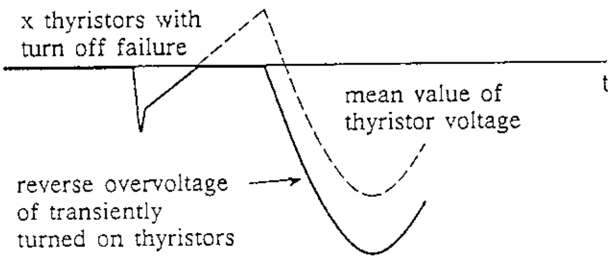
A.C. voltage is reduced during the conduction of the fault current which delays the next current zero crossing. All the protective actions explained above can be applied, but blocking of the valve can only be achieved after the first current zero.

a) Valve current and voltage



b) Thyristor voltages with partial blocking of the valve

b1) Thyristors which fail to block forward voltage



b2) Thyristors which successfully block forward voltage

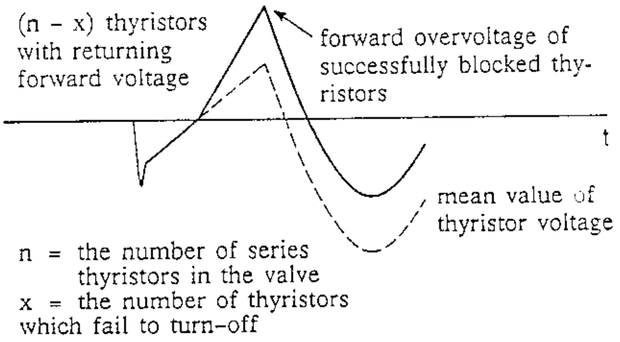
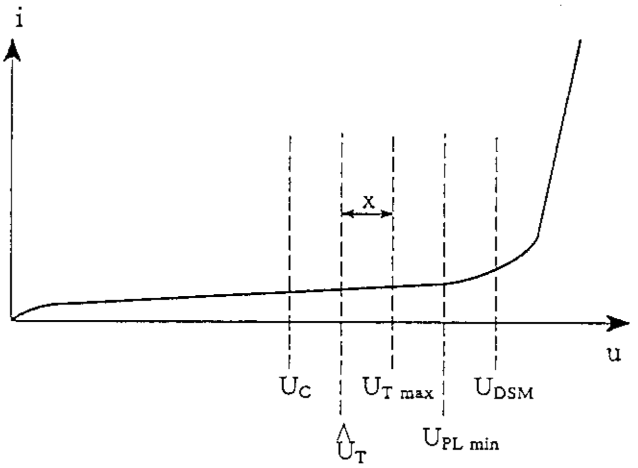


Fig. 15 . **Partial blocking at turn-off with resulting thyristor overvoltage**

APPENDIX 3

COORDINATION OF OPERATIONAL THYRISTOR VOLTAGE AND INDIVIDUAL PROTECTIVE FIRING LEVEL

To protect the thyristor, the protective firing level must be lower than the maximum repetitive blocking voltage of the thyristor. On the other hand, unnecessary protective action must be avoided. Therefore the protective firing level U_{PLmin} is chosen to be above the maximum thyristor voltage U_{Tmax} in normal operation, taking into account tolerances and temperature dependency of thyristor and grading network characteristics and assuming that redundant thyristor levels are short circuited. Fig. 16 shows the coordination of individual thyristor voltages, minimum protection firing level and thyristor blocking capability expressed by the non-repetitive peak off-state voltage U_{DSM}.



U_{DSM}	given by thyristor specification or data sheet
$U_{PL\,min}$	minimum protective firing voltage, taking into account tolerances and temperature dependency
x	maximum voltage deviation due to spread of recovery charge
$U_{T\,max}$	maximum operating thyristor voltage
$\hat{U}_T$	peak operating thyristor voltage including extinction overshoot and voltage sharing unbalance due to grading network component tolerances
U_C	maximum normal a.c. voltage (peak) per thyristor with redundant thyristor levels short circuited

Fig. 16 . Coordination of protective firing levels

The causes of increased voltage stress of the thyristors are:

- A.C. voltage (peak) per thyristor at the limit of controlled operation and assuming that the redundant thyristors are short circuited, U_c
- extinction overshoot factor, k_c
- tolerances of damping components (factor f_v) and spread in reverse recovery charges resulting in voltage deviation x.

The peak value of the operating thyristor voltage, ignoring voltage deviation due to spread in reverse recovery charge is

$$\hat{U}_T = f_v\, k_c\, U_c$$

The voltage deviation,x, due to the spread in reverse recovery charge, can be calculated as

$$x = \frac{\overline{Q}_{rr} - Q_{rr}\,min}{C}$$

where $\overline{Q}_{rr}$ is the mean value of the reverse recovery charge, Q_{rrmin} is the minimum reverse recovery charge and C is the damping capacitance of a thyristor level.

The maximum thyristor voltage U_{Tmax} equals

$$U_{Tmax} = \hat{U}_T + x$$

The value of the VBO voltage must be chosen between the maximum operating thyristor voltage and the maximum permitted thyristor voltage U_{DSM}. Therefore the relation for the minimum VBO voltage U_{PLmin} becomes:

$$U_{DSM} > U_{PLmin} \geq f_v\, k_c\, U_c + x$$

APPENDIX 4

THYRISTOR CHARACTERISTICS WITH RESPECT TO DIELECTRIC TEST STRESSES

Valve dielectric tests are usually performed at room temperature since it is not economical or even possible to reproduce normal working temperature of the valve in the factory. Therefore stresses of dielectric tests may differ from operating stresses. In terms of voltage withstand, the thyristors have lower capability at low ambient temperature than at normal working temperature [9]. Therefore tests applied under low ambient conditions represent the most difficult voltage duty for the thyristor. On the other hand, thyristors at maximum service temperature, though exhibiting increased voltage blocking capability, have reduced du/dt capability.

It is important to note that the thyristor is sensitive not only to du/dt and temperature but also to the magnitude of the excursion and the initial voltage from which the excursion commences.This is because detrimental du/dt initiated turn-on is displacement charge dependent as well as displacement current dependent and because the thyristor junction capacitance varies as a non-linear function of applied voltage, with the principal variation taking place within a few hundred volts off zero. This voltage dependence on junction capacitance is important because a pre-bias of a few hundred volts in either direction can significantly reduce the displacement current and charge due to a transient of given magnitude and rate-of-rise. The worst case occurs for an impulse initiated from zero pre-bias but requires, as a minimum, a certain design-dependent voltage excursion in order to exceed the charge threshold for firing. This means that steep-front transients below a certain amplitude do not pose a threat to the thyristors, whatever the steepness of the wavefront. This should be considered when deciding on the need, or otherwise, for lightning or steep front impulse voltage tests between valve terminals.

PART II

VALVES

FOR

THYRISTOR SWITCHED CAPACITOR (TSC) TYPE

STATIC VAR COMPENSATORS

Principal Author

KAJ ENGBERG

1. INTRODUCTION

A Static Var Compensator (SVC) in a power transmission system often comprises thyristor-switched capacitors (TSCs) in combination with thyristor-controlled reactors (TCRs), see Fig.1. Sometimes a fixed capacitor bank (FC) or a tuned filter bank is connected in parallel with the TSC. The operating requirements and protection arrangements for the thyristor valves used for capacitor switching are generally quite different from those for a TCR valve.

Part II of this CIGRE Technical Brochure deals with steady-state and transient stresses of a thyristor valve used for switching a shunt capacitor bank in a static compensator and serves as a basis for defining proper testing of the valve.

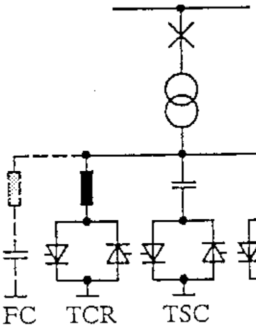


Fig.1: Single line diagram of an SVC comprising TSCs and TCRs

2. BASIC CONFIGURATIONS

As mentioned in the introduction, a SVC for a transmission system often comprises a combination of TSCs and TCRs, but it can also sometimes comprise only TSCs. The TSCs are switched on or off in steps, unlike the TCR which is phase angle controlled. A suitable combination of TSCs and TCRs can provide continuous control of reactive power, see Ref.5 , chapter 2.

A single line diagram of a basic thyristor-switched capacitor bank is shown in Fig.2a. It consists of a capacitor bank, a series reactor and an electronic switch composed of a string of anti-parallel connected thyristors. The series reactor is selected with due consideration to resonance of the system and it also serves to limit the inrush current from the capacitor at the instant of firing of the valve.

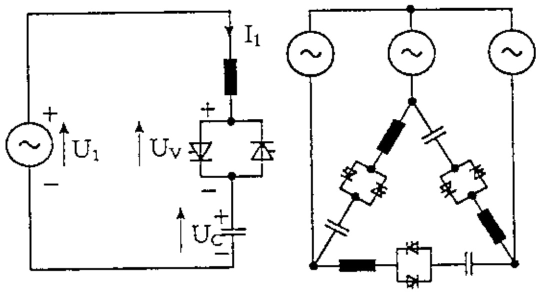
Fig.2b shows the full three-phase representation of the circuit for the delta-connection of the TSC. Wye-connection is also possible (see Fig.2c) but it requires that the neutral point of the secondary of the SVC transformer is available and can be connected to the neutral point of the TSC bank (4-wire system). It should be noted that any harmonic distortion of the system voltage will result in different harmonic current flow in the TSC depending on whether the TSC is delta or wye connected.

3. FUNCTIONS OF THE VALVE

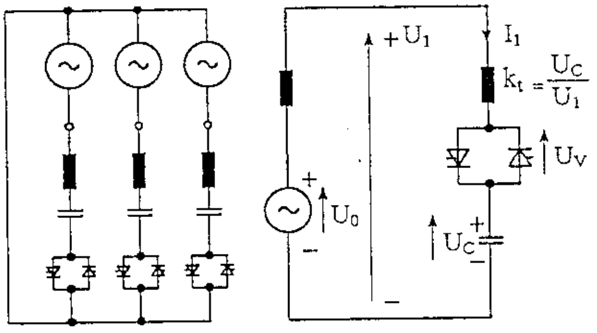
3.1 General

A TSC valve is operated as a switch, which is either on or off. When on, the valve is fired periodically each half-cycle at the natural zero crossing of the TSC current. The valve then conducts the full capacitor current. When off, no firing pulses are applied and the valve blocks the current. Contrary to the case for a TCR, continuous control of a TSC by phase angle control is not possible. An attempt to reduce the current by delaying the firing of the valve would just result in a severely distorted current waveform, but with the fundamental current component almost unaffected.

In the rest of section 3.1 it will be assumed that the TSC is directly connected to a bus with infinite fault level, i.e. the system and the coupling transformer impedances are negligible. In practice this assumption can seldom be justified, and due consideration has to be given to the effects of the step-down transformer and network impedances. Here the assumption, that the TSC is directly connected to an infinite bus, is made for the sake of simplicity and with the intention of making the description of the basic TSC operating characteristics easier to comprehend.



a) Single line diagram b) Delta-connection



c) Wye-connection d) Definition of voltages

Fig.2: Basic TSC connections

Fig.3 shows the waveforms of voltage and current for a single-phase TSC or one of the phases of a three-phase TSC when on. The firing angle α of the TSC valve is defined as the system fundamental frequency phase angle corresponding to the time interval from the zero crossing of the system voltage to the instant of firing of the valve. Ideally the firing angle α is $\pi/2$ radians (90 degrees) in steady state operation with the TSC on.

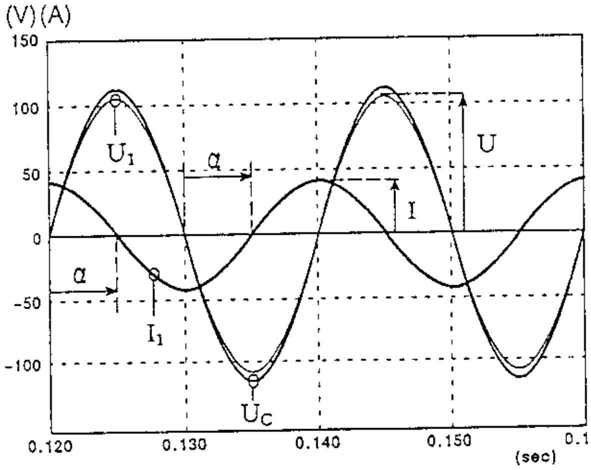


Fig.3: Waveforms of voltage and current of a TSC when on

TSC bus voltage (U_1), capacitor voltage (U_C) and TSC current (I_1). Infinite fault level at the TSC bus. TSC tuned to 4.5 times the system fundamental frequency.

Switching-off of a TSC valve is performed by blocking the firing pulses. Since an already conducting thyristor continues to conduct until the anode current decreases to zero even if the firing pulse is blocked, the extinction of the valve is executed at the next zero crossing of the TSC current. During steady-state operating conditions, the switching-off therefore takes place at system crest voltage. At this instant the capacitor voltage is also at its crest value. After extinction of the valve current the charge trapped in the capacitor will discharge via the internal capacitor discharge resistors and via external discharge paths, for instance through the voltage grading circuits of the thyristor valve. As the discharge resistances are usually large, the discharge process is slow and it may last up to several minutes.

Due to the presence of the series reactor, the capacitor crest voltage is $k_t=n^2/(n^2-1)$ times higher than the crest voltage U at the infinite bus. Here n denotes the TSC tuning factor defined as the ratio between the TSC self-resonant frequency $f_n=1/(2\pi\sqrt{LC})$ and the system fundamental frequency f_1, where L is the inductance of the series reactor and C is the capacitance of the TSC capacitor. Consequently, $n=1/(2\pi f_1\sqrt{LC})$

For a typical TSC the tuning factor n is between 3 and 5 and the voltage factor k_t then becomes 1.13 to 1.04. After extinction of the valve current, the difference between the system voltage and the capacitor voltage appears across the valve. The waveforms associated with blocking of the valve are shown schematically in Fig.4.

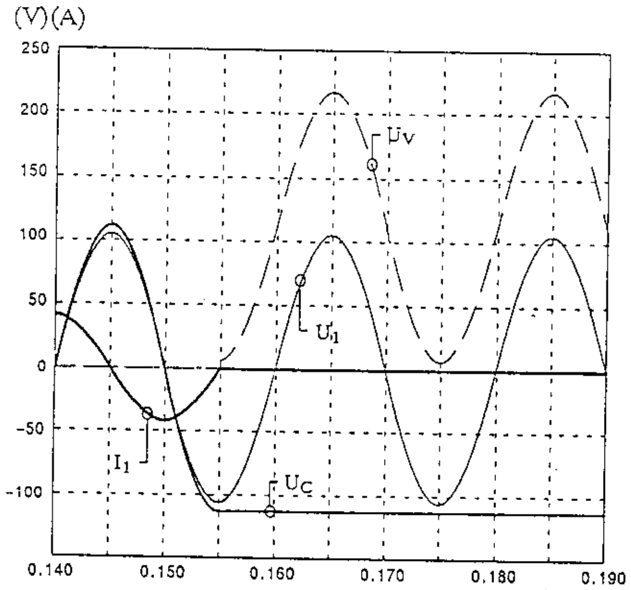


Fig.4: Waveforms when blocking the TSC

TSC bus voltage (U_1), capacitor voltage (U_C), voltage across TSC valve (U_v) and TSC current (I_1). TSC tuned to 4.5 times the system fundamental frequency.

The extinction of the valve current initiates a transient overshoot on the valve voltage similar to that of a TCR valve. However, at the extinction, the voltage which appears across the valve is $(k_t-1)*U$ (i.e. typically only 0.04 to 0.13) times the infinite bus crest voltage U. The peak value of the extinction overshoot under steady state operating conditions is therefore several times lower than the maximum voltage across the valve appearing half a cycle after the extinction. This maximum voltage is $(1+k_t)*U$, i.e. typically 2.04 to 2.13 times the crest voltage U.

As can be seen from Fig.4, the voltage across the valve after switching-off includes, in addition to the alternating component originating from the system, also a direct component originating from the charge trapped in the capacitor. If the TSC off interval is long enough, the capacitor will discharge completely, and only the alternating component will be present across the valve. The voltage stress on the valve is then substantially reduced, compared to what it was initially after blocking. Operation at a high switching on and off repetition frequency therefore means more severe voltage stresses on the valve, than operation with longer on and off intervals.

At switching-on of the TSC, a transient oscillatory current component is superimposed on the steady state fundamental frequency current component. The frequency of the transient is determined by the capacitance of the TSC capacitor and the inductance of the series reactor and is normally 3 to 5 times higher than the system fundamental frequency. The initial amplitude I_T of the transient component depends on the switching-on firing angle and the capacitor voltage at the instant of switching-on. Switching-on should be executed at the firing angle α_{opt}, for which the minimum switching-on transient is generated. This optimum firing angle is:

α_{opt} [radians] $= 3\pi/2$ for $U_{CO} \leq -U$

α_{opt} [radians] $= \pi-\arcsin(U_{CO}/U)$ for $-U < U_{CO} < U$

α_{opt} [radians] $= \pi/2$ for $U_{CO} \geq U$

where
U_{CO} = instantaneous voltage across the capacitor at the instant of switching-on
U = infinite bus crest voltage

The optimum firing angle α_{opt} and the relative amplitude I_T/I of the switching-on transient current, i.e. the ratio between the initial amplitude I_T of the transient component and the amplitude I of the steady state current component are shown in Fig.5.

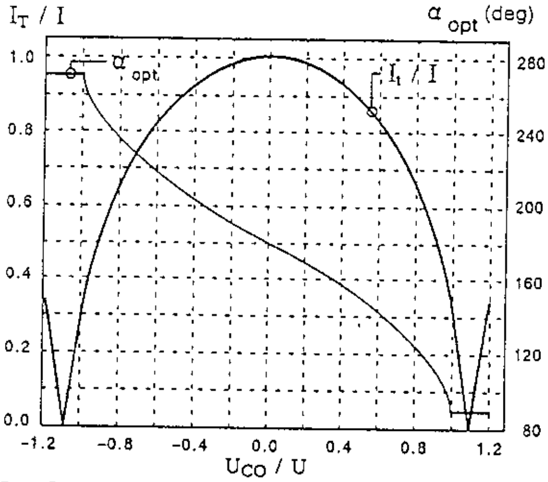


Fig.5: Optimum switching-on angle α_{opt} and switching transient I_T/I versus capacitor voltage U_{C0} for switching-on at the optimum angle for n = 3.5, i.e. k_t = 1.089.

The form of the curve for I_T/I depends on the tuning factor n and is drawn for n=3.5, i.e. the voltage factor k_t=1.089. The curve for α_{opt} is independent of the value of tuning factor n, and remains the same for all tuning factors. The above shows that the switching-on should take place when the voltage across the thyristor valve crosses zero. If there is no zero crossing, it should occur when the voltage across the valve is at a minimum. Typical waveforms at switching-on at the optimum firing angle are shown in Fig.6 for four different capacitor voltages U_{CO}. Note, that there exist two values of capacitor voltages, U_{CO} = $+k_tU$ and

$U_{CO} = -k_tU$, for which the amplitude I_T of the transient component is zero, when the TSC is switched on at the optimum firing angle α_{opt}. Thus, switching-on can be achieved without transients when the capacitor is charged to the voltage $U_{CO} = \pm k_tU$. Here k_tU is the crest value of the capacitor voltage, when the TSC is on in a steady-state condition.

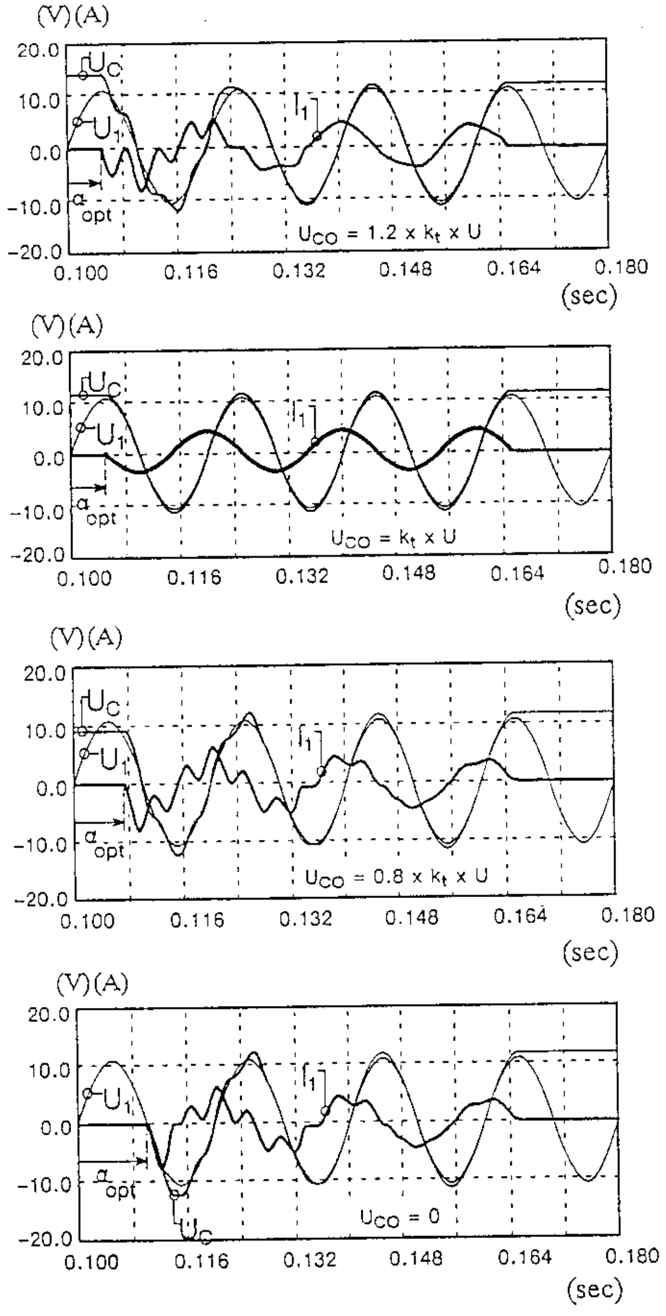


Fig.6: TSC switching-on at the optimum angle α_{opt} for minimum transients and TSC switching-off

TSC bus voltage (U_1), current (I_1) and capacitor voltage (U_C)
U_{CO} = capacitor voltage at the instant of switching-on
U = crest value of TSC bus voltage and k_t = voltage factor

The above formulae can also be used when the TSC is connected to a bus with finite fault level, provided that the value of the inductance L includes the inductance of the series reactor plus the equivalent inductance of the coupling transformer and the network as seen from the TSC. The value of the voltage U should then be the equivalent Thevenin source voltage rather than the bus voltage. For a delta-connected TSC with common line impedances of two or more phases it may be quite complicated to determine the correct equivalent inductance and source voltage, in which case a true three-phase representation of the system is recommended.

3.2 Functional Structure of the Valve

Descriptions of typical TSC valves can be found in reference [4]. With respect to electrical stresses on the valve it is practical to consider the functional structure of the valve shown in Fig. 4 of Part I.

In order to achieve sufficient voltage withstand capability, each phase of a TSC valve is built of an appropriate number of series-connected thyristor pairs. Each pair consists of a pair of thyristors in direct anti-parallel connection, i.e. the anode of one thyristor is connected to the cathode of the other thyristor of the pair and vice versa. Alternatively, two separate strings of series-connected thyristors can be used for each phase, one string for the positive current direction and one string for the negative current direction. An important advantage of the direct anti-parallel thyristor pair arrangement is that a common voltage grading circuit can be used for the two thyristors in the pair.

One thyristor or a thyristor pair and its associated auxiliary equipment at the same voltage potential represent a thyristor level.

For full utilization of the thyristor current handling capability forced cooling is required. The thyristors are therefore mounted on heat sinks. Air or water is normally used as the cooling medium for the heatsinks.

Paralleling of thyristors or strings is possible but normally not used. If the power handling capability is not sufficient, it is instead common practice to select a higher secondary voltage on the SVC transformer or to connect two or more complete TSC branches in parallel.

For valve structures including more than one phase, due consideration has to be given to additional stresses occuring between phases because of the charging of the capacitors. Depending on the switching-off instants for nearby phases, capacitors might be charged to full voltage with opposite polarities. The combined d.c.-a.c. stress also depends on the connection of the TSC-branch, wye or delta.

3.2.1 Grading Network

For uniform voltage sharing between the series connected thyristors voltage, grading circuits are connected in parallel to each thyristor pair (or thyristor in case of separate strings for each current direction).

The sharing of the direct voltage component, which originates from the voltage trapped in the capacitor bank at the extinction of the valve current, can be greatly improved by voltage grading resistors connected directly across each thyristor level. Without such resistors the distribution of the direct voltage component is determined by the thyristor leakage currents, which may vary considerably from thyristor to thyristor.

The voltage grading network also includes series resistor-capacitor (RC) circuits (also called damping or snubber circuits) across each thyristor level for an even distribution of alternating voltage components along the thyristor string as well as voltage transients from the power system. The RC-circuits should be designed for optimal damping of the extinction voltage overshoot. In addition, they should be designed to reduce the difference in voltage distribution at turn-on of the valve caused by differences in turn-on times of the thyristors and at turn-off caused by differences in the reverse recovery charges.

During steady-state operating conditions, the step in the voltage across a TSC valve at turn-on and turn-off is low, typically 4 to 13 % of the crest voltage U across the complete TSC. However, the TSC valve should also be able to operate under fault conditions, for instance a line-to-line fault in the system, or at false firing with subsequent blocking. Under such conditions the voltage step at turn-on and turn-off may be much greater. In addition, the rate of change of the current at the zero crossings may be several times higher than in steady state operating conditions and consequently imposes a higher than normal recovery charge in the thyristors. These conditions must be considered when designing the voltage grading circuits.

3.2.2 Valve Reactor

The valve design for a TSC may include saturable reactors connected in series with the valve in addition to the series reactor. The purposes of these reactors are:

- to reduce the thyristor current stresses immediately after turn-on, resulting from commutation of arrester current (where arresters are provided) and from discharging of parasitic capacitances in parallel with the valve;
- to limit the du/dt of the thyristor voltage during fast front voltage surges;
- to reduce radio interference.

The valve reactor must be designed for the worst overvoltage conditions. In normal operation the valve voltage at turn-on is rather low which means that, if the valve reactor is saturating, the time to saturate the reactor is rather long. This will cause a delay in the real turn-on of the valve, and generate current harmonics which must be allowed for in the rating of other SVC components.

3.2.3. Firing System

Firing of the thyristors at the appropriate instant in the cycle is initiated from the SVC control circuits at earth potential. The valve firing system transmits this information from earth potential to the thyristor levels at which point gating pulses are generated to turn on the thyristors.

3.2.3.1. System Requirements

From the system performance point of view it should be possible to fire the thyristors at any instant required by the system. Thus restrictions in the operation of the TSC should not be introduced by the firing system, i.e. unrestricted firing capability should be provided (see Ref.1).

The firing system should be arranged to deliver gate pulses in such a way so as to cover the complete conduction intervals of the thyristors in order to achieve a diode-like conduction. The system must ensure that the thyristors will start to conduct as soon as a forward voltage appears across them. Also, in the case of multiple current zero crossings during a half-cycle, it must ensure that the thyristors will be re-gated if necessary. If a "pulse on demand" system using short gate pulses is employed instead of a long gate pulse system, then the forward voltage threshold for release of gate pulses must be kept low to minimize the generation of harmonic currents.

For TSC turning on from a significant voltage, imperfection in the coherent turn-on of the thyristors should be minimized in order to prevent turn-on overvoltages on individual thyristors.

The front of the gate pulses should be as steep as possible and the pulses should have a sufficient amplitude so as to minimize the thyristor turn-on stresses.

When blocking a TSC, particularly during transient conditions, the firing system must be able to deliver additional gate pulses, as necessary, to protect the thyristors from damage arising from forward recovery failure or from overvoltage arising from a partially blocked valve caused by insufficient recovery time (see part I, appendix 1).

3.2.3.2. Description of Different Techniques

The valve firing systems in use today can be divided into two major groups:
- magnetic systems
- optical systems.

The magnetic systems utilize magnetic firing pulse transformers for transmission of the firing information from earth potential up to the thyristor levels. Most often these systems also supply the energy required for firing of the thyristors from earth potential via the firing pulse transformers. Such a system can offer unrestricted firing capability. The energy for firing is supplied from an auxiliary source at earth potential, and therefore is available at any instant independently of the voltage across the valve. In addition it is possible to design a magnetic firing system, so that the duration of the firing pulses to the thyristors is equal to the expected conduction interval and with sufficient amplitude during the complete pulse length in case refiring should occur. It should be realized that presence of a gating current during the blocking of the reverse voltage will increase thyristor leakage current which increases its loss and may upset voltage distribution.

The optical systems can be based on direct or indirect light triggering.

The thyristors used in most TSC valves in operation today require an electrical gating signal. Then the optical firing system must be of the indirect type, where the firing information is transmitted in the form of light pulses by fibre-optic light guides from earth potential to the thyristor levels. Each thyristor level is then provided with a circuit, which converts the light pulses into electrical pulses applied to the gate of the thyristor. The energy required for these circuits can be obtained from the voltage across and the current through the thyristor, or it can be supplied via auxiliary transformers from earth potential. It is not sufficient to derive the energy only from the voltage across the thyristor or only from the current through it. A combination of both is necessary, because there may be a requirement for keeping the valve on or off for long intervals of time.

Thyristors which can be fired directly by a light pulse have been developed. For valves employing such thyristors, direct light firing via fibre-optic light guides is used.

Some systems generate short pulses with a duration of some tens of microseconds. In such case monitoring of the thyristor voltage is required, so that the firing pulse can be released only when there is a forward blocking voltage across the thyristor and also that a refiring can take place in case of multiple current zero crossings during the half-cycle.

The availability of light sources which can provide firing pulses long enough to cover the complete conduction interval simplifies the optical firing systems.

Properly designed, both the magnetic and optical systems can meet the system requirements.

3.2.4. Supervision System

It is known that failed thyristors become short circuit and are able to safely carry current. It is therefore possible to continue the operation of the valve, provided that redundant thyristors have been installed, and that a sufficient number of series-connected thyristors are still available to match the voltage requirement.

Most TSC valves therefore include a supervision system continuously monitoring the status of the thyristors. Failed thyristors can be detected only during the blocking state. This system senses the voltage across each thyristor level. The monitoring signals can be sent from the thyristor potentials to earth potential for processing system information. Light guides or magnetic transformers can be used for the signal transmission. The supervision system normally provides information on the number of failed thyristors and their locations and prevents prolonged operation when more thyristors than the redundant ones have failed. It can also contain information on failed thyristor level electronics, repeated VBO operation and the voltage across individual thyristors.

3.2.5. Overvoltage Protection

Overvoltage protection can be provided for the whole valve (i.e. across the complete string of thyristors), and/or for each thyristor level (i.e. across each individual thyristor pair). For valve protection, metal oxide arresters are usually employed. Voltage break-over devices (VBOs) may be installed as a protection for each individual thyristor level.

The development of the metal oxide arrester has provided the TSC design engineer with an effective tool for limitation of overvoltages. Thanks to its strongly nonlinear V/I characteristic, the metal oxide arrester can effectively limit overvoltages while consuming practically negligible power at normal operating voltages. Protective levels (instantaneous values) of 1.6 to 1.8 times the crest value of the continuous operating voltage (CCOV) of the arrester can be achieved.

In order to limit transient overvoltages arising from the power system, an SVC is normally provided with line-to-earth arresters both on the high and the low voltage sides of the SVC main transformer. In some cases it is preferable to employ line-to-line protection. The design of these arresters is similar to that of conventional line metal oxide arresters, although the required energy capabilities may be higher, since large capacitor banks are often involved in SVC applications.

An effective way to protect a TSC valve against overvoltages is the connection of an arrester across the valve terminals, see reference [2] and Fig.4 of Part I. When the TSC is switched out, the valve is subjected to the voltage from the system plus the voltage trapped in the capacitor bank. This must be considered when selecting the rated voltage of the arrester. The selection of the arrester should be such, that the SVC can operate without the arrester being overstressed when the TSC is switched in and out with a high repetition frequency compared to the capacitor discharge time constant. In designs where the arrester is connected directly across the valve, precautions should be taken to avoid firing of the valve when there is a high current in the arrester. Such a firing would cause a very high rate of rise of the valve current and may be hazardous for the thyristors.

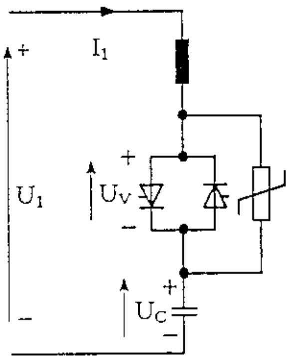
Besides the common method to protect a TSC valve against overvoltages by connecting an arrester directly across the valve, other locations and combinations of arresters are in use, e.g.:

- Arrester parallel to the valve and arrester parallel to the series connection of valve and reactor
- Arrester parallel to the capacitor and arrester parallel to the series connection of valve and reactor.
- Instead of being connected directly across the valve terminals the arrester could also be connected in parallel with the series combination of the valve and the series reactor. For this alternative the protection level with regard to the valve is not so well defined because of the voltage across the reactor. The benefit of this arrangement is that the rate of rise of the thyristor current is limited if the valve is fired when the arrester is carrying a high current.

The main purpose of using arresters or combinations of arresters is to limit the valve voltage resulting from external circumstances (surge impulse voltages coming from the a.c. system) or from internal faults (e.g. valve recovery voltage after false firing), thus minimizing the number of series connected thyristor levels.

The energy dissipation the arrester has to be designed for depends on the worst operating and fault conditions. The arrester design may require system studies to establish adequate design criteria.

A TSC capacitor may be overcharged, for instance at recovery from an a.c. system fault or if there is a fault in the control system. If the capacitor is charged to a high positive voltage, it begins to discharge slowly after the valve has been turned off. As soon as the system voltage becomes sufficiently negative, so that the voltage across the arrester exceeds the knee-point, the arrester provides a discharge path to the capacitor. The voltage across the capacitor then drops to approximately two times the system nominal crest voltage U, see Fig.7



Meaning of Symbols:
TSC bus voltage (U_1), capacitor voltage (U_C), thyristor valve voltage (U_v)and TSC current (I_1).
Expected capacitor voltage (U_{C1}) and valve voltage (U_{V1}) without arrester are also shown below.

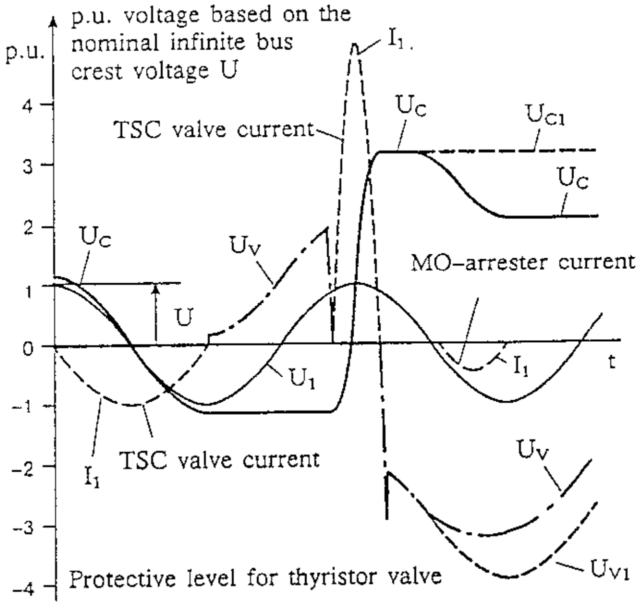


Fig.7: **Waveforms due to a single false firing in a TSC provided with an arrester directly across the valve**

In many applications, the capacitor can withstand the maximum voltage it may be exposed to, before discharging via the arrester across the valve takes place. In some applications, with very severe overvoltage conditions, it is necessary to also employ an arrester directly across the capacitor terminals. Theoretically, it would be possible to select the rated voltage of this arrester such that a protective level (instantaneous value) of approximately 2.5 times the nominal capacitor voltage (rms value) is achieved, i.e. approximately 1.8 times the nominal capacitor crest voltage. This however would require a very high energy dissipation capacity of the arrester. Therefore for practical reasons the arrester is often selected in such a way that the protective level equals 2 to 3 times the nominal capacitor crest voltage.

In addition, the capacitor may also be provided with an overcharge protection, which prevents the valve from being switched out, when there exists an excessive voltage across the capacitor. This prevents the capacitor from being switched out with a trapped voltage higher than the protection set level. This protection ensures that, after blocking of the TSC, the discharge current through the valve arrester is reduced. Setting of the levels for the overcharge protection requires due consideration of the system aspects. The setting must be high enough in order not to prevent switching off of the TSC during even the most severe system overvoltage situation caused by external faults or operating conditions. Internal faults such as false firing may cause even higher overvoltages across the TSC capacitor than external faults. The internal faults are often associated with strongly distorted waveforms with multiple zero crossings of the current during each half-cycle. In such conditions the overcharge protection defines the highest voltage level across the capacitor at which blocking of the TSC takes place. If the voltage across the capacitor at the current zero crossing is above the set level, blocking is prevented at that zero crossing. However, the next current zero crossing normally is associated with a capacitor voltage below the protection setting and then blocking takes place at that instant. In other words blocking of the TSC, when the overcharge protection is in operation, takes place at the first current zero crossing with a sufficiently low capacitor voltage. The overcharge protection thus sets an upper limit for the capacitor voltage at blocking and hence also for the valve arrester stresses due to the discharge current from the capacitor. Due to the reduced discharge current through the arrester, the voltage stress on the valve is somewhat reduced.

It is a common practice to provide TCR valves with some type of voltage break-over device (VBO) in order to protect the valve against overvoltages (see part I, section 3.2.4). Often, individual protection is provided for each thyristor level. When an overvoltage exceeds a specified level, the device fires the thyristor. Since the thyristor pairs are connected in direct anti-parallel connection, each of the two thyristors of the pair protects the other in the reverse direction. Alternatively, this device can also be designed as a valve protection, measuring the total valve voltage and firing all the thyristors in one direction simultaneously.

For TSC valves, use of this type of protection as a main overvoltage protection has the following disadvantages:

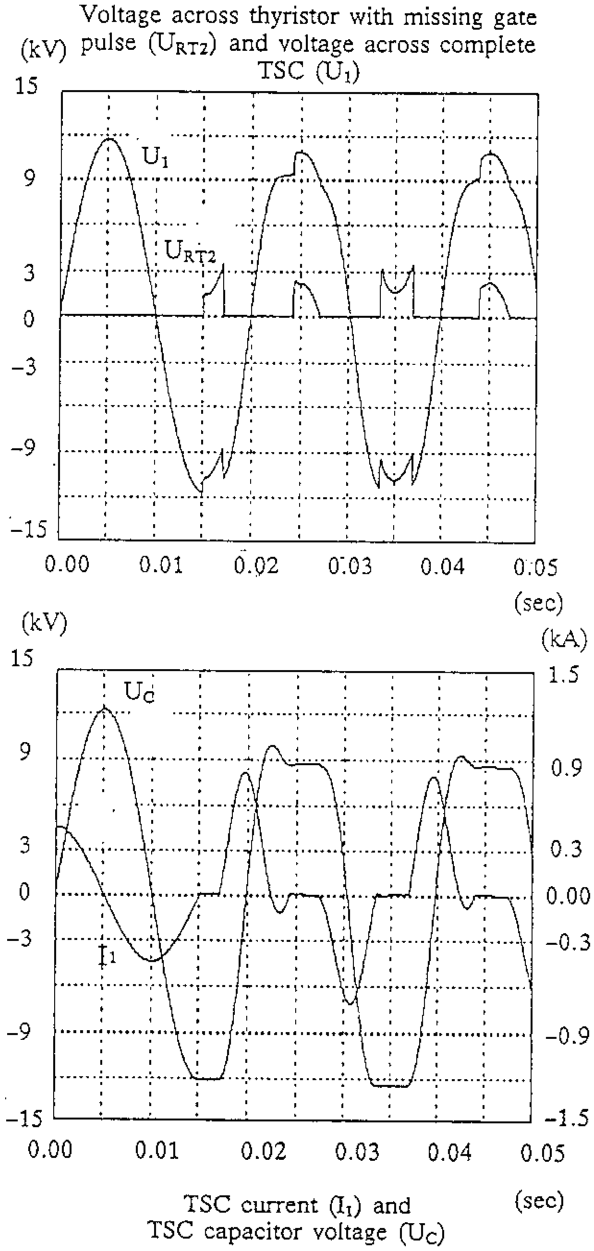
- From a system point of view a TSC should, contrary to a TCR, be switched off during overvoltage conditions. This is because a conducting TSC will raise the voltage and therefore compound the overvoltage situation.

- Firing of the TSC valve, when exposed to a high voltage, means a high inrush current, which may be hazardous to the valve.

- Finally, repetitive firing of a thyristor level by the VBO (e.g. due to failure of the normal firing circuit) will generate harmonics. It should be checked that the harmonic injection does not jeopardize the system operation (e.g. disturbance to telecommunication systems).

If VBO protection is provided, the valve break-over level must be selected sufficiently above the arrester level in order not to fire the valve, but solely to give individual thyristor protection. Redundancy and uneven voltage sharing in the valve must also be considered.

As an illustration of the harmonic generation caused by repetitive VBO firing of one thyristor level, Fig.8 shows the resultant TSC delta-phase current (for further details, see Ref.1).



Voltage across thyristor with missing gate pulse (U_{RT2}) and voltage across complete TSC (U_1)

TSC current (I_1) and TSC capacitor voltage (U_C)

Fig.8: TSC operation with missing firing pulse to one thyristor. The valve is provided with individual thyristor level VBO protections of 3.5 kV.

At t=0 the TSC is on and the operation is normal. Starting from t=15 ms, the firing pulse to one thyristor in the positive current direction fails permanently. The only thyristor, which can block any forward voltage is that with the missing pulse. Note that the corresponding waveforms for a firing system with a firing pulse length for each thyristor corresponding to its expected conduction interval would be different and they would include more even harmonics.

The main reason for installing VBO protection is to protect individual thyristor levels from the stresses due to partial blocking (see appendix 1 of Part I).

Thyristors turning on by themselves when the voltage exceeds the forward blocking capability may, in the case of loss of the firing pulse to one thyristor, give the same effect as VBO firing. However a thyristor of normal design for TSC applications cannot usually withstand repeated break-over from high voltage. A loss of a firing pulse to one thyristor then results in a permanent short circuit of the affected thyristor level.

3.2.6 Overcurrent and Thermal Protections

The temperature of the thyristors in the valve is an important parameter for the valve current handling capability. A thyristor valve is designed for a specified rated current. Steady-state operation with this current should not, under specified cooling conditions, cause the thyristor junction temperature to exceed the design temperature for the conditions specified. If operation at system overvoltage is required, the TSC nominal current must be chosen to be lower than the valve rated current in order to allow for sufficient margins, so that the thyristor design temperature is not exceeded during specified overload cycles.

The thyristor voltage blocking capability decreases if the thyristor data sheet rated junction temperature is exceeded. This is especially true for the forward voltage blocking capability. This decrease is not dramatic for moderate overtemperatures. For thyristors of normal design, more than 90% of the voltage blocking capability is still available for temperatures up to 20 to 30°C above the rated junction temperature. The increased leakage current may however affect the voltage distribution in the thyristor string.

High overcurrents in a TSC may be an indication of an a.c. system fault or a false firing of the valve. If the amplitude of the overcurrent is high and causes high thyristor junction temperatures, it may be hazardous to block the valve. For coordination of the valve overcurrent design with the system requirements, it is important that a.c. system faults are closely defined so that, for the worst case specified condition, valve blocking is still possible (see sections 5.1 and 5.2).

Depending on the system requirements, different strategies for overcurrent protection can be adopted. Selection of the strategy is often a compromise between different requirements. One possible arrangement would be to design the valve to allow one false firing, after which blocking should be possible. For repeated false firings or overcurrents, the protection generates a continuous firing of the valve and initiates a tripping of the SVC. The duration of the continuous firing should be sufficient to ensure that no blocking of the valve occurs before the SVC main circuit breaker has been tripped and, in addition, the thyristors have cooled down sufficiently for safe blocking of any voltage that may be trapped in the SVC capacitors.

More sophisticated versions of the instantaneous overcurrent protection are combined with a thermal overload protection which simulates the thyristor junction temperature. The junction temperature is predicted from measured current and cooling conditions and a mathematical model of the thyristor and its heatsink. With this temperature prediction, it can be decided when the valve can be safely returned from continuous firing to normal control, thereby avoiding tripping of the SVC.

Apart from the above mentioned reasons, the need for a thermal overload protection is not as obvious for a TSC as it is for a TCR. In most applications, the TSCs are switched out during overvoltage conditions and will not be exposed to overload currents to the same extent as TCRs.

4. STRESSES UNDER STEADY-STATE OPERATING CONDITIONS

The principal voltage and current waveforms of the thyristor valve under steady-state operating conditions are shown in Fig.3 and have been previously discussed in section 3.1. The waveforms apply to a single-phase TSC supplied from a sinusoidal voltage source with negligible internal impedance. They are also valid for an idealized three-phase TSC with no common line impedance of the three delta-connected phases of the TSC.

For TSCs with trickle charge control, the capacitor banks are kept charged to minimize the switching-on transients. In such systems the thyristor valve is re-fired, when the TSC is off, in one direction as necessary. In this way the charge trapped in the capacitor at switching-off is restored and the capacitor voltage is kept equal to the system peak voltage. For such systems the thyristor valve must be designed to withstand the full direct voltage from the capacitor bank on a continuous basis.

Switching-off transients must also be considered. Ideally, the voltage across the valve at the instant of extinction would change instantaneously as a step directly from zero up to a value corresponding to the difference between the capacitor voltage and the bus voltage. However, due to thyristor recovery charge, capacitances and inductances in the circuit, the extinction of the valve current causes a damped transient oscillation in the valve voltage, which is superimposed on the ideal step and produces an overshoot. Since the ideal step in steady state operation is low, typically 0.04 to 0.13 of the TSC bus crest voltage, the extinction peak voltage including the overshoot is several times lower than the maximum voltage appearing across the valve half a cycle after the extinction. In steady-state operation therefore the requirements on the RC-circuits in the voltage grading circuits are much less severe for a TSC valve than for a TCR valve.

A situation in which with the TSC is repeatedly switched on and off with a high repetition rate means that the switching-off peak voltage will appear frequently across the valve. The possibility of such a situation should be considered when determining the possible voltage stresses on the valve and its components. In this context, special attention should be paid to the arrester across the valve, so that the high repetition of the switching-off peak voltage doesn't overheat the arrester.

For stresses caused by parallel connected TCR or FC see Part I, Section 4.1.2-4.1.3.

5. STRESSES UNDER TRANSIENT CONDITIONS

5.1 A.C. System Faults

A fault in the a.c. system, for instance a line to earth fault, may expose a TSC valve to overcurrents and overvoltages. When the fault occurs, there is a sudden change in the system voltage. If the TSC is on, the voltage change results in an oscillation between the TSC capacitor and the inductances of the circuit. This oscillatory current may have a considerable amplitude, especially for a nearby fault initiated at the instant of system crest voltage. The peak value of the oscillatory current component can be estimated by the simple formula

$$I_{Opeak} = U_{step}\sqrt{C/L_{tot}}$$

where

U_{step} = instantaneous value of the step in the voltage

C = capacitance of the TSC capacitor bank

L_{tot} = total inductance in the circuit, including transformer and system

The peak value of the fundamental power frequency current from the TSC bank is
$I_{1peak} = \omega\ C\ k_t\ U_{peak}$

where
ω = power system fundamental angular frequency
k_t = voltage factor according to section 3.1
U_{peak} = TSC bus crest voltage

To give an example, assume that $U_{step}=U_{peak}$ yields
$I_{Opeak}/I_{1peak} = 1/(\omega\ k_1\ \sqrt{L_{tot}C}) = \omega_r/(k_t\omega)$

where ω_r is the resonant angular frequency of L_{tot} with C $= 1/\sqrt{L_{tot}C}$

For typical TSC tuning factors of n = 3 to 5 and typical power system and SVC transformer inductances, the value of the ratio $\omega_r/(k_t\omega)$ is 2.5 to 4.5. Assuming that the fault occurs at nominal system voltage, an oscillatory current 2.5 to 4.5 larger than the TSC fundamental current at nominal system voltage can be expected. If the fault occurs during an overvoltage condition, the oscillatory current can be correspondingly higher.

During the fault the amplitude of the oscillation attenuates at a rate depending on the system damping and the control of the thyristor valve.

At fault clearing, the system voltage recovers and a new sudden change in the voltage is applied to the TSC bank. As the fault current extinguishes near the natural zero crossing of the current, and the system impedance is inductive, the fault clearing takes place at an instant where the system voltage is close to its crest value. The voltage change at fault clearing may therefore also initiate a considerable magnitude of the oscillatory current in the TSC, if on.
For faults leading to sudden collapse of system voltage to a low value (eg. to less than 50% of U_n) it is advantageous to block the TSC for the following reasons:

- The transient currents initiated by the fault are suppressed.
- The TSC will be blocked at fault clearance so that the large current transients which can occur at recovery are not excited.
- Because the TSC is blocked, the system is not exposed to further increased overvoltages following fault clearance, which, with a conducting TSC, will persist for the time it takes the control system to switch off the TSC.
- The TSC valves, capacitors and surge arresters are not exposed to the large stresses which would otherwise arise as a result of having to block a conducting TSC during high system voltage after fault recovery.

On the other hand, blocking removes the voltage support being provided to the system during the fault. (Note that the MVAr output falls with the square of the voltage and is therefore only 25 % of the rated value at 50 % U).

Given that application of undervoltage blocking can be an important way of reducing SVC stresses, and hence costs, it is important that the system requirements are considered carefully and clearly specified.

5.2 Temporary Overvoltages

Fault clearing is often followed by a temporary overvoltage in the system. If the TSC is on at the instant of fault clearing and if it is then switched-off, because of the system overvoltage, the valve will be exposed to a higher than normal blocking voltage. Firstly, there will be a higher than normal voltage trapped in the capacitor bank due to the fault clearing overvoltage and, in addition to that, the oscillatory current may charge the capacitor even higher. Secondly, the system voltage is higher than normal.

If blocking at fault recovery is not applied then the valve will experience transient overcurrent as described in 5.1 above. Depending on the functional principles of the instantaneous overcurrent protection, the maximum value of the oscillatory current must be considered when determining the setting of the protection. The oscillatory current generated by a fault in the power system should not cause the SVC to trip or to continuously fire the valve by activating the instantaneous overcurrent protection. Normally this requirement determines the lowest possible setting of the instantaneous overcurrent protection.

Section 5.1 discussed the overvoltage stresses on the valve due to an a.c. system fault and a switching-off of the TSC during the subsequent fault clearing overvoltage. However, depending on the protection strategy during temporary overvoltages, fault clearing after a.c. system faults may not be the decisive case (see Ref. 4). Blocking of the TSC during other overvoltage conditions, for instance after a load rejection, is also a conceivable situation of high voltage stress on the valve. For SVCs in voltage control applications the TSCs should be switched-off in overvoltage situations. Since the rate of rise of a system overvoltage is often fast, it cannot normally be ensured that the TSCs will be blocked before the maximum voltage is reached.

The design of the TSC valve should therefore take into account the possibility of the TSC being switched-off with a trapped voltage across the capacitor corresponding to the maximum system overvoltage.

A high oscillatory current will also be generated at switching-on of the TSC, when the capacitor is charged to a voltage considerably higher than the crest value of the TSC bus voltage. Such a situation may occur, for instance if the TSC is switched off due to a temporary overvoltage and then switched on again when the system voltage swings down. The maximum overvoltage and the sudden increase in system voltage, for which the SVC has to be designed, should be specified. Note that "sudden" voltage changes means changes that take place in significantly less than one half of a power frequency cycle and which are sustained. Changes in voltage slower than this or which are sustained for only a small fraction of a power frequency cycle will not excite the natural frequency of the TSC.

For the design of the valve with respect to stresses resulting from a.c. system faults, the following system conditions have to be considered:

- system fault circuit level,
- type of fault,
- fault distance,
- point-on-wave of fault application,
- duration of the fault,
- repetition rate of successive faults,
- single phase or three phase operation of fault clearing breaker,
- angle of recovery voltage at instant of fault clearance,
- temporary overvoltage factor and magnitude of sudden increase,
- prefault current in the TSC and the initial thyristor junction temperature (normally specified as rated maximum conditions),
- Presence of FCs, TCRs or other SCs at the same location and the effect that these have on the fault recovery waveshape for both the "on" and "off" states,
- inrush effect/harmonic overcurrent and overvoltage and possibly loss of control
- protective actions of the valve and/or of the valve firing system (threshold for undervoltage blocking, forward recovery protection, capacitor overcharge protection etc.)

5.3 Fast Surges Transferred from the A.C. System

Fast surges such as lightning and switching surges are transferred from the a.c. system via the SVC step-down transformer and busbars to the TSC valve. The arresters on the primary side limit the maximum amplitude of the surges from lines and breakers in the power system. The surges are transferred mainly via the stray capacitances of the transformer from the primary side to the secondary side. However, the voltage division between this stray primary to secondary capacitance and the capacitance to earth on the secondary side reduce the magnitudes of the fast surges. Normally surge capacitors are installed line to earth on the secondary side. These capacitors increase the secondary capacitance and reduce the magnitudes of the surges. Further reduction of the surges is provided by the inductance and capacitance of the secondary busbars and the voltage grading circuits of the thyristor valve.

5.4 Lightning Strikes Directly on the Low Voltage Bus

Normally, the secondary system is protected against direct strikes by overhead wires or lightning rods. If such protection is adequately arranged the risk of a direct strike is minimal. For systems, where the risk of a direct strike must be considered as a possibility, it may be necessary to employ saturable reactors in the valve for limitation of the steepness of the front of the lightning waves associated with a direct strike.

5.5 Switching Surges

For low voltage equipment, switching surge overvoltages are usually ignored. The insulation coordination is based mainly on lightning surges. However the TSC forms a resonant circuit with a low natural frequency and low losses. Disturbances in the system such as fault application and fault clearing, line switching and transformer energization will excite the resonant circuit. The resulting transient overvoltages will have rise times which can be characterized as switching surges according to IEC 71-1 clause 51. As a proper means for evaluation of the resulting voltage stresses on the TSC valve, transient network analyzers (TNA) and digital computer simulations have been used.

5.6 Current Stresses on Conducting Valve as a Result of the Previous Cases 5.3 – 5.5

Fast voltage surges from the power system will normally have a minor impact on an already conducting valve, because the amplitude of the current through the valve caused by such surges is small compared to the nominal valve current.

Lightning strikes on the other hand are often associated with considerable current amplitudes. For SVCs, where direct lightning strikes on the low voltage bus must be considered as a possibility, it is therefore important to take precautions, so that the thyristor valves do not have to divert the lightning current. Adequate earthing, shielding and installation of suitable arresters may be a means of diverting the lightning current safely to earth.

Switching overvoltages may generate current components, which distort the TSC current and may cause multiple zero crossings of the current. Depending on the firing system characteristics such zero crossings may cause a valve, which should be on, to block during a part of each half-cycle. If so, the stresses on the valve voltage grading circuits increase. Also, the thyristor stresses increase due to the increase in their switching losses. However the switching overvoltages will normally persist only for a short time interval, and the additional heating of the thyristors is normally small.

5.7 Insulation Failures

5.7.1. Phase to Earth

Normally, the system on the low-voltage side of the SVC transformer is high-impedance earthed. Therefore the fault current caused by a single line-to-earth fault will be practically negligible and, in principle, it would be possible to continue the operation of the SVC with a permanent single line-to-earth fault. However, it is recommended to trip the SVC for a single fault due to the risk that the fault develops into a double fault.

At the initiation of a fault, the voltage potentials in the system will change at a high rate. This may cause high discharge currents from the stray capacitances in the system. The stresses which are caused by these currents and voltages in the thyristors and the voltage grading circuits should be considered in the TSC valve design.

If the system is low-impedance earthed, the fault current may flow through the valve. In such case the valve should be designed to withstand the increased current loading caused by a line to earth fault.

5.7.2 Phase to Phase

A phase to phase fault generates a full short-circuit current and the fault must be cleared as fast as possible. Providing the SVC with differential current protections is a means of achieving a fast and reliable indication of such a fault. Depending on the location of the fault and the breaker arrangement, this protection can be used to initiate a tripping of part of the SVC or of the complete SVC if necessary. The phase to phase fault may cause considerable capacitor discharge currents through the thyristor valve. These discharge currents are similar to those caused by a.c. system faults and described in section 5.1.

5.8. Control Malfunction

Many different types of abnormal operation can arise due to malfunction of the SVC control. Some conceivable examples are:

- false firing of the valve, i.e. spurious firing for instance by noise in the firing pulse circuits
- loss of firing signals
- instability of voltage control loop
- loss of synchronization.

5.8.1. False Firing

For a TSC with properly designed control and firing pulse systems, the risk of false firing is very low. However, in spite of this, a worst case false firing is often used as a design criterion for a TSC valve. Such a false firing will generate a high overcurrent in the valve, i.e. it will generate an oscillatory current component superimposed on the normal fundamental current component. The formulas derived in section 5.1 can be used for calculation of the amplitude of the oscillatory current and the oscillation frequency..

5.8.2. Loss of Firing Signals

If the individual firing signal to one thyristor is lost, the affected thyristor will, in most cases, be permanently damaged, i.e. the result will normally be a short-circuit of the thyristor, unless voltage break-over devices are employed as a protection for each individual thyristor level. However with individual thyristor level VBOs or self-triggered thyristors, the risk of generation of high harmonic currents must be considered. See section 3.2.5.

Loss of the firing signals to all the thyristors in one direction of one phase of a TSC valve means that the capacitor can be charged by the valve in one direction only. The result of a switching on of the faulty phase of the TSC bank will be that the capacitor is charged during the first cycle to the crest value of the TSC bus voltage or higher. Then the valve cannot carry current in the opposite direction and discharge the capacitor. The capacitor in the faulty phase of the TSC bank will therefore stay charged at one polarity and, after the first current pulse, there will be no more current in the faulty phase. For a three-phase TSC bank with symmetrical control the result of a loss of all the firing signals to the thyristors in one direction of one phase therefore results in an unbalanced operation with full current in two phases and zero current in the faulty phase. This may generate an unacceptable unbalance in the a.c. system voltages, and therefore the TSC should be provided with a suitable protection against such an unbalanced operation.

Such protection may be based on a measurement of the negative sequence current in the TSC bank or a comparison between the control order for the bank and the current responses from the bank.

5.8.3. Misoperation of the Voltage Control Loop

The gain of the voltage control loop depends on SVC internal parameters as well as system parameters such as the fault level at the SVC connection point. A decrease in the fault level means a higher gain in the voltage control loop with an increased risk of control instability due to a too high gain. Unless a system is provided which automatically adapts the gain to the actual fault level, the gain of the voltage controller must be set with respect to the lowest fault level. If the fault level should fall below the lowest expected value, or if the gain should increase too much due to some fault in the control, the voltage control could go unstable. In such a situation the TSC bank may be switched on and off with a high repetition frequency. Such a situation imposes a higher than normal stress on the valve and especially on the arrester across the valve, if employed, see section 4.

5.8.4. Loss of Synchronization

Correct timing of the firing pulses is essential for the correct operation of the TSC. The result of an incorrect timing depends on the magnitude of the timing error, the characteristics of the firing system and the the protection system adopted.

Moderate phase advancements in the timing of the firing pulses have normally no significant impact on the valve operation and stresses, provided the firing pulses are long enough or it is ensured by other means, that the thyristors are fired as soon as there appears a forward blocking voltage across the thyristors in the intervals they should conduct.

The impact of a delay of the firing pulses with respect to the correct firing instants is normally more severe, because it generates a distortion of the waveforms, which causes an increase in the capacitor voltage and current. Large timing errors may cause high overcurrents and overvoltages similar to those caused by false firings.

5.9.. Transformer Saturation Harmonic Effects

Energization of a power transformer or voltage changes due to fault clearing or load shedding are often associated with inrush currents of considerable amplitudes. This is due to the strongly non-linear characteristic of the transformer magnetizing curve which means that, depending on the instant of closing the breaker, the transformer will be driven more or less deeply into saturation at energization. If capacitive shunt elements such as harmonic filters or TSC banks are connected to a system containing saturable inductive elements, oscillations due to resonances between the capacitive and inductive elements can develop. These oscillations following a transformer energization can last from several cycles of the power frequency to several seconds, depending on the time constant of the transformer inrush currents.

The oscillations generated at energization of a nearby transformer can result in high currents in SVC harmonic filter banks and TSC banks. In general, the transformer energization is a more severe case for a harmonic filter bank than for a TSC bank. This depends to some extent on the damping introduced by the conduction losses of the thyristor valve. Probably more important is the property of the valve to block during certain intervals of each cycle, when the current becomes strongly distorted. However the performance of the valve in that case is very much dependent on the characteristics of the control strategy. Fig.9a shows the TSC current waveforms at energization of a 300 MVA transformer in a power system,

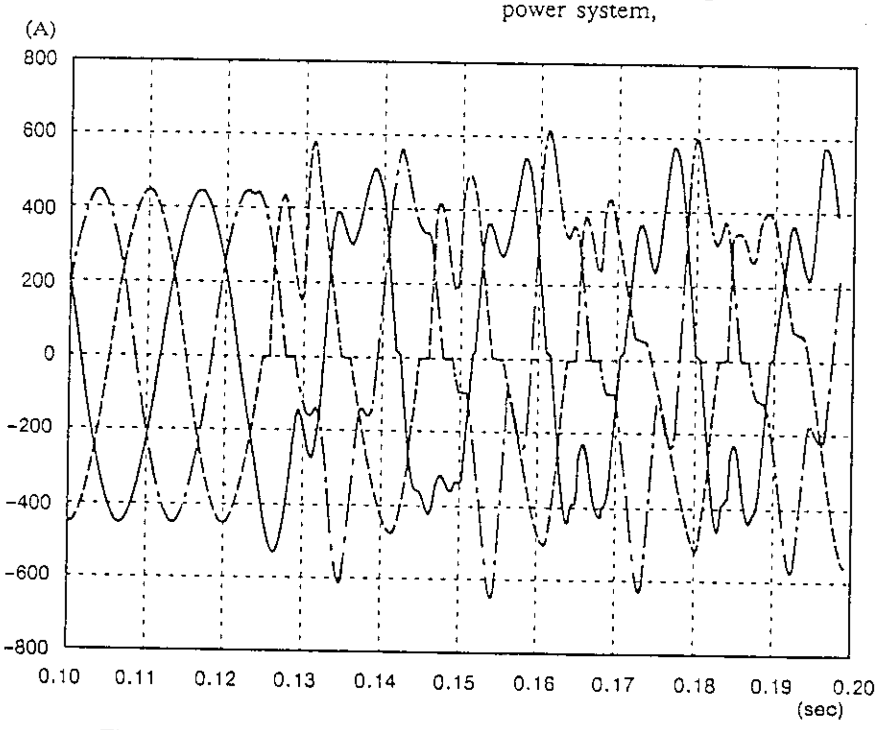
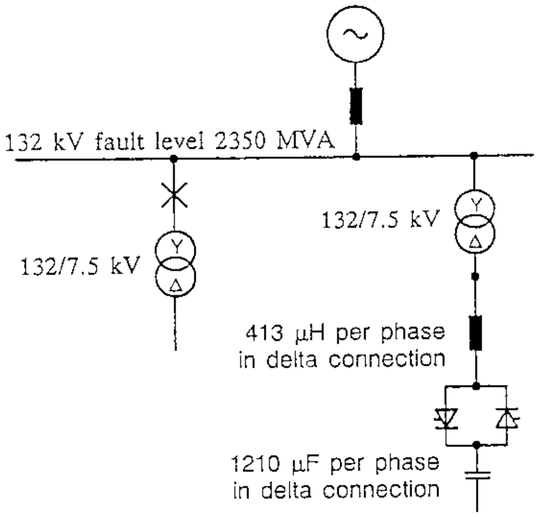


Fig. 9a TSC operation at energizing of a nearby transformer (TSC currents)

Fig.9b shows a single line diagram of the system with the SVC and with the transformer being energized. It was anticipated that the transformer was energized directly from the bus to which the SVC is connected. The fault level at this bus was 2350 MVA. The energizing is initiated simultaneously for all three phases at an instant of zero crossing of the voltage on one phase.



Data for transformers based on 300 MVA:

e_x = 10%
e_r = 0.5%
X_{sat} = 40%

Saturation knee-point = 120%

Nominal TSC power to 132 kV bus = 69 Mvar

Fig. 9b TSC operation at energizing of a nearby transformer (Single line diagram)

The harmonics in the transformer inrush current distort the TSC current waveform and increase considerably the crest values of the current and the conduction losses in the thyristors. They also increase the crest values of the capacitor voltage. The blocking of the valve during certain intervals of each cycle also introduces additional stresses on the valve voltage grading circuits and additional switching losses in the thyristors..

6. CONCLUSIONS

The stresses on the TSC valve are greatly influenced by the overall SVC design, protection philosophy and power system contingencies to which the SVC will be exposed.

Part II describes typical stresses on TSC valves for different operating conditions, both transient and steady state, and could serve as a basis for understanding the relationship between different designs and the corresponding stresses the valve must be able to withstand. It should serve as a guide for determining the critical stresses for which the valve should be tested.

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21, rue d'Artois
FR-75 008 PARIS
Tél. : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99

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