BS EN 60143-4:2010

Series capacitors for power systems

Part 4: Thyristors controlled series capacitors

National foreword

This British Standard is the UK implementation of EN 60143-4:2010. It is identical to IEC 60143-4:2010.

The UK participation in its preparation was entrusted to Technical Committee PEL/33, Power capacitors.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Series capacitors for power systems - Part 4: Thyristor controlled series capacitors (IEC 60143-4:2010)

Condensateurs série destinés à être installés sur des réseaux -
Partie 4: Condensateurs série commandés par thyristors
(CEI 60143-4:2010)

Reihenkondensatoren für Starkstromanlagen -
Teil 4: Thyristorgesteuerte Reihenkondensatoren
(IEC 60143-4:2010)

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European Committee for Electrotechnical Standardization
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Foreword

The text of document 33/472/FDIS, future edition 1 of IEC 60143-4, prepared by IEC TC 33, Power capacitors, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60143-4 on 2010-12-01.

This part of EN 60143 is to be used in conjunction with the following standards:

– EN 60143-1:2004, *Series capacitors for power systems – Part 1: General*

– EN 60143-2:1994, *Series capacitors for power systems – Part 2: Protective equipment for series capacitor banks*

– EN 60143-3:1998, *Series capacitors for power systems – Part 3: Internal fuses*

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The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2011-09-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2013-12-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60143-4:2010 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

[1] IEC 60068-1	NOTE	Harmonized as EN 60068-1.
[2] IEC 60721-1	NOTE	Harmonized as EN 60721-1.
[3] IEC 60068-3-3	NOTE	Harmonized as EN 60068-3-3.
[4] IEC 60060-2	NOTE	Harmonized as EN 60060-2.
[5] IEC 61000-4-2	NOTE	Harmonized as EN 61000-4-2.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-436	-	International Electrotechnical Vocabulary (IEV) - Chapter 436: Power capacitors	-	-
IEC 60060-1	-	High-voltage test techniques - Part 1: General definitions and test requirements	EN 60060-1	-
IEC 60068-1	-	Environmental testing - Part 1: General and guidance	EN 60068-1	-
IEC 60068-2-2	-	Environmental testing - Part 2-2: Tests - Test B: Dry heat	EN 60068-2-2	-
IEC 60068-2-78	-	Environmental testing - Part 2-78: Tests - Test Cab: Damp heat, steady state	EN 60068-2-78	-
IEC 60071-1	-	Insulation co-ordination - Part 1: Definitions, principles and rules	EN 60071-1	-
IEC 60071-2	-	Insulation co-ordination - Part 2: Application guide	EN 60071-2	-
IEC 60076-1	1993	Power transformers - Part 1: General	EN 60076-1	1997
IEC 60076-6	2007	Power transformers - Part 6: Reactors	EN 60076-6	2008
IEC 60143-1	2004	Series capacitors for power systems - Part 1: General	EN 60143-1	2004
IEC 60143-2	1994	Series capacitors for power systems - Part 2: Protective equipment for series capacitor banks	EN 60143-2	1994
IEC 60143-3	1998	Series capacitors for power systems - Part 3: Internal fuses	EN 60143-3	1998

Publication	Year	Title	EN/HD	Year
IEC 60255-5	-	Electrical relays - Part 5: Insulation coordination for measuring relays and protection equipment - Requirements and tests	EN 60255-5	-
IEC 60255-21	Series	Electrical relays - Part 21: Vibration, shock, bump and seismic tests on measuring relays and protection equipment	EN 60255-21	Series
IEC 60270	-	High-voltage test techniques - Partial discharge measurements	EN 60270	-
IEC 61000-4-29	-	Electromagnetic compatibility (EMC) - Part 4-29: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests	EN 61000-4-29	-
IEC 61954	1999	Power electronics for electrical transmission and distribution systems - Testing of thyristor valves for static VAR compensators	EN 61954	1999

CONTENTS

SERIES CAPACITORS FOR POWER SYSTEMS –

Part 4: Thyristor controlled series capacitors

1 Scope

This part of IEC 60143 specifies testing of thyristor controlled series capacitor (TCSC) installations used in series with transmission lines. This standard also addresses issues that consider ratings for TCSC thyristor valve assemblies, capacitors, and reactors as well as TCSC control characteristics, protective features, cooling system and system operation.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE If there is a conflict between this part of IEC 60143 and a standard listed below in Clause 2, this standard prevails.

IEC 60050-436, *International Electrotechnical Vocabulary – Chapter 436: Power capacitors*

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60068-1, *Environmental Testing – Part 1: General and guidance*

IEC 60068-2-2, *Basic environmental testing procedures – Part 2-2: Tests – Tests B: Dry heat*

IEC 60068-2-78, *Basic environmental testing procedures – Part 2-78: Tests – Tests C: Damp heat, steady state*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2, *Insulation co-ordination – Part 2: Application guide*

IEC 60076-1:1993, *Power transformers – Part 1: General*

IEC 60076-6:2007, *Power transformers – Part 6: Reactors*

IEC 60143-1:2004, *Series capacitors for power systems – Part 1: General*

IEC 60143-2:1994, *Series capacitors for power systems – Part 2: Protective equipment for series capacitor banks*

IEC 60143-3:1998, *Series capacitors for power systems – Part 3: Internal fuses*

IEC 60255-5, *Electrical relays – Part 5: Insulation coordination for measuring relays and protection equipment – Requirements and tests*

IEC 60255-21 (all parts), *Electrical relays – Vibration, shock, bump and seismic tests on measuring relays and protection equipment*

IEC 60270, *High-voltage test techniques – Partial discharge measurements*

IEC 61000-4-29, *Electromagnetic compatibility (EMC) – Part 4-29: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations on d.c. input port immunity tests*

IEC 61954:1999, *Power electronics for electrical transmission and distribution systems – Testing of thyristor valves for static VAR compensators*

NOTE Additional useful references, not explicitly referenced in the text, are listed in the Bibliography .

3 Terms, definitions and abbreviations

For the purposes of this document, the following terms, definitions and abbreviations as well as those given in IEC 60143-1, IEC 60143-2, IEC 60143-3 and some taken from IEC 60050-436 apply.

NOTE In some instances, the IEC definitions may be either too broad or too restrictive. In such a case, an additional definition or note has been included.

3.1 Abbreviations

ETT	Electrically triggered thyristors
FACTS	Flexible ac transmission systems
FSC	Fixed series compensation
LTT	Light-triggered thyristors
MC	Master control
MTBF	Mean time between failure
MTTR	Mean time to repair
POD	Power oscillation damping
RAM	Reliability, availability, and maintainability
RIV	Radio influence voltage
RTU	Remote terminal unit
SCADA	Supervisory control and data acquisition
ER	Events recorder
FR	Fault recorder
RTDS	Real time digital simulation
SSR	Sub synchronous resonance
SVC	Static var compensator
TCR	Thyristor-controlled reactor
RMS	Root mean square

3.2 Terms and definitions

3.2.1
thyristor valve
electrically combined assembly of thyristor levels, complete with all connections, auxiliary components and mechanical structures, which can be connected in series with each phase of the reactor or capacitor of a TCSC

3.2.2
bypass current
the current flowing through the bypass switch, protective device, thyristor valve, or other devices, in parallel with the series capacitor, when the series capacitor is bypassed

3.2.3
capacitive range
TCSC operation resulting in an effective increase of the power frequency reactance of the series capacitor (See Figure 5)

3.2.4
temporary overload
short duration (typically 30 min) overload capability of the TCSC at rated frequency and ambient temperature range

3.2.5
dynamic overload
short duration (typically 10 s) overload capability of the TCSC at rated frequency and ambient temperature range. (See Figure 5 and Figure 10)

3.2.6
platform-to-ground cooling/air-handling insulator
an insulator that encloses cooling/air handling paths between platform and ground level

3.2.7
thyristor-controlled series capacitor bank
TCSC
an assembly of thyristor valves, TCSC reactor(s), capacitors, and associated auxiliaries, such as structures, support insulators, switches, and protective devices, with control equipment required for a complete operating installation

3.2.8
valve electronics
VE
electronic circuits at valve potential(s) that perform control functions

3.2.9
TCSC reactor
one or more reactors connected in series with the thyristor valve (see NOTE This figure contains material reproduced from IEEE Std 1534-2002. IEEE Std 1534-2002 IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors, Copyright 2002 IEEE. All rights reserved.

Figure 1, item 12)

3.2.10
thyristor valve enclosure
a platform-mounted enclosure containing thyristor valve(s) with associated valve cooling and electronic hardware

3.2.11
valve varistor
an assembly of varistor units that limit overvoltages to a given value. In the context of TCSCs, the valve varistor is typically defined by its ability to limit the voltage across a thyristor valve to a specified protective level while absorbing energy. The valve varistor is designed to withstand the temporary overvoltages and continuous operating voltage across the thyristor valve

3.2.12
valve blocking
an operation to prevent further firing of a thyristor valve by inhibiting triggering

3.2.13
valve deblocking
an operation to permit firing of a thyristor valve by removing valve blocking action

3.2.14
valve base electronics
VBE
an electronic unit, at earth potential, which is the interface between the control system of the TCSC and the thyristor valves

3.2.15
voltage breakover protection
VBO
means of protecting the thyristors from excessive voltage by firing them at a predetermined voltage

3.2.16
redundant thyristor levels
the maximum number of thyristor levels in the thyristor valve that may be short-circuited, externally or internally, during service without affecting the safe operation of the thyristor valve as demonstrated by type tests; and which if and when exceeded, would require either the shutdown of the thyristor valve to replace the failed thyristors, or the acceptance of increased risk of failures

3.2.17
capacitor current
I_C
current through the series capacitor (see Figure 2)

3.2.18
line current
I_L
power frequency line current (see Figure 2)

3.2.19
rated current
I_N
the RMS line current (I_L) at which the TCSC should be capable of continuous operation with rated reactance (X_N) and rated voltage (U_N)

3.2.20
valve current
I_V
current through the thyristor valve (see Figure 2)

3.2.21
capacitor voltage
U_C
voltage across the TCSC (see Figure 2)

3.2.22
protective level
U_{PL}
magnitude of the maximum peak of the power frequency voltage appearing across the overvoltage protector during a power system fault

NOTE The protective level may be expressed in terms of the actual peak voltage across a segment or in terms of the per unit of the peak of the rated voltage across the capacitor.

3.2.23
rated TCSC voltage
U_N
the power frequency voltage across each phase of the TCSC that can be continuously controlled at nominal reactance (X_N), rated current (I_N), frequency, and reference ambient temperature range

3.2.24
apparent reactance
$X(\alpha)$
TCSC apparent power frequency reactance as a function of thyristor control angle (α) (see Figure 4)

3.2.25
rated frequency
f_N
frequency of the system in which the TCSC is intended to be used

3.2.26
rated capacitance
C_N
capacitance value for which the TCSC capacitor has been designed

3.2.27
physical reactance
X_C
the power frequency reactance for each phase of the TCSC bank with thyristors blocked and a capacitor internal dielectric temperature of 20 °C; $X_C = 1/(2\pi f_N \times C_N)$

3.2.28
boostfactor
k_B
the ratio of $X(\alpha)$ divided by X_C; $k_B = X(\alpha) / X_C$

3.2.29
nominal reactance
X_N
the nominal power frequency reactance for each phase of the TCSC with rated line I_N and nominal boost factor

3.2.30
conduction interval
σ
that part of a cycle during which a thyristor valve is in the conducting state, $\sigma = 2\beta$ (see Figure 3)

3.2.31
control angle
α
the time expressed in electrical angular measure from the capacitor voltage (U_C) zero crossing to the starting of current conduction through the thyristor valve. (see Figure 3)

3.2.32
internal fault
an internal fault is a line fault occurring within the protected line section containing the series capacitor bank

3.2.33
external fault
an external fault is a line fault occurring outside the protected line section containing the series capacitor bank

4 Operating and rating considerations

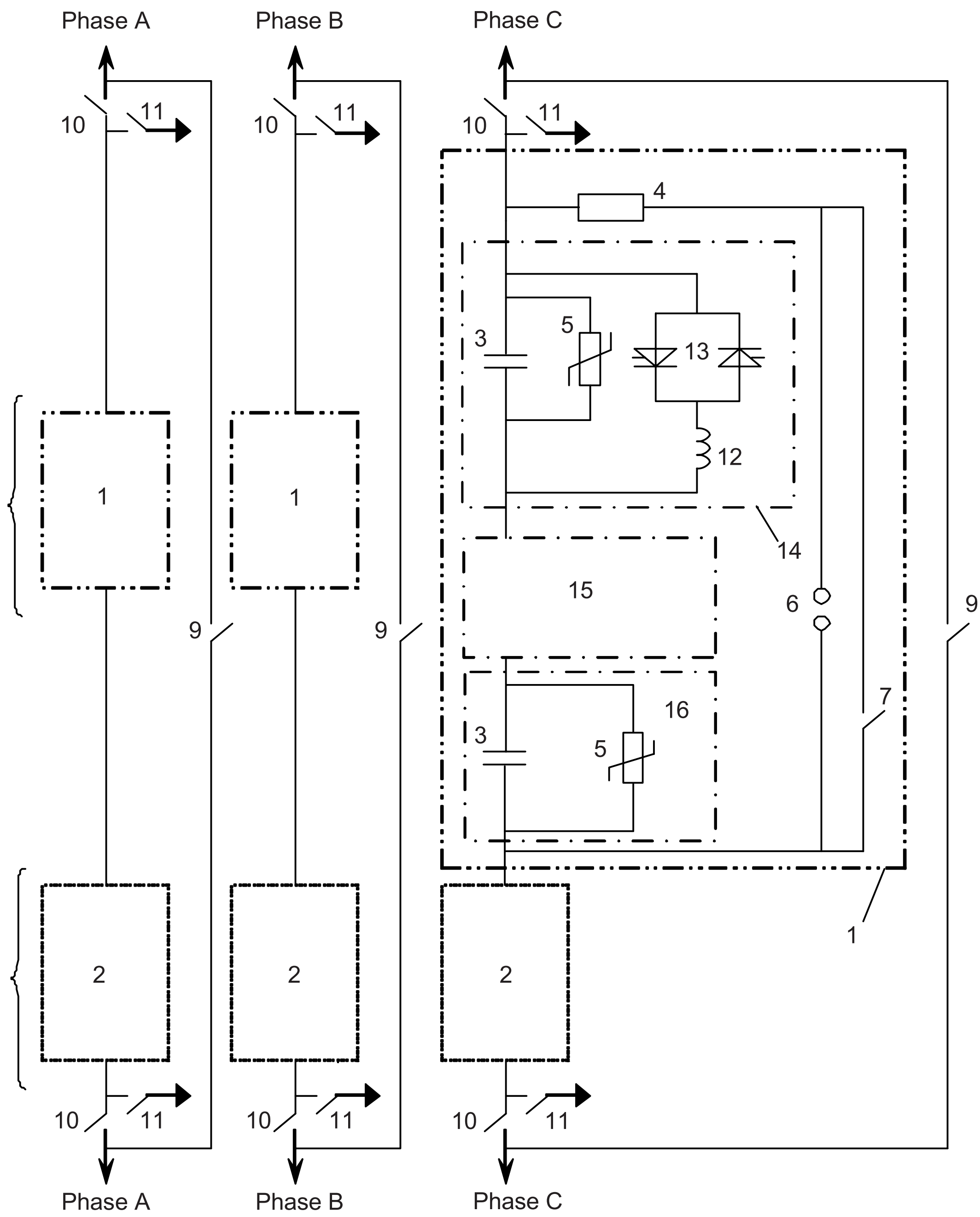
4.1 General

Transmission line series reactance can be compensated by combinations of fixed series capacitors and TCSC capacitors and TCSC banks (see NOTE This figure contains material reproduced from IEEE Std 1534-2002. IEEE Std 1534-2002 IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors, Copyright 2002 IEEE. All rights reserved.

Figure 1). TCSC banks use one or more controllable modules to achieve the range of performance requirements specified by the purchaser. This clause discusses requirements of TCSC operating and rating considerations.

The TCSC circuit configurations discussed in this standard (see Figure 2) consider three basic operating modes:

- BLK operation with thyristors blocked (no current through the thyristor valve)
- BP operation with continuous thyristor current
- CAP operation in capacitive boost mode.



Key

1 Segment (-phase)
2 Switching step or module (3-phase)
3 Capacitor units
4 Discharge current limiting and damping equipment
5 Varistor
6 Bypass gap
7 Bypass switch
8 Additional switching steps when required
9 External bypass disconnect switch
10 External isolating disconnect switch
11 External grounding disconnect switch
12 TCSC reactor
13 Thyristor valve
14 Controllable subsegment (1-phase)
15 Additional controllable subsegments when required
16 Additional FSC segment when required

NOTE This figure contains material reproduced from IEEE Std 1534-2002. IEEE Std 1534-2002 IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors, Copyright 2002 IEEE. All rights reserved.

Figure 1 – Typical nomenclature of a TCSC installation

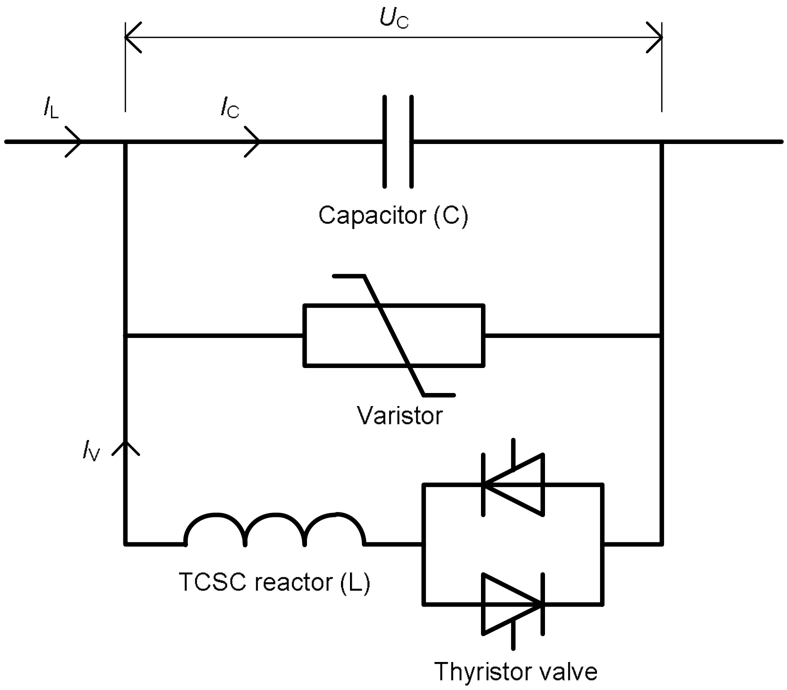


Figure 2 – TCSC subsegment

The definition of control angle (α) with reference to voltage zero crossing is selected to be consistent with other power electronic devices (see Figure 3). However, it should be noticed that many TCSC control systems use the line current wave form as an important control reference.

When a TCSC is operating in CAP mode, the current in the thyristor valve branch can boost the voltage across the capacitor, resulting in an apparent capacitive reactance larger than the physical capacitor reactance, see Figure 4. In a TCSC application, the increased capacitive reactance would increase the line current. The current pulses through the thyristor valve, distorts the capacitor voltage (U_C). The distorted waveform means that the capactor voltage includes non-power frequency components and that the relationship between total RMS and total peak voltage is not $\sqrt{2}$ as in the case for a pure sinusoidal waveform, see Table 1.

Table 1 – Peak and RMS voltage relationships

Boost factor k_B	Normalized discharge frequency λ	Power frequency RMS voltage	Power frequency peak voltage	Total RMS voltage	Total peak voltage
1,0	2,5	1,0	1,41	1,00	1,41
2,0	2,5	2,0	2,83	2,02	2,55
3,0	2,5	3,0	4,24	3,05	3,70
1,0	3,5	1,0	1,41	1,00	1,41
2,0	3,5	2,0	2,83	2,03	2,54
3,0	3,5	3,0	4,24	3,07	3,67

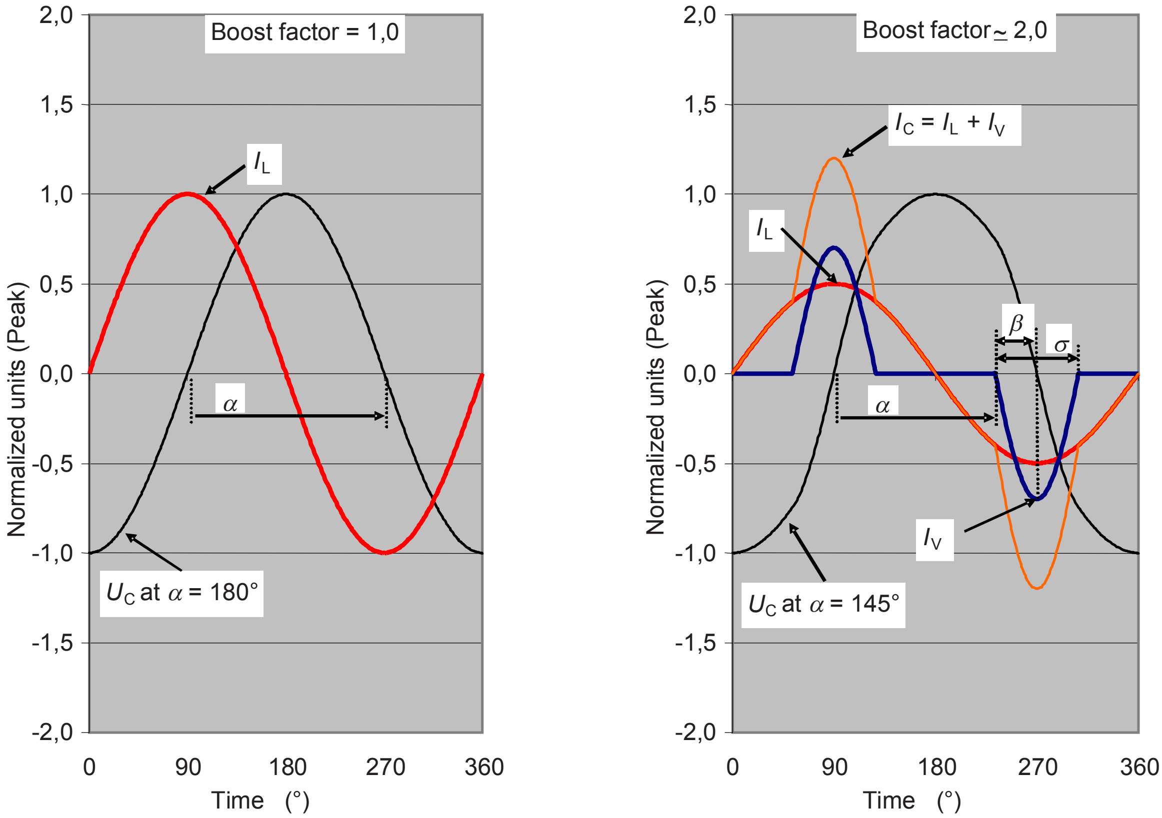


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Figure 3 – TCSC steady state waveforms for control angle *α* and conduction interval *σ*

4.2 TCSC characteristics

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TCSC characteristics are determined from the series capacitor (*C*) and reactor (*L*) circuit parameters shown in Figure 2. The steady state TCSC power frequency reactance *X*(*α*) as a function of thyristor control angle (*α*) can be calculated from Equation (1).

$$X(\alpha)=\frac{1}{2\pi f_N C}\left[1-\frac{\lambda^2}{(\lambda^2-1)}\times\frac{2\beta+\sin(2\beta)}{\pi}+\frac{4\lambda^2}{(\lambda^2-1)^2}\times\cos^2(\beta)\times\frac{\lambda\times\tan(\lambda\beta)-\tan(\beta)}{\pi}\right] \qquad (1)$$

where

β is half the conduction interval (π-*α*);

α is control angle from capacitor voltage zero;

λ is the normalized discharge frequency $\frac{1}{2\pi f_N\sqrt{LC}}$;

C is the series capacitor capacitance;

L is the TCSC reactor inductance.

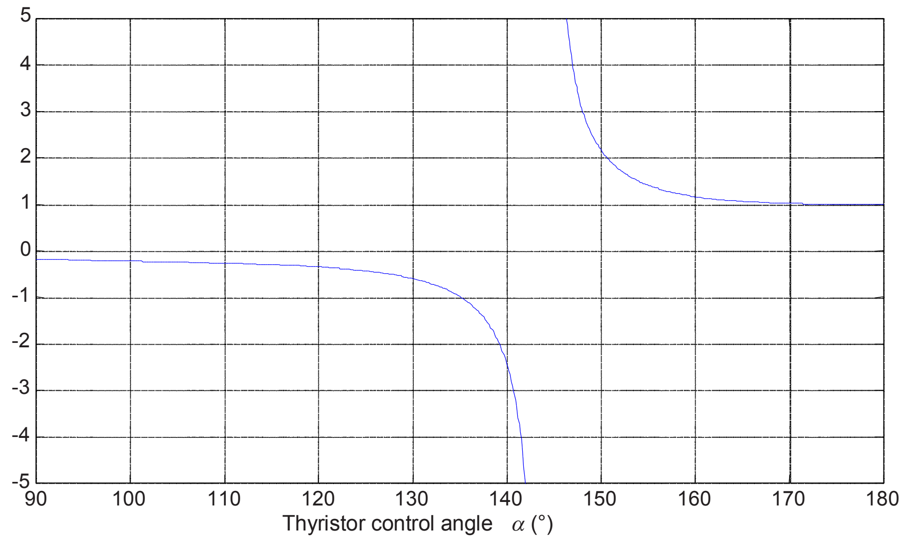

Figure 4 – TCSC power frequency steady state reactance characteristics according to Equation (1), with λ = 2,5

4.3 Operating range

The operating range is one of the most important factors for rating of a TCSC. It has a major impact on the main circuit components stresses and must therefore be clearly specified by the purchaser. The TCSC shall be designed to withstand operation with the different reactances and line currents within the specified operating range. The required operating range shall be defined by system studies performed by the purchaser and be clearly stated in the specification with a set of curves of the apparent fundamental frequency TCSC reactance or boost factor (k_B) versus the line current as indicated in Figure 5. The required operating range depends on the purpose of the TCSC. Generally a TCSC for power oscillation damping (POD) requires a larger operating range than a TCSC for SSR-mitigation.

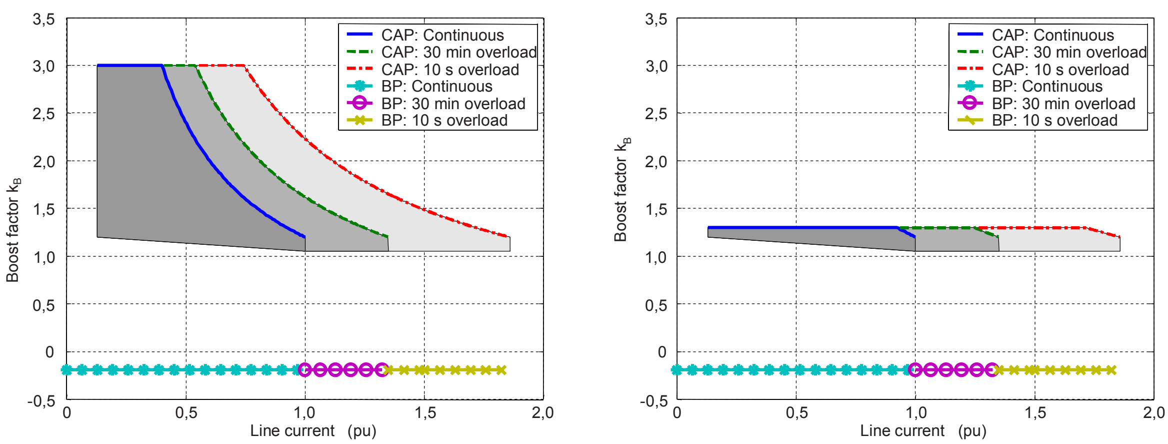

Figure 5 – Example of TCSC operating range for POD (left) and SSR mitigation (right)

The operating range does not extend all the way to zero line current because steady-state firing of a thyristor valve is not possible at very low thyristor valve voltages and currents. All thyristors and associated firing and monitoring electronics have a minimum voltage below which firing and condition monitoring is not possible. In addition, some thyristor valves have power supplies for the firing circuits that may place additional constraints on the firing of the thyristor valve when the line current is low. This results in a minimum line current and boost factor (k_B) below which operation in CAP mode is not feasible. This can have implications on the application and operation of the TCSC. The impact of series compensation is of limited value at low line currents. If SSR is a concern, it is recommended that the TCSC be bypassed at line current levels below which operation in CAP mode cannot be maintained.

4.4 Reactive power rating

When a TCSC is operating in capacitive boost mode the reactive power seen by the power system differs from the reactive power of the capacitors. The reactive power output of a TCSC and the reactive power of the capacitors are given by

$$Q_{TCSC} = 3 \times k_B \times \frac{1}{\omega C} \times I_L^2$$

$$Q_{CAP} = 3 \times k_B^2 \times \frac{1}{\omega C} \times I_L^2$$

The nominal reactive power rating of the TCSC shall be defined as the reactive power output given by Q_{TCSC} in the above expressions with nominal boost and nominal line current.

4.5 Power oscillation damping (POD)

Power oscillation damping (POD) is a specialized subset of closed loop reactance control which can be realized by modulating the TCSC reactance in response to transmission system conditions to dampen power system oscillations. By using BP mode during power oscillations, the damping performance of a TCSC can be increased significantly since this extends the reactance range of a TCSC to a lower inductive reactance.

A TCSC for POD applications shall fulfil the following fundamental requirements:

- The POD controller shall be able to handle system disturbances that results in power oscillations through zero and be insensitive to the direction of the average power flow.
- The POD controller shall be able to handle large system disturbances. This means that the structure of the POD controller must be such that the desired phase shift between the input and output signal of the TCSC is maintained independently of the magnitude of the power oscillation.
- The TCSC control system shall be able to handle mode switching from CAP to BP and BP to CAP during power oscillation damping.

4.6 SSR mitigation

When properly designed and applied, TCSC can provide a degree of SSR mitigation when operated with a boost factor greater than one. The TCSC can help mitigate the resonant SSR series combination that results from fixed series capacitors.

If the TCSC application requires that SSR concerns be addressed, it is recommended that studies be performed involving detailed models of the power system, the nearby turbine generators and the TCSC. This recommendation is heightened in situations when the power system includes a combination of fixed series capacitors and TCSC and the combined series compensation exceeds 50 %. If the studies indicate that fixed series capacitors with the desired level of compensation will result in an SSR problem, the TCSC supplier shall be actively involved in the SSR studies.

A TCSC can only provide SSR mitigation if the valves are firing on a continuous basis. The result is that for the TCSC to meet the SSR mitigation objectives its operating region must be constrained to a boost factor equal to or greater than the minimum value at which it provides the desired SSR-mitigation. The degree of mitigation can be a function of the control angle but it is desirable that the TCSC control system can provide a sub-synchronous impedance that depends as little as possible on the boost factor.

In an application where SSR mitigation is critical, the operation of the TCSC under low line current condition must be reviewed, see 4.3.

4.7 Harmonics

A TCSC operating in CAP mode will produce harmonics. The magnitude of the harmonics depends on the operating point in terms of line current and boost factor.

In application where TCSC is used for SSR-mitigation or power oscillation damping purposes, the TCSC normally operates with the nominal boost factor and only temporarily during system disturbances operates with a higher boost factor. Therefore harmonic requirements on such TCSC installation shall be given for nominal operation i.e. rated line current and nominal boost factor.

Harmonic requirements for a TCSC shall be given in terms of maximum allowed voltage distortion caused by the TCSC at the busses connecting the series compensated line segment. Harmonic studies for a TCSC installation requires detailed transmission line data of the series compensated line together with harmonic network equivalents for the line ends to be supplied by the purchaser.

4.8 Control interactions between TCSCs in parallel lines

In situation where two TCSC are located on parallel lines, there is a risk for control interactions between the TCSC's during system disturbances. To reduce the risk for harmful interactions between parallel connected TCSC's the following is recommended:

- The POD controllers to use the same input signals, i.e. the sum of the power flow on the parallel circuits.
- The POD controllers to have similar dynamics.
- The reactance controllers to have similar dynamics and respond in similar ways when hitting limits.
- The degree of compensation of a line segment at maximum boost factor should be well below 100 %.

4.9 Operating range, overvoltages and duty cycles

4.9.1 Operating range

The TCSC shall be capable of withstanding the operation within the specified continuous and temporary operating ranges. The operating range is generally specified by the purchaser.

4.9.2 Transient overvoltages

The TCSC shall be suitable for repeated operations at transient overvoltages caused by power system faults, with the highest possible value U_{PL} that is expected to occur across the TCSC terminals. The transient overvoltage is normally limited by a varistor overvoltage protector.

4.9.3 Duty cycles

The TCSC equipment shall be designed to withstand the required sequences of faults, dynamic overload, temporary overload, and continuous currents as specified by the purchaser. These sequences form the duty cycles that all of the components of the TCSC bank shall be designed to withstand. The duty cycle shall be consistent with the manner in which the surrounding power system will be operated for both internal and external line faults. The purchaser shall define duty cycles for faults of normal and extended duration and for faults of different types (three-phase and single phase). Phase-to-phase faults shall be considered if specifically defined by the purchaser. Examples of typical duty cycles are found in 8.5.

The purchaser shall specify a power system equivalent to be used in the studies of external and internal transmission line faults for equipment rating.

Although the focus of this subclause is duty cycles involving power system faults, it is understood that the TCSC shall be designed to operate for other events such as insertion and reinsertion under the conditions specified by the purchaser.

5 Valve control

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5.1 Triggering system

The valve base electronics (VBE) subsystem is an interface between the TCSC control system for a subsegment and the platform-mounted valve electronics (VE) subsystem, as shown in Figure 6.

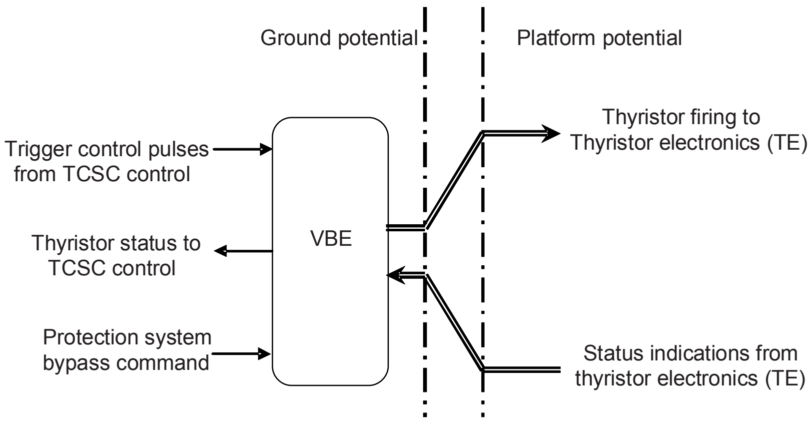

Figure 6 – Valve base electronics (VBE)

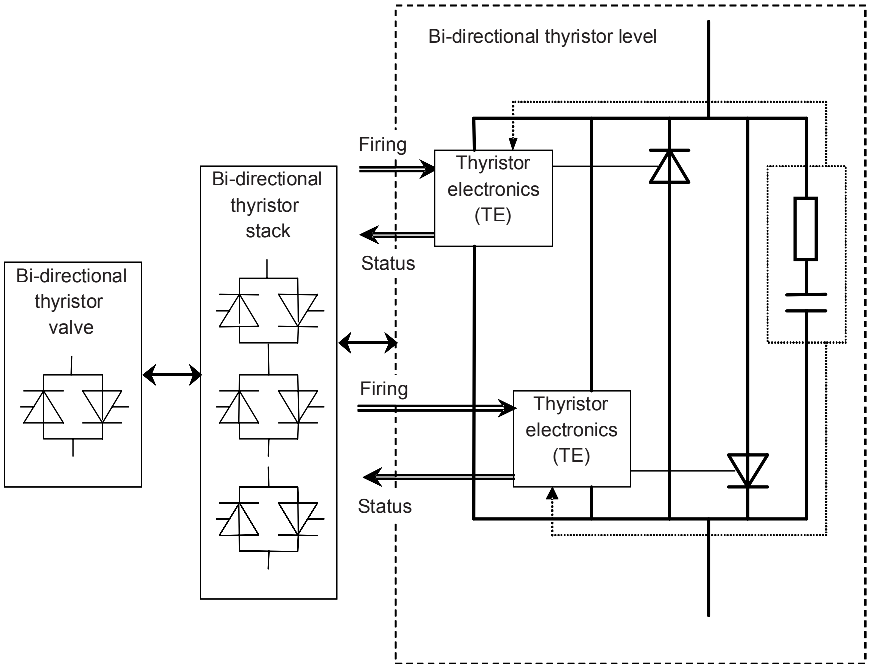

Figure 7 – Valve electronics (VE)

The TCSC control system generates trigger pulses that are transferred to the VBE. The VBE distributes firing pulses to each individual TE via fiber optics. Additionally, status information on each thyristor level is sent from the TE to the VBE which makes diagnostics of the thyristor valve condition. The diagnostics information is sent to the TCSC control system, see Figure 6.

The thyristor valve protection, resistive-capacitive snubbers, and power supply for the TE are located on the platform at the thyristor level where a gate pulse is generated for each thyristor, as shown in Figure 7.

5.2 System aspects

The following requirements apply to the valve control system independently of the type of thyristors. It shall be possible to fire the thyristors during all applicable operating conditions in order to:

- control the valve during normal operating conditions in capacitive boost mode and bypass mode;
- control the valve in order to bypass the series capacitor during system faults;
- ensure that the valve will not be blocked in a situation that would cause dangerous voltage across the valve;
- ensure that the valve will not be blocked in a situation where the thyristors have had no time to recover after previous (fault current) conduction.

5.3 Normal operating conditions

It shall be possible to control the valve in the whole operating range of interest. Valve triggering at low voltage is likely to occur at low line currents, or with low boost factors in capacitive boost mode, see also 4.3 and 5.5.

5.4 Valve firing during system faults

Thyristor valve firing at the capacitor protective level may be required during system faults in order to avoid overloading of the varistor. In this case, a thyristor valve firing results in a total valve current that is the sum of the capacitor discharge current and the fault current through the TCSC. Blocking of the valve during these conditions would lead to thyristor overvoltage. Therefore, the valve should remain conducting. It should be noted that the thyristor valve shall always be designed to handle the fault current independently of fault-handling strategy because a system fault can occur when the thyristor valve is conducting.

In situations with system faults and high current derivatives in the thyristor valve current, it is essential that the thyristor firing system is fast enough to prevent high voltage from building up across the thyristors when the current passes through zero.

5.5 Actions at low line current

The TCSC cannot remain operating in capacitive boost mode when the line current becomes very low, typically in the range of one tenth of the rated line current. There are two reasons for this:

a) The measuring system has a limited resolution and noise suppression capability. Therefore, the accuracy of the response signals becomes too low for the control system.
b) The auxiliary power used for thyristor triggering and monitoring is often being picked up from the main circuit. When the line current becomes too low, this power supply fails and the thyristors cannot be fired.

When the line current is low, the corresponding fundamental power frequency component of the inserted capacitor voltage is also low. In this condition, the power flow in the line depends very little on whether or not the series capacitor is inserted or bypassed. However, from a subsynchronous resonance (SSR) point of view, it could be important that the operating mode of the TCSC is well defined, see 4.3.

Normal operation should automatically be started when the low line current condition disappears.

From the equipment protection standpoint, low line current appears to be harmless. When auxiliary firing power is being picked up from the main circuit, it is important that the system is sufficiently fast acting so that the thyristors can be fired in order to prevent an overvoltage in case a sudden voltage rise would occur across the capacitor.

5.6 Monitoring

The valve control system shall have monitoring systems that allow indication of the number of faulty thyristor positions per phase. These indications shall be available at the operator control system (HMI).

6 Ratings

The ratings of the different components, forming part of the TCSC, are derived from the operating requirements as outlined in Clause 4.

6.1 Capacitor rating

Capacitors for the TCSC shall be designed, manufactured, and tested in accordance with applicable requirements of IEC 60143-1. Consideration to operation in capacitive boost mode shall be taken when specifying the rated current and voltage of the capacitor. It shall be noted that the rated current of a TCSC capacitor normally is higher than the rated through current of the TCSC. The actual capacitor current waveforms related to operation in capacitive boost mode shall be included in the equipment specification to the capacitor manufacturer. The rated voltage of the capacitor shall be taken as the total RMS voltage of the power frequency and harmonic voltage components. The rated current of the capacitor shall be based on the square root sum of the corresponding current components.

6.2 Reactor rating

The TCSC reactors shall be designed, manufactured, and tested in accordance with applicable requirements of 60076-6, Clause 9. The actual reactor current waveforms related to operation in capacitive boost mode shall be included in the equipment specification to the reactor manufacturer. The rated current of the reactor shall be based on the square root sum-of-squares (r.s.s) of the power frequency and the harmonic current components. The insulation level between the reactor terminals shall be based on the protective level of the TCSC bank as outlined in IEC 60143-1.

6.3 Thyristor valve rating

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The required current and voltage capabilities of the thyristor valve shall be derived from the operating range and duty cycles specified by the purchaser. In the design procedure it is assumed that the line current during non fault conditions remains sinusoidal (undistorted) at the rated power frequency.

6.3.1 Current capability

The current capability requirements shall be considered both for operation in capacitive boost mode and operation in bypass mode. The thyristor junction temperature shall be within acceptable limits for all specified loading and fault duty cycles agreed upon between the purchaser and the supplier.

6.3.1.1 Current capability at internal faults

An internal fault is a line fault occurring within the protected line section containing the series capacitor bank. The thyristor valve shall be designed to carry the fault current passing through the valve for line fault cases specified. Consideration shall be taken to the case that the thyristor valve is initially blocked when the fault occurs and then triggered during the fault resulting in a thyristor current consisting of both a line fault current component and a capacitor discharge current component. If separate reactors are used for the thyristor valve branch and for the bypass circuit breaker branch, means to prevent or to grant sufficient damping of ‘‘trapped current’’ shall be provided. The thyristor valve stresses depends on the design principle.

a) **The thyristor valve is used to bypass the capacitor at line faults.** In this case, the thyristor valve shall be designed to carry the current until the parallel connected bypass switch closes. It is required that the reliability of the devices that command the thyristor valve to enter and to remain in its bypass mode (i.e. to be continuously conducting during the fault is being secured. As the valve remains in a conducting state until the parallel bypass switch closes, no voltage stress is being imposed on the thyristor valve. This means that the maximum allowed surge current is determined by the maximal temperature in the thyristor junction, which shall not exceed the destructive level considering worst case overload before fault.
b) **The fault current is commutated into a parallel bypass gap.** In this case the thyristor valve shall be designed to carry the current during a half cycle of the power frequency. In order to trigger the bypass gap, the thyristor valve must be able to block so that the capacitor voltage becomes sufficiently high for successful triggering of the bypass gap. This means that the thyristor valve surge current stress shall be kept below a level that permits reverse blocking voltage to appear across the thyristor valve following the fault current.

6.3.1.2 Current capability at external faults

An external fault is a line fault occurring outside the protected line section containing the series capacitor bank. Often such faults cause line currents to exceed the maximum line current in the operational range of the TCSC. In such cases, it may be permitted to bypass the TCSC via the thyristor valve during the fault duration. It is necessary that the TCSC can be reinserted as soon as the line current drops and enters the normal operational range. The reinsertion can take place under overcurrent conditions (temporary overload or dynamic overload), if specified. Accordingly, the current capability of the thyristor valve shall be sufficient to carry the bypass current during the fault time without causing a temperature rise in the thyristor that is prohibitive with respect to fast reinsertion of the TCSC following fault clearing. Note that the valve shall carry the capacitor discharge current appearing at initiation of the bypass operation, in addition to the fault current from the line.

6.3.2 Voltage capability

The voltage rating of the TCSC valve is derived from the capability curves as depicted in Figure 5. In these curves different thyristor valve voltages have been defined for rated (continuous) operation, for temporary overload and for dynamic overload. Normally, the continuous operation requirement dictates the ‘‘protective level’’ U_{PL} of the varistors that are connected in parallel with the capacitor bank. The protective level is the maximum instantaneous voltage that occurs across the varistor in any fault case. Typically, the protective level is about 2,0 to 2,5 times the peak voltage at continuous rating.

$$U_{PL} = K_1 \hat{U}_N = \sqrt{2}\, K_1 U_N \tag{2}$$

where

$K_1 = 2{,}0$ to $2{,}5$

If the requirements on temporary or dynamical overload are severe, a higher protection factor can be necessary. The varistor limits the voltage across the thyristor valve to the protective voltage level U_{PL} in the off-state.

In designing the voltage capability of the valve, it is also necessary to consider the voltage overshoot, which occurs at turn-off. Figure 8 shows the typical appearance of a thyristor voltage in a TCSC operating capacitive boost mode.

The maximum thyristor voltage depends mainly on the capacitor voltage at turn-off plus an added thyristor turn-off voltage overshoot, which depends on the current derivative at turn-off and the TCSC reactor inductance.

NOTE Independently of the required operating range, the thyristor valve must be designed to withstand at least the protective level voltage of the series capacitor. This is important when a TCSC is designed with a relatively low maximum capacitive boost factor, because then the maximum valve voltage in capacitive boost mode may be lower than the protective level of the series capacitor.

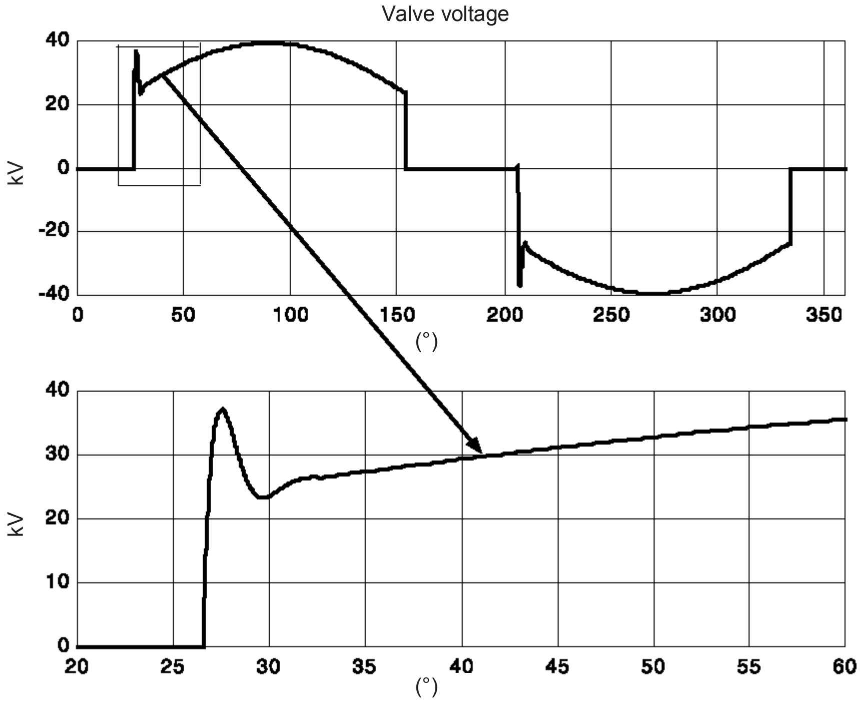

Figure 8 – Thyristor valve voltage in a TCSC

In the voltage/current capability curves in Figure 5, it has been assumed that the continuous, temporary and dynamic overload areas are limited by constant capacitor voltage curves for a range of line currents. Such limits are motivated by consideration of the voltage capability of the capacitor. The reactance varies along this limit, and it increases inversely proportional to the line current. Accordingly, the turn-off voltage and the current derivative increase when the line current decreases along the constant voltage limit. The highest thyristor valve turn-off voltage for a given capacitor voltage thus appears for the highest boost level giving this capacitor voltage. For example, operation in points A2, B2 and C2 of Figure 10 results in the highest thyristor valve turn-off voltages for continuous operation, temporary overload and dynamic overload respectively. Depending on the required operational capability curves and on the main circuit layout, the turn-off voltage can be higher or lower than the maximum protective off-state voltage defined by the varistor.

A maximum turn-off voltage, $U_{\mathrm{max,turn\text{-}off}}$, should be determined for the thyristor valve design. This voltage is higher than the turn-off voltage in the steady-state, when the TCSC is operating at any point within the capability diagram. Measures in the control system shall prevent turn-on from occurring, resulting in turn-off voltages exceeding $U_{\mathrm{max,turn\text{-}off}}$.

Overvoltage protection at turn-off of the valve may be arranged by different approaches. Some examples are:

- individual protective firing implemented for each thyristor;
- measuring system arranged across the whole valve, generating protective firing at overvoltage;
- measuring system supervising the thyristor branch d*i*/d*t*, generating protective firing when the current derivative exceeds the design level.

6.3.2.1 Voltage rating of TCSC valve, normal operation

When the maximum thyristor valve voltages with respect to the varistor protective level and the maximum thyristor turn-off voltage have been determined, the valve can be designed. When selecting the number of devices and the voltage rating, the following factors shall be considered:

- maximum valve voltage including turn-off overshoot;
- voltage sharing between the individual thyristor levels connected in series;
- required redundancy in the number of thyristor levels connected in series.

6.3.2.2 Voltage rating of TCSC valve, fault cases

If the protection system utilizes a bypass gap, which requires a high spark-over voltage, the thyristor withstand voltage following a surge current shall be considered.

If the protection system utilizes continuous bypass, no specific voltage capability requirement for fault cases is applicable.

6.4 Varistor rating

A thyristor controlled series capacitor can be bypassed via the thyristor valve almost instantaneously when a fault current is detected, and then reinserted quickly after fault clearing. Due to the fast reinsertion after fault clearing the TCSC can be bypassed during an external fault without causing any significant negative impact on system stability.

Thyristor valve bypass during both external and internal transmission line faults is often used for TCSC. This greatly reduces the required amount of varistor energy compared to a conventional series capacitor since almost no energy injection into the varistor will take place due to system fault currents. For internal faults also the bypass switch is closed.

The TCSC manufacturer shall, via simulations demonstrate that the control and protection system is fast enough to avoid varistor energy injection due to the fault currents that the TCSC may be exposed to. If energy injection does take place during system faults, then this energy injection must be considered in the varistor rating.

Reinsertion of a series capacitor causes a d.c. offset in the capacitor voltage, which may cause energy injection into the varistor. Energy injection due to reinsertion against a swing current must be considered in the varistor rating. The maximum magnitude of the varistor current and energy injection due to reinsertion against swing currents also needs to be considered when setting the varistor overload protections in order to make sure that the TCSC can be reinserted against a swing current.

Examples of external and internal fault duty cycles for TCSC are included in 8.5.

6.5 Insulation level and creepage distance

The insulation voltages, creepage distances and air clearances for the TCSC equipment shall be selected according to the principles defined in Clause 6 of IEC 60143-1. The TCSC voltage to be used in the calculation of creepage distances shall be the maximum continuous total RMS value of the capacitor voltage including the effect of capacitive boost. If the total RMS value of the capacitor voltage during temporary overload (U_{C30}) exceeds 1,35 pu, the creepage distance shall be linearly increased with (U_{C30}/1,35).

7 Tests

TCSC equipment shall be subjected to the type tests specified in this standard. For a specific project, these tests shall demonstrate that the equipment to be provided can withstand the required duties. When a type test has previously been successfully performed on equipment of demonstrably similar design at stress or duty levels that are equal to or greater than that for the specific project, then the manufacturer does not have to repeat the test if a written report describing the previously performed test is provided. In this case also a separate report detailing the differences in the design and demonstrating how the referenced type test report satisfies the test objectives for the specific project shall be provided.

New type tests must be performed for a specific project only if the equipment design is new or if a critical manufacturing process is new, or if it is to be applied at a higher stress or duty than previously tested designs, or if specifically contracted by the purchaser. The need for new type tests is assessed on an individual equipment type test basis.

Data obtained during stage fault tests involving a complete TCSC may be used to demonstrate the sufficiency of certain aspects of the design.

TCSC main circuit equipment for which tests are not specified in this standard shall be tested according to IEC 60143-2.

7.1 Test of the capacitor

The routine, type and special tests of the capacitors should be carried out in accordance with relevant parts of the series capacitor standard IEC 60143-1 and IEC 60143-3 taking into account the rated current and voltage determined as mentioned in 6.1 above.

The following tests shall be performed.

7.1.1 Routine tests

The following routine tests shall be carried out:

a) Capacitance measurement (5.3 of IEC 60143-1)
b) Capacitor loss measurement (5.4 of IEC 60143-1)
c) Voltage test between terminals (5.5 of IEC 60143-1)
d) AC voltage test between terminals and container (5.6 of IEC 60143-1)
e) Test on internal discharge device (5.7 of IEC 60143-1)
f) Sealing test (5.8 of IEC 60143-1)
g) Discharge test of internal fuses (3.1.2 of IEC 60143-3)

NOTE A discharge test should be performed also for fuseless capacitors in order to verify internal connections.

The test sequence is not necessarily that indicated above. The routine test shall be carried out by the manufacturer on every capacitor unit before delivery.

7.1.2 Type tests

The following routine tests shall be carried out:

a) Thermal stability test (5.9 of IEC 60143-1)
b) AC voltage test between terminals and container (5.10 of IEC 60143-1)
c) Lightning impulse test between terminals and container (5.11 of IEC 60143-1)
d) Cold duty test (5.12 of IEC 60143-1)
e) Discharge current test (5.13 of IEC 60143-1)
f) Disconnecting test on internal fuses (3.2.3 of IEC 60143-3)
g) Voltage test on internal fuse after opening the container (3.2.4 of IEC 60143-3)

The type tests are carried out in order to ensure that the capacitor unit complies with the contractual characteristics and with the operational requirements as specified in the standards.

It is not essential that all type tests are carried out on the same capacitor unit.

The above list of type tests does not indicate any test sequence.

Unless otherwise specified, every capacitor sample to which a type test will be applied shall have first withstood satisfactorily the application of all the routine tests.

7.1.3 Special test (endurance test)

The endurance test will be carried out only after a contractual agreement between the manufacturer and purchaser. This test will be carried out in accordance with 5.14 of IEC 60143-1.

7.2 Tests of the TCSC reactor

The routine, type and optional tests for the TCSC reactor should be carried out in accordance with relevant clauses of the reactor standard IEC 60076-6, Clause 9, taking into account the rated current and voltage determined as mentioned in 6.2 above.

The following tests shall be performed.

7.2.1 Routine tests

The following routine tests shall be carried out.

a) Measurement of winding resistance (9.10.2 of IEC 60076-6 and IEC 60076-1)
b) Measurement of inductance (9.10.5 of IEC 60076-6)
c) Measurement of loss and quality factor (9.10.6 of IEC 60076-6)
d) Winding overvoltage test (9.10.7 of IEC 60076-6)

7.2.2 Type tests

The following type tests shall be carried out:

a) Measurement of inductance (9.10.5 of IEC 60076-6)
b) Measurement of loss and quality factor (9.10.6 of IEC 60076-6)
c) Temperature rise test (9.10.8 of IEC 60076-6)
d) Lightning impulse test (9.10.9 of IEC 60076-6)

7.2.3 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

a) Short-circuit current test (9.10.10 of IEC 60076-6)
b) Measurement of acoustic sound level (9.10.11 of IEC 60076-6)
c) Separate source a.c. withstand voltage test (9.10.12 of IEC 60076-6)
d) Discharge current test (9.10.14 of IEC 60076-6)
e) Mechanical resonance test (9.10.16 of IEC 60076-6)
f) Measurement of winding resistance versus harmonic frequency (7.2.3.1)

NOTE If the short-circuit current test is performed, then the discharge current test should only be carried out if the discharge current amplitude is larger than the short-circuit current amplitude.

7.2.3.1 Measurement of winding resistance versus harmonic frequency

Measurement of the winding resistance as a function of frequency shall be carried out with an approved bridge method at reduced voltage. The frequency range shall be the harmonic frequency interval specified by the customer.

7.3 Tests of thyristor valves

7.3.1 Guidelines for the performance of type tests

7.3.1.1 Test object

The tests described apply to the valve (or valve sections), the valve structure and those parts of the coolant distribution system and firing and monitoring circuits which are contained within the valve structure or connected between the valve structure and platform. Other equipment, such as valve control and protection and valve base electronics may be essential for demonstrating the correct function of the valve during the tests but are not in themselves the subject of the valve tests.

Dielectric tests shall be performed on completely assembled valves, whereas operational tests may be performed on either complete valves or an appropriate number of valve sections, as specified, to verify that the valve design meets the specified requirements. When type tests are performed on valve sections, the total number of thyristor levels subjected to such type tests shall be at least equal to the number of thyristor levels in a valve.

The same valve (or valve section) shall be used for all type tests unless otherwise specified.

7.3.1.2 Sequence of tests

Prior to commencement of type tests, the valve, valve sections and / or the components of them should be demonstrated to have withstood the routine tests to ensure proper manufacture. The type tests specified can be carried out in any order.

7.3.1.3 Test conditions for dielectric tests

The valve shall be assembled with all auxiliary components except for the valve varistor, if used. Unless otherwise specified, the valve electronics shall be energized. The cooling and insulating fluids in particular shall be in a condition that represents service conditions such as conductivity, except for the flow rate and antifreezing media content, which can be reduced. If any object or device external to the structure is necessary for proper representation of the stresses during the test, it shall also be present or simulated in the test. Metallic parts of the valve structure (or other valves in a MVU) which are not part of the test shall be shorted together and connected to enclosure earth in a manner appropriate to the test in question.

When specified in the relevant clause, atmospheric correction shall be applied to the test voltages in accordance with IEC 60060-1. The reference conditions to which correction shall be made are the following:

– Pressure:

- If the insulation coordination of the tested part of the thyristor valve is based on standard rated withstand voltages according to IEC 60071-1, correction factors are only applied for altitudes exceeding 1 000 m. Hence if the altitude of the site (a_s) at which the equipment will be installed is ≤1 000 m, then the standard atmospheric air pressure (b_0 = 101,3 kPa) shall be used with no correction for altitude. If a_s >1 000 m, then the standard procedure according to IEC 60060-1 is used except that the reference atmospheric pressure b_0 is replaced by the atmospheric pressure corresponding to an altitude of 1 000 m ($b_{1\ 000m}$).
- If the insulation coordination of the tested part of the thyristor valve is not based on standard rated withstand voltages according to IEC 60071-1, then the standard procedure according to IEC 60060-1 is used with the reference atmospheric pressure b_0 (b_0=101,3 kPa).

– Temperature: design maximum valve hall air temperature (°C);

– Humidity: design minimum and maximum valve hall absolute humidity (g/m3).

The values to be used shall be specified by the supplier.

7.3.1.4 Test conditions for operational tests

Where possible, a complete thyristor valve should be tested. Otherwise the tests may be performed on thyristor valve sections. The choice depends mainly upon the thyristor valve design and the test facilities available. Where tests on the thyristor valve sections are proposed, the tests specified in this standard are valid for thyristor valve sections containing five or more series-connected thyristor levels. If tests on thyristor valve sections with fewer than five thyristor levels are proposed, additional test safety factors shall be agreed upon. Under no circumstances shall the number of series-connected thyristor levels in a thyristor valve section be less than three.

Operational tests are allowed to be performed at a power frequency different from the service frequency, i.e. 50 Hz instead of 60 Hz or vice versa. Some operational stresses such as switching losses or I^2t of short-circuit current are affected by the actual power frequency during tests. When this situation occurs, the test conditions shall be reviewed and appropriate changes made to ensure that the valve stresses are at least as severe as they would be if the tests were performed at the service frequency or actual waveshape.

The coolant shall be in a condition representative of service conditions. Flow and temperature, in particular, shall be set to the most unfavourable values appropriate to the test in question. Anti-freezing media content should, preferably, be equivalent to the service condition; however, where this is not practicable, a correction factor agreed between the supplier and the purchaser shall be applied.

7.3.1.5 Criteria for successful type testing

Experience in industry shows that, even with the most careful design of valves, it is not possible to avoid occasional random failures of thyristor level components during service operation. Even though these failures may be stress-related, they are considered random to the extent that the cause of failure or the relationship between failure and stress cannot be predicated or is not amenable to precise quantitative definition. Type tests subject valves or valve sections, within a short time, to multiple stresses that generally correspond to the worst stresses that can be experienced by the equipment not more than a few times during the life of the valve. Considering the above, the criteria for successful type testing set out below therefore permit a small number of thyristor levels to fail during type testing, providing that the failures are rare and do not show any pattern that is indicative of inadequate design.

The valves or valve sections shall be checked before each test, after any preliminary calibration tests, and again after each type test to determine whether or not any thyristors or auxiliary components have failed during the test. Failed thyristors or auxiliary components found at the end of a type test shall be remedied before further testing of a valve.

One thyristor level is permitted to fail due to short-circuiting in any type test. If, following a type test, one thyristor level has become short-circuited, then the failed level shall be restored and this type test repeated. A total of two thyristor levels are permitted to fail due to short-circuiting in all type tests together. If more than two thyristor levels fail during the type testing, the complete set of valve type tests shall be repeated.

The total number of thyristor levels exhibiting faults (short-circuited levels or faults that do not result in thyristor level short circuit), which are discovered during the type test program and the subsequent check, shall not exceed the number of redundant levels.

The location of short-circuited levels and of other thyristor level faults at the end of all type tests shall not show any pattern indicative of inadequate design.

7.3.2 Routine tests

The specified tests define the minimum testing required. The supplier shall provide a detailed description of the test procedures to meet the test objectives.

a) Visual inspection (8.1 of IEC 61954)
b) Connection check (8.2 of IEC 61954)
c) Voltage-dividing/damping circuit check (8.3 of IEC 61954)
d) Voltage withstand check (8.4 of IEC 61954)
e) Check of auxiliaries (8.5 of IEC 61954)
f) Firing check (8.6 of IEC 61954)
g) Cooling system pressure test (8.7 of IEC 61954)

7.3.3 Type tests

7.3.3.1 Dielectric tests

All dielectric tests on a complete valve shall be carried out with redundant thyristor levels short-circuited except where otherwise indicated. Tests for the following dielectric stresses are specified:

- a.c. voltage;
- impulse voltages.

In the interest of standardization with other equipment, lightning impulse tests between valve terminals and enclosure are included. For tests between valve terminals, the only impulse test specified is a switching impulse.

7.3.3.1.1 Tests on valve structure

Tests are defined for the voltage withstand requirements between a valve (with its terminals short-circuited) and the thyristor valve enclosure. The tests shall demonstrate that

- sufficient clearances have been provided to prevent flashovers;
- there is no disruptive discharge in the insulation of the valve structure, cooling ducts, light guides and other insulation parts of the pulse transmission and distribution systems;
- partial discharge inception and extinction voltages are above the maximum steady-state operating voltage appearing on the valve structure.

For these tests, each thyristor level shall be short-circuited. It may be necessary to disconnect the connection of low voltage bushing during this test.

7.3.3.1.1.1 Power frequency voltage withstand test between terminal and earth

a) Test values and waveshapes

The test is performed with a 1 min test voltage U_{ts1} and a 10 min test voltage U_{ts2} that have sinusoidal wave shapes with a frequency of 50 Hz or 60 Hz, depending on the test facilities. The test voltages shall be calculated according to

$$U_{ts} = \frac{U_{ms}}{\sqrt{2}} \times k_{s2} \times k_t$$

where

U_{ms} is the peak value of the maximum repetitive operating voltage, including extinction overshoot, across the valve support. (Typically derived from operation with maximum dynamic overload in CAP mode or the series capacitor protective level);

U_{ts1} is the 1 min test voltage;

U_{ts2} is the 10 min test voltage;

k_{s2} is equal to 1,30 for the 1 min test;

k_{s2} is equal to 1,10 for the 10 min test;

k_t is the atmospheric correction factor;

k_t is the value according to 7.3.1.3 for the 1 min test;

k_t is equal to 1,0 for the 10 min test.

b) Test procedures

The test consists of applying the specified test voltages U_{ts1} and U_{ts2} for the specified duration between the two interconnected valve terminals and earth.

1) Raise the voltage from 50 % to 100 % of U_{ts1}.
2) Maintain U_{ts1} for 1 min.
3) Reduce the voltage to U_{ts2}.
4) Maintain U_{ts2} for 10 min, record the partial discharge level and then reduce the voltage to zero.
5) The peak value of the periodic partial discharge recorded during the last minute of step 4) shall be less than 200 pC, provided that the components which are sensitive to partial discharge in the valve have been separately tested, or alternatively, 50 pC if they have not.
6) The measurement of inception and extinction voltage shall be performed in accordance with IEC 60270.

7.3.3.1.1.2 Lightning impulse test between terminal and earth

A standard 1.2/50 μs wave shape shall be used. The peak value of the test voltage is the standard lightning impulse withstand voltage according to 6.1.3 of IEC 60143-1.

7.3.3.1.2 Tests between valve terminals

The purpose of these tests is to verify the design of the valve with respect to its capability to withstand overvoltages between its terminals. The tests shall demonstrate that

- sufficient internal insulation has been provided to enable the valve to withstand specified voltages;
- partial discharge inception and extinction voltages are above the maximum steady-state operating voltage appearing on the valve;
- the protective overvoltage firing system (if provided) works as intended;
- the thyristors have adequate d*u*/d*t* capability for in-service conditions. (In most cases the specified tests are sufficient; however in some exceptional cases additional tests may be required).

7.3.3.1.2.1 Switching impulse test between terminals

a) Test values and waveshape

Wave shape: Standard 250/2500 μs wave shape.

1) Test 1

This test is applicable for valves with a protective firing system. The test shall comprise three applications of positive polarity and three application of negative polarity switching impulse voltages of specified amplitude with the valve electronics initially energized and de-energized cases, i.e. totally 12 applications.

This test is intended to verify that the protective firing system of the valve will not operate for voltage values up to the test voltages.

The test voltage U_{tsv1} is determined as follows:

$$U_{tsv1} = k_s \times U_1$$

where

U_1 is the maximum instantaneous value of the valve terminal-to-terminal voltage that the valve shall withstand without initiating operation of the protective firing system (if provided) under service conditions. (Typically derived from operation with maximum dynamic overload in CAP mode or the series capacitor protective level);

k_s is a test safety factor (k_s = 1,05).

2) Test 2

The test is intended to verify the valve insulation and the proper operation of the protective firing system (if applicable to the valve design).

- Valves protected by thyristor valve varistors:

The prospective test voltage U_{tsv2} is determined as follows:

$$U_{tsv2} = k_s \times U_{apl}$$

where

U_{apl} is the arrester protective level;

k_s is a test safety factor (k_s = 1,1).

- Valves protected by VBO:

The prospective test voltage U_{tsv2} is determined as follows:

$$U_{tsv2} = k_s \times U_{VBO}$$

where

U_{VBO} is the maximum VBO protective voltage level with redundant thyristor levels operational;

k_s is a test safety factor (k_s = 1,1).

The upper and lower limits of the protective VBO firing threshold, with the redundant thyristor levels operational, shall be stated by the manufacturer and a check made that the observed voltage at firing lies between the two limits.

The test shall be repeated with the valve electronics initially de-energized.

NOTE In valve designs where the regular firing circuits are energized independently of the main power circuit, this additional test is not applicable.

- Valves protected by indirect overvoltage protection via measurement of valve current derivative:

The prospective test voltage U_{tsv2} is determined as follows:

$$U_{tsv2} = k_s \times U_{didt}$$

where

U_{didt} is the maximum valve peak voltage defined by the di/dt overvoltage protection;

k_s is a test safety factor;

k_s = 1,1* k_i

k_i is a measurement interpretation factor

k_i = 1,05.

- Valves with neither arresters, VBOs nor d*i*/d*t* overvoltage protections

This test is intended to verify the valve insulation when neither arresters, VBOs nor di/dt overvoltage protections are used.

$$U_{tsv2} = k_s \times U_{cms}$$

where

U_{cms} is the switching impulse prospective voltage according to IEC 60071, or as determined by insulation coordination studies;

k_s is a test safety factor (k_s= 1,3).

The valve shall withstand the test voltage without switching or insulation breakdown.

b) Test procedures

For any of these tests, three applications of switching impulse voltages of each polarity shall be applied between the valve terminals, with one terminal earthed. Instead of reversing the polarity of the surge generator, the test may be performed with one polarity of the surge generator and reversing the valve terminals.

Special additional conditions are listed below.

1) Test 1

The valve protective firing system is operational and the test voltage below the firing level, taking into account the presence of a valve varistor if one is included in the design.

The valve shall not be fired by any control or protective system during this test.

2) Test 2

The valve protective firing system is operational and the voltage above the firing level (if applicable).

Where the VBO firing is based on measurements of voltage on individual thyristor levels, the test shall be performed with the redundant thyristor levels operational.

7.3.3.1.2.2 Power frequency voltage withstand test between terminals

The test is performed with a 1 min test voltage U_{tv1} and a 10 min test voltage U_{tv2} that have sinusoidal waveshapes with a frequency of 50 Hz or 60 Hz, depending on the test facilities.

$$U_{tv1} = \frac{U_1}{\sqrt{2}} \times k_{s1}$$

where

U_1 is the peak value of maximum repetitive over-voltage, including extinction overshoot, across the valve terminals. (Typically derived from operation with maximum dynamic overload in CAP mode, point C2 for the example given in Figure 10, or the series capacitor protective level);

k_{s1} is a test safety factor (k_{s1}= 1,10).

NOTE 1 The prescribed test may thermally overstress some valve components unrealistically. Where this is the case, subject to agreement between purchaser and supplier, the 1 min a.c. voltage withstand test may be replaced by several shorter tests whose minimum duration is determined from the maximum possible duration of the specified overvoltage condition multiplied by 2, but with a total duration of not less than 1 min.

$$U_{tv2} = \frac{U_2}{\sqrt{2}} \times k_{s2}$$

where

U_2 is the peak value of maximum repetitive over-voltage, including extinction overshoot, across the valve terminals for the most severe temporary overload specified. (Typically derived from point B2 for the example given in Figure 10)

k_{s2} is a test safety factor (k_{s2} = 1,10).

- **Test procedures**

The test procedure consists of applying the specified test voltages, for the specified duration, between the two valve terminals with one terminal earthed.

a) Raise the voltage from 50 % to 100 % U_{tv1}.
b) Maintain U_{tv1} for 1 min.
c) Reduce the voltage to U_{tv2}.
d) Maintain U_{tv2} for 10 min, record the partial discharge level and reduce the voltage to zero.
e) The peak value of the periodic partial discharge recorded during the last minute of step d) shall be less than 200 pC, provided that the components which are sensitive to partial discharge in the valve have been separately tested, or alternatively 50 pC if they have not been separately tested.
f) The measurement of inception and extinction voltage shall be performed in accordance with IEC 60270.

If protective VBO firing is provided, it shall not operate during this test.

7.3.3.2 Electromagnetic interference test

7.3.3.2.1 Objectives

The objective of these tests is to demonstrate the insensitivity of the valve to electromagnetic emission imposed by external events.

The tests shall demonstrate that, as a result of electromagnetic emission,

- spurious triggering of thyristors does not occur;
- false indication of thyristor level faults or erroneous signals sent to the converter control and protection systems by the valve electronics do not occur.

7.3.3.2.2 Test procedures

Insensitivity to electromagnetic interference is verified by monitoring the valve during the switching impulse test between terminals. The electronics of the valve under test shall be energized. Those parts of the valve base electronics that are necessary for the proper exchange of information with the test valve shall be included. The criteria for test acceptance are that no spurious valve firing or false indication from the valve to control or protection system occur.

7.3.3.3 Operational tests

The purpose of the operational tests is to verify the valve design for combined voltage and current stresses under normal and abnormal repetitive conditions as well as under transient fault conditions. They shall demonstrate that, under specified conditions:

- the valve functions properly in entire operating area as specified in valve operating pattern;
- the turn-on and turn-off voltage and current stresses are within the capabilities of the thyristors and other internal circuits;
- the cooling provided is adequate and no component is overheated;
- the over-current and over-voltage withstand capability of the valve is adequate.

7.3.3.3.1 Periodic firing test and extinction test

The purpose of the test is to show that the valve can withstand the combined voltage and current stresses resulting from the most severe dynamic overload specified. Therefore, the test conditions shall correspond to the specified worst-case, time-dependent boost mode, taking into account the control and protection characteristics of the scheme. In particular, it shall be demonstrated that the valve can block the highest voltage (including extinction overshoot) combined with the maximum thyristor junction temperature given by the load cycle.

The valve or valve sections shall be subjected to current and voltage waveshapes as close as possible to those experienced by the valve during firing and extinction, for the most critical operating conditions specified below. The time interval of principal interest for firing is the first 10-20 μs while, for extinction, the interval of interest is between 0,2 ms before and 1 ms after current zero.

In particular, the following conditions shall be no less severe than in service

a) voltage magnitudes at turn-on and turn-off;
b) the di/dt at turn-on and at least for 0,2 ms before current zero;
c) the thyristor junction temperature.

The following factors shall also be considered:

1) the representation of stray capacitance between valve terminals;
2) sufficient magnitude and duration of the load current to achieve full area conduction of the thyristor junction.

7.3.3.3.1.1 Operation with maximum temporary capacitive boost

a) Test values

The test current and test voltage shall be based on the worst temporary overload (see point B2 in Figure 10).

The coolant temperature shall be not less than that which will give the highest temporary overload thyristor junction temperature in service at maximum ambient temperature.

The test current shall incorporate a test safety factor of 1,05.

The test duration shall be 30 min after the return coolant temperature has stabilized.

The test voltage at valve firing / extinction is

$$U_{\text{f\_max}} = \frac{\lambda \times X_0 \times i_L}{\lambda^2 - 1} \times \frac{N_t}{N_{tot} - N_{red}} \times \left[\sin\beta - \lambda \times \cos\beta \times \tan(\lambda \times \beta)\right] \times k_{s3}$$

where

λ is the ratio of natural frequency of LC branch and network frequency;

X_0 is the impedance of LC branch;

i_L is the line current;

N_t is the number of series connected thyristor levels under test;

N_{tot} is the total number of series connected thyristor levels in a complete valve, including redundant levels;

N_{red} is the number of redundant thyristor levels in a complete valve, including redundant levels;

β is the steady state control angle of TCSC valves;

k_{s3} is a test safety factor;

k_{s3} = 1,05.

b) Test procedure

The tests shall be performed using suitable test circuits, such as an appropriate synthetic test circuit, giving turn-on and turn-off stresses equivalent to the appropriate service conditions.

All the auxiliary systems which may influence the behaviour of the valve in the operating conditions specified below (e.g. forced firing) shall be in operation.

Ideally, the test would be performed by reproducing the specified time-dependent source current. For practical reasons, a modified test procedure may be adopted as follows:

1) establish maximum steady state conditions for current and voltage and maintain them until thermal equilibrium is reached;
2) raise the source current to the test value and adjust the firing angle to reach the test voltage. Maintain operation for 30 min.

7.3.3.3.1.2 Operation with maximum dynamic capacitive boost

a) Test values

The test current and test voltage shall be based on the worst dynamic overload, see point C2 in Figure 10.

The coolant temperature shall be not less than that which will give the highest dynamic overload thyristor junction temperature in service at maximum ambient temperature.

The test current shall incorporate a test safety factor of 1,05. The test voltage is calculated according to the equation in 7.3.3.3.1.1 using values corresponding to dynamic overload.

The test duration shall be 1,1 times the specified dynamic overload duration.

b) Test procedure

The tests shall be performed using suitable test circuits, such as an appropriate synthetic test circuit, giving turn-on and turn-off stresses equivalent to the appropriate service conditions.

All the auxiliary systems which may influence the behaviour of the valve in the operating conditions specified below (e.g. forced firing) shall be in operation.

Ideally, the test would be performed by reproducing the specified time-dependent source current. For practical reasons, a modified test procedure may be adopted as follows:

1) establish maximum temporary overload conditions for current and voltage and maintain them until thermal equilibrium is reached;
2) raise the source current to the test value and adjust the firing angle to reach the test voltage. Maintain operation for 1.1 times the specified dynamic overload duration.

7.3.3.3.1.3 Operation with minimum capacitive boost

The purpose of this test is to verify proper operation of the firing system in the TCSC valve at the specified minimum line current and capacitive boost.

The test current shall be based on the specified minimum continuous line current permissible with capacitive boost operation, point D1 in Figure 10.

The test current shall incorporate a test safety factor of 0,95.

The test duration shall be 10 min.

The test voltages U_{f_min} (valve steady-state voltage at firing instant) and U_{p_min} (valve steady-state power frequency peak voltage) shall be determined as follows:

$$U_{f\_min} = \frac{\lambda \times X_0 \times i_L}{\lambda^2 - 1} \times \frac{N_t}{N_{tot}} \times \left[\sin\beta - \lambda \times \cos\beta \times \tan(\lambda \times \beta)\right] \times k_{s4}$$

$$U_{p\_min} = \lambda \times X_0 \times \sqrt{2} \times i_{L\_min} \times \frac{N_t}{N_{tot}} \times \left[1 + \frac{\lambda \times (\cos\beta \times \tan(\lambda \times \beta) - \lambda \times \sin\beta)}{\lambda^2 - 1}\right] \times k_{s4}$$

where

i_{L_min}	is the minimum line current for capacitive boost;
β_{min}	is the minimum conduction angle of TCSC valves for capacitive boost at i_{L_min}
k_{s4}	is a test safety factor;
k_{s4}	= 0,95.

7.3.3.3.1.4 Operation at bypass

When a TCSC valve is designed for operation with a relatively low capacitive boost factor, the valve losses in capacitive boost mode could be comparable with that in valve bypass operation mode.

If calculations indicate that the thyristor losses in bypass mode is greater than the thyristor losses in capacitive boost mode, the following bypass test should be done to verify the thermal capability of the valve. Otherwise, bypass test is not necessary since the verification of valve thermal capability has been covered by the test with maximum capacitive boost.

$$I_{bypass} = \frac{1}{1 - \omega^2 \times L \times C} \times I_L \times k_{s5}$$

where

I_L	is the maximum temporary overload line current with the TCSC bypassed;
L	is the inductance of TCSC LC branch;
C	is the capacitance of TCSC LC branch;

k_{s5} is a test safety factor;

k_{s5} = 1,05.

The test duration shall be 2 times the specified temporary overload duration or maximum 30 min after the return coolant temperature has stabilized.

- **Test procedure**

The tests shall be performed using suitable test circuits. All the auxiliary systems which may influence the behaviour of the valve in the operating conditions specified below shall be in operation.

a) establish maximum continuous conditions for line current and maintain it until thermal equilibrium is reached;

b) raise the source current to the test value. Maintain operation for the specified test duration.

7.3.3.3.2 Fault current test

The principle objective of the fault current tests is to demonstrate proper design of the valve to withstand the maximum current, voltage and temperature stresses arising from short-circuit currents.

The tests shall demonstrate that the valve is capable of:

- conducting the maximum fault current due to a close internal transmission line fault until the parallel bypass switch is closed, commencing from maximum steady state operating temperature. No sub-sequent blocking is required.
- conducting the maximum fault current due to an external fault until the fault is interrupted by opening of the line circuit breakers within the normal fault clearing time, commencing from maximum temperature. Subsequent blocking after fault clearing is required. This is applicable only if the TCSC valve is used for bypassing during external faults.

7.3.3.3.2.1 Fault current without subsequent blocking

When an internal fault occurs the fault current is high and the line circuit breakers will be tripped to interrupt the fault current and isolate the healthy part of network from the faulted point. Depending on the fault handling procedure, the TCSC protection may order bypass of the series capacitor via both the thyristor valve and the bypass switch. No subsequent blocking voltage appears on the TCSC valve after fault current conduction.

The wave shape of test current does not need to be identical to the fault current that could occur in service. The current shall have a peak value at least equal to the highest value of overcurrent and also it shall give the thyristor temperature at least equal to the highest value that could occur in service conditions considering the closing time of the bypass switch.

- **Test procedure**

The tests shall be performed using suitable test circuits. All the auxiliary systems which may influence the behaviour of the valve in the operating conditions specified below shall be in operation.

a) establish thyristor junction temperature (in any suitable way) corresponding to the maximum steady state condition;

b) apply the test current for the specified time.

7.3.3.3.2.2 Fault current with subsequent blocking

This test is applicable if the TCSC is operated in such way that the valve is exposed to fault current followed by a blocking voltage.

The test current and voltage shall stress the TCSC valve / valve section at least as severe as they would meet in service. A test safety factor of 1.05 shall be applied to the subsequent blocking voltage. The current shall have a peak value at least equal to the highest value of overcurrent and also it shall give the thyristor temperature at least equal to the highest value at the instance when the voltage is re-applied.

- **Test procedure**

The tests shall be performed using suitable test circuits. All the auxiliary systems which may influence the behaviour of the valve in the operating conditions specified below shall be in operation.

a) Establish thyristor junction temperature (in any suitable way) corresponding to the maximum steady state condition.

b) Apply the test current for the specified time.

c) Apply the test voltage.

7.4 Tests of protection and control system

Testing of the TCSC protection and control system consists of routine, type and special tests. The purpose of the type tests is to verify proper design of the equipment, that it is capable of operating in specified ambient conditions and meet the specified performance and electromagnetic compatibility requirements. The functional tests shall include simulations to demonstrate proper functioning of the control and protection system for all specified operating modes. These simulations can readily be carried out with the control and protection system connected to a real time (digital) network simulator where different system conditions are simulated. The simulation of the performance of the control and protection system should demonstrate the operation of the TCSC during specified operating modes.

Coordination shall be made with IEC 60068-2-2 and IEC 60068-2-78 for environmental conditions, IEC 60255-21 for mechanical tests, IEC 60255-5 for dielectric tests, IEC 61000-4-11 and IEC 61000-4-29 for auxiliary power voltage variations and IEC 61000-4 for electromagnetic compatibility requirements unless otherwise stated.

7.4.1 Routine tests

The following tests shall be carried out as a minimum.

a) Visual examination

b) Dielectric withstand test (IEC 60255-5)

c) 100 h burn-in test

d) Operational test

The listed test shall apply to the platform located part of the equipment, to the platform to ground communication equipment and to the ground located part of the equipment.

The objective of the tests is to verify the manufacturing quality of all components and of the complete assembly.

7.4.1.1 Operational test

The procedure consists of injecting signals that simulate conditions requiring protective action into each control input. Each output is monitored during these tests. All hardware and software settings are verified. Software settings may be verified by software techniques.

If optical platform-to-ground communication is used, the output power of the transmitters shall be checked.

An optical loss test shall be performed on each fiber of the platform-to-ground communication insulators.

7.4.2 Type tests

The following type tests shall be carried out as a minimum.

a) Environmental tests: Dry heat test and Damp heat test (IEC 60068-2-2 and IEC 60068-2-78)
b) Dielectric test (IEC 60255-5)
c) Electromagnetic compatibility tests (IEC 61000-4)
d) Mechanical test (IEC 60255-21)

The listed test shall apply to the platform located part of the equipment, to the platform to ground communication equipment and to the ground located part of the equipment.

NOTE Pre-commissioning tests at site, on relay protection, control equipment and platform to earth communication equipment, are normally specified. These tests are performed before the bank is energised to the high voltage network.

7.4.3 Special tests

7.4.3.1 Real time protection- and control system test with network simulator

The real time protection- and control system test with network simulator is optional.

The use of real time (digital) network simulator is recommended for verifying correct and intended operation of protection- and control system. The test is optional depending on the availability of such a simulation system.

The protection- and control system is connected to a network simulator. All applicable signals are connected between control system and simulator. The network under simulation is designed based on data available of the real network. Protection and control functions are tested based on system requirement and specified features. Recorded network data is injected in the simulation if available and applicable. Figure 9 shows a typical block diagram of such a simulation system.

The network in the simulation can be partly replaced by recorded data of an existing network which is injected into the simulation. In such case it must be taken into account that the operation of TCSC controller is not affecting the part of the network replaced by recorded signals.

The correct dimensioning of HV equipment is verified by monitoring voltage and current values during worst case situation simulations. The verification requires detailed modelling of TCSC HV equipment in the simulation.

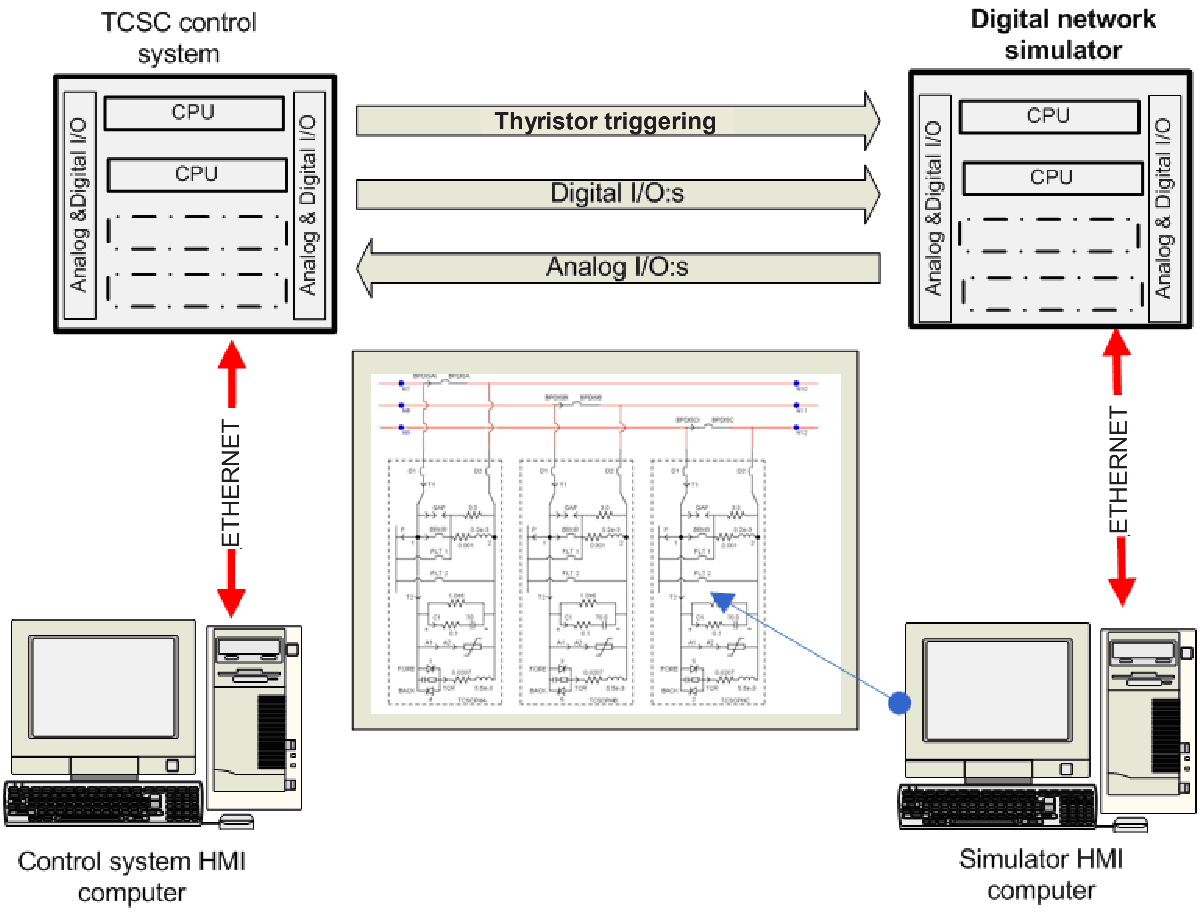

Figure 9 – Typical block diagram of a real time TCSC protection- and control system simulation environment

8 Guidance for selection of rating and operation

8.1 General

The purchaser should specify general conditions and objectives for which the TCSC installation is to be designed and operated including the following:

Project scope: The purchaser should define the scope of supply to be provided by the purchaser and supplier for the overall TCSC project.

Application studies: The purchaser should define the design documentation that shall be completed by the supplier.

Systems design: It is to the purchaser's advantage to allow the supplier to design the overall TCSC installation based on the specification requirements.

The purchaser should:

a) specify the desired TCSC system performances requirements;

b) provide the yard layout drawings (for existing substation) or define the maximum dimensional areas (for new substation);

c) indicate whether the control building will be the responsibility of the purchaser, the supplier or others;

d) require, from the supplier, to provide an equipment layout drawing of ground control equipment, cooling and power requirements for the control equipment;

e) specify any internal design habits which may have an impact on the operation and maintenance of the installation: low voltage equipments, colour code used (if any), security rules, tools, IHM symbols, etc.

Supply of equipment: The scope of equipment supply should be clearly defined by the purchaser. Generally, it is to the purchaser's advantage to require the supplier to design and provide the entire system including all platform mounted equipment, controls, communication with ground level controls, thyristor cooling equipment, and bypass switch.

- **Installation**

The purchaser should:

a) define the area limitations and location of the existing and future overhead lines, utilities, roads;

b) indicate who will provide required permits and geotechnical studies;

c) indicate who will provide the site preparation, grounding system, foundation, fence, platform, required yard structure, bus work and switches, control building, and TCSC equipment installed, tested, and commissioned.

- **Testing and commissioning, maintenance, training and documentation**

The purchaser should:

1) define the testing and commissioning requirements of the supplier;

2) define the required operator training, training and operating manuals, and instruction books;

3) require the supplier to provide a recommended maintenance schedule and contract warranty provisions.

- **List of applicable standards**

The purchaser should provide a summary list of standards for which the TCSC installation is to be designed, manufactured, and tested. Each of the listed standards should be referenced, where applicable, in the appropriate clauses of the TCSC specification.

- **Site service conditions**

The purchaser should specify the TCSC installation site service conditions at the specified current, voltage, frequency, and fault sequence ratings, including: altitude, ambient temperature, ice load, wind velocities, seismic conditions, snow depth, exposure to dust, exposure to salt (damaging fumes, or vapours), swarming insects, flocking birds, conditions requiring over insulation or extra leakage distance on insulators, continuous harmonic currents in the power system, unusual transportation or storage conditions, non-transposed lines, etc.

8.2 Thyristor controlled series capacitor

8.2.1 AC transmission system

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The purchaser should specify the electrical characteristics of the transmission line being compensated and associated ac transmission system including the following:

a) Rated line-to-line voltage:
   1) Continuous
   2) Maximum operating voltage and duration
b) Rated frequency:
   1) Continuous power frequency and steady-state variations
   2) Transient power frequency variations and duration
c) Electrical insulation levels (phase-to-ground):
   1) Basic impulse level (BIL)
   2) Wet switching surge withstand level
   3) Power frequency withstand voltage (1 min)
   4) Specific creepage distance and pollution level
d) System data:

The purchaser should provide transmission line data and system information adequate for the supplier to perform specified studies and design of the TCSC equipment.

– Short circuit equivalent for rating purposes.
– Dynamic equivalent for POD studies, if applicable.
– Generator and turbine data for SSR-studies, if applicable.

8.2.2 TCSC operational objectives

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The purchaser should specify any special operating conditions and system events for which the TCSC components and equipment are to be designed and operated including radio influence voltage level, corona level, and audible noise level.

The principal operational objectives that may be the motivation for a TCSC application are the following:

a) Sub-synchronous resonance (SSR) considerations:

   The TCSC supplier should be involved in the SSR studies, if the studies indicate that fixed capacitors with the desired level of compensation will result in an SSR problems.
b) Power oscillation damping (POD) Control

   The current swings of the system interacting with the modulation of the TCSC reactance by the POD create oscillating voltage across the TCSC. The voltage constraints of the TCSC override an unacceptable reactance order; therefore, it is imperative that the system studies properly account for this limitation.
c) Transient stability
d) Current or power control
e) Voltage control

8.2.3 TCSC ratings

The purchaser should specify the TCSC continuous, bypass, temporary overload, and dynamic overload, and duty cycle operating requirements. It is recommended that these parameters be presented in graphical form as indicated in Figure 5 and Figure 10.

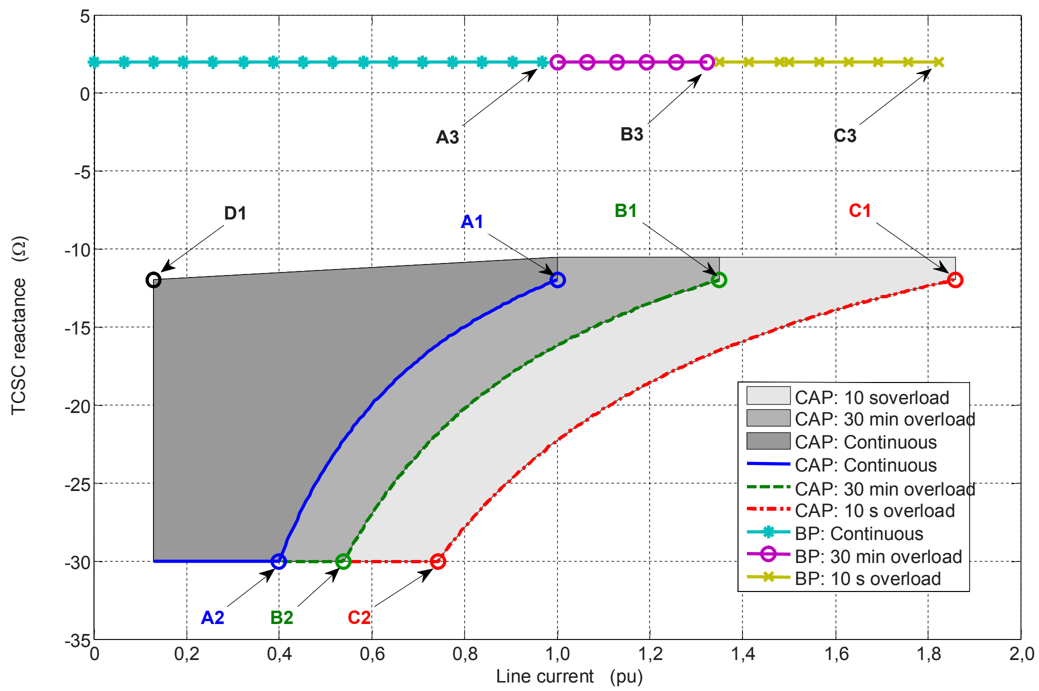

Figure 10 – Example of operating range diagram for TCSC

The following operating parameters should be defined for capacitive reactance and bypass modes of operation, as these can be very different.

- **Continuous operation in CAP mode:**
  - Maximum line current and nominal TCSC reactance (point A1)
  - Maximum reactance or boost factor together with the corresponding line current (point A2)
  - Minimum current for which the thyristor valve remains operational
- **Temporary overload operation in CAP mode (typically 30 min):**
  - Maximum line current and nominal TCSC reactance (point B1)
  - Maximum reactance or boost factor together with the corresponding line current (point B2)
  - Duration of temporary overload
- **Dynamic overload operation in CAP mode (typically 10 s):**
  - Maximum line current and nominal TCSC reactance (point C1)
  - Maximum reactance or boost factor together with the corresponding line current (point C2)
  - Duration and frequency of dynamic overload
- **Continuous operation in BP mode:**
  - Maximum line current (point A3)
- **Temporary overload operation in BP mode (typically 30 min):**
  - Maximum line current (point B3)

– Duration of temporary overload

- **Dynamic overload operation in BP mode (typically 10 s):**
  – Maximum line current (point C3)
  – Duration and frequency of dynamic overload

8.3 Thyristor valves

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The thyristor valves should be designed by the supplier to meet the operating and rating requirements of the TCSC installation. Design features that the purchaser should consider when specifying the TCSC thyristor valves include the following:

a) Maintenance
   1) Tools, handling, and facilities for maintenance
   2) Time between maintenance periods
   3) Time to replace an individual thyristor level
b) Monitoring and diagnostic provisions indicating the number and position of a failed thyristor
c) Redundancy factors
d) Control features
e) Cooling system electrical requirements
f) Mechanical design features
g) Type tests
h) Routine tests

8.4 Capacitors and reactors

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It is recommended that the purchaser refer to the applicable IEC standards for TCSC capacitor and reactor component design, manufacturing, and testing requirements to the extent possible.

General requirements that the purchaser should consider include:

a) Capacitor and reactor components furnished by the supplier should be provided with identical interchangeable components, to simplify maintenance and stocking of spare parts.
b) Components should be equipped with lifting eyes or have similar provisions for lifting individual units for ease of transportation, installation, and maintenance.
c) Support insulators used for mounting TCSC capacitor and reactor components should be furnished with sufficient creepage and clearance for reliable operation and maintenance of the equipment.
d) The current rating of the capacitors and reactors should be based on the sum of the squares of the current at the power and harmonic frequencies through the equipment.

8.4.1 Capacitor considerations

Capacitors for the TCSC shall be designed, manufactured, and tested in accordance with applicable requirements of IEC 60143-1.

8.4.2 Reactor considerations

The TCSC thyristor reactors should be designed, manufactured, and tested in accordance with applicable requirements of IEC 60143-2. General requirements that the purchaser should consider include:

a) Air-core reactors are surrounded by a magnetic field created by the winding ampere-turns. The location of the reactor relative to metallic structures should be considered by the supplier with regard to inductive heating effects during normal operation, or coupled forces during short-circuit loading of the reactor.

b) Acoustic noise in the human audible range of the sound spectrum can be produced as a result of vibrations in the thyristor reactor due to the presence of harmonic currents. The user, as applicable, should specify the maximum allowable acoustic noise criteria and levels.

8.5 Fault duty cycles for varistor rating

It is essential that the buyer clearly specifies the fault duty cycles for the TCSC. One way to specify the fault duty cycles is to utilize tables as shown in Table 2 through Table 4.

Table 2 – Typical external fault duty cycle with unsuccessful high speed auto-reclosing

Time ms	**Power system event**	**Thyristor controlled series capacitor action**
0,0	Fault application	-
0,0 to 100	Fault remains	The TCSC line current supervision detects high line current and bypasses the TCSC via the tyristor valve
100,0	Line circuit breakers clear the fault	
100,0 to 600,0	Power flows through the line	The TCSC is reinserted
600,0	Line circuit breakers reclose into the fault	-
600,0 to 700,0	Fault remains	The TCSC line current supervision detects high line current and bypasses the TCSC via the tyristor valve
700,0	Line circuit breakers clear the fault and lock out	
700,0 to -		The TCSC is reinserted

Table 3 – Typical duty cycle for internal fault with successful high speed auto-reclosing

Time ms	**Power system event**	**Thyristor controlled series capacitor action**
0,0	Fault application	-
0,0 to 100	Fault remains	The TCSC line current supervision detects high line current and bypasses the TCSC via the tyristor valve and the bypass switch
100,0	Line circuit breakers clear the fault	Series capacitor remains bypassed
100,0 to 600,0	The line is disconnected	
The fault disappears	The series capacitor remains bypassed	
600,0	Line circuit breakers reclose	-
600,0 to -		The series capacitor is reinserted

Table 4 – Typical duty cycle for internal fault with unsuccessful high speed auto-reclosing

Time ms	Power system event	Thyristor controlled series capacitor action
0,0	Fault application	-
0,0 to 100	Fault remains	The TCSC line current supervision detects high line current and bypasses the TCSC via the tyristor valve and the bypass switch
100,0	Line circuit breakers clear the fault	Series capacitor remains bypassed
100,0 to 600,0	The line is disconnected	The series capacitor remains bypassed
600,0	Line circuit breakers reclose into the fault	-
600,0 to 700,0	Fault remains	Series capacitor reinsertion is inhibited by the series capacitor line current supervision
700,0	Line circuit breakers clear the fault and lock out	

8.6 Valve cooling system

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The purpose of the thyristor-valve cooling system is to remove the heat produced by the thyristor valve. The cooling system should be completely furnished with all necessary interconnecting piping, ductwork, circulating pumps, make-up reservoirs, heat exchangers, filters, instrumentation, automatic controls, alarms, control power systems, and other necessary equipment. For normal TCSC applications, only liquid cooling is applicable.

The heat transfer from the closed liquid system to the ambient should take place in a water-to-air or water-to-water heat exchanger. Some important requirements for the cooling system are as follows:

a) Redundant pumps: one pump is normally operating and a redundant pump is standing by.The cooling system should be designed to permit work on the defective pump unit without shutting down the TCSC.
b) Purification system: The purification system should be designed to maintain the resistivity of the water above the required level. Highly purified water is required for the thyristor valve cooling because of the potential difference between ground and valve potential.
c) Protection against freezing: If a low ambient outdoor temperature is specified, the water can be mixed with glycol or other chemical agents in order to avoid freezing of the coolant.
d) Replacement: Filters and deionizer material should be designed to allow replacements in a relatively short time without shutdown of the cooling unit.
e) TCSC isolation: Deionized water is used for thyristor valve cooling due to the potential difference between ground and valve position

8.7 TCSC control and protection

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The purchaser should specify the TCSC control and protection requirements.

8.7.1 Control

The TCSC control systems should be specified to meet specific control objectives for which the controller needs to respond. The TCSC control system objectives specified by the purchaser should include:

a) Required control modes
b) Manual mode for site testing and maintenance
c) Emergency shut down by operator (local and remote)
d) Voltage, current, reactance, and reactive power measurements
e) Synchronization for appropriate generation of firing pulses to the thyristor valves
f) Startup and shutdown sequencing
g) Monitoring
h) Control self-supervision
i) Capacitor bank protection

8.7.1.1 Control functions

Various hierarchy control levels and strategies are typically required to meet specified performance control functions. Control strategies and settings can vary with ac network configuration and are specific to the project objectives. The effectiveness of any particular TCSC control function should be validated by appropriate studies, simulation, and testing. Typical control functions for TCSC applications include reactance control, current (power) flow control, SSR mitigation, power oscillation damping control, voltage control, and open-loop control.

8.7.1.2 Control structure

More than one TCSC controllable sub-segment can be specified by the purchaser or provided by the supplier depending on the project objectives. To facilitate coordination between controllable sub-segments and to ensure appropriate net reactance, the TCSC control system is typically structured in several levels that can be defined as master control (MC) (high level), sub-segment control (low level), valve base electronics (VBE), and valve electronics (VE).

- **Master control**

The main features are:

a) Control mode selection: The two most common are reactance control and current (power) control with other control functions available selectively (to the operator).
b) Set point and transmission order: A reference can be set based on the control mode selected (In the case of power flow control, the regulator will sense the actual flow and adjust the reactance to meet the set point).
c) Current and voltage signals: Line current and voltage from all sub-segments are measured and sent through a fiber optic interface to the control. It is recommended that all instrumentation, measurements, and cabling are included in the project scope for the supplier for reasons of compatibility with the controls to be supplied.
d) Sub-segment coordination: Controllable sub-segments shall be coordinated according to their availability to meet the appropriate net reactance and to establish priorities for meeting control objectives.
e) Set priority: Based on the availability of each sub-segment and status information received, the MC should set priorities for each controllable sub-segment.
f) Interlocking: Interlocking may be required by the purchaser to prevent certain inadvertent operations (e.g., simultaneous operation between local and remote operation or breaker operations).

g) Status information: Status of controllable sub-segments received from low-level control should be interfaced with the remote terminal unit (RTU), supervisory control and data acquisition (SCADA) system, and operator interface subsystem.

8.7.1.3 Operating levels

Control of the TCSC installation should be specified for operation at a local and remote (when required) level. Selection of local or remote operation should be selectable by a hardware switch or via the operator interface.

8.7.1.4 Start up procedure

Start up and shutdown procedures are required to ensure safe insertion of TCSC equipment into the transmission system. A typical start up procedure consists of the following steps:

a) Confirmation of no protection alarms
b) Open external grounding and close external isolating disconnect switches.
c) Report from line current supervision (minimal current, platform power active, etc.)
d) Open external bypass disconnect switch
e) Selection of control mode (default standby mode or blocking)
f) Selection of reference
g) Execute start command that will open the capacitor bank bypass switch for insertion, followed by control enabled.

8.7.1.5 Operator interface

The purchaser should specify the operator interface required to operate the TCSC controller locally as well as the interface with SCADA and RTU subsystems. This would include such features as requirements for a HMI, mosaic panel, or additions to an existing substation’s controls. It is recommended that the operator interface should have the following minimum characteristics:

a) Selection and execution:

– Emergency shutdown
– Control mode
– Operating mode
– Set point or reference
– Open/close breakers and disconnect switches

To prevent misoperation, it is recommended that the selection and execution process should involve a two-step operation where confirmation of the selected function shall be received and confirmed before its execution is allowed.

b) Display of information:

– System parameters (control settings and thresholds)
– Set point or transmission order
– Confirmation of selected control mode
– System information (current unbalance ratio, energy, varistor temperature, cooling, etc.)
– Status of the TCSC (position of switching devices, thyristor conduction, trend after overload, time to resume normal operation, etc.)

c) Change of system parameters:

Change of some settings, thresholds, and system conditions (e.g. varistor temperature) should be made possible through this interface and permitted only by qualified personnel.

d) Reset:

The purchaser can choose to have the possibility to reset the control system from the operator interface, in addition to a reset button on the control panel.

e) Diagnostics:

In addition to supervising permanently the status of the TCSC bank, it should be continuously self-monitored. The messages and indications resulting from these diagnoses should identify necessary maintenance work or repair. In addition to information related to the TCSC control system, it should provide status information related to:

– equipment redundancies;
– power supplies (a.c. and d.c.);
– transmission line.

8.7.2 Protection

Some TCSC protection and control functions are similar to those required for a fixed series capacitor bank installation. Protection and control functions that should be considered for a TCSC include the following:

a) Protection of TCSC equipment against overstress from system conditions:

– Capacitor overload
– Varistor overload
– Bypass gap protections
– Thyristor valve overcurrent
– Thyristor valve overvoltage
– Thyristor junction temperature (calculated)
– Thyristor reactor overload

b) Protection functions associated with TCSC equipment failure:

– Capacitor unbalance
– Flashover to platform
– Varistor failure
– Bypass switch failure
– Pole disagreement
– Thyristor failure
– Controllable subsegment failure
– Cooling system
– Bypass gap failure
– Protection and control system failure
– Current and voltage sensor failures

c) TCSC control functions:

– Bypassing
– Insertion (automatic or manual) and reinsertion

– Lockout
– Temporary block insertion
– Operation of disconnect switches

8.7.3 Monitoring and recording

a) Alarms and indications:

The purchaser should specify that sufficient alarms and indications be installed locally on the TCSC control panel. Typically, the annunciation provides the following information:

– control and protection system failure;
– power equipment failure;
– normal power system condition and operation (e.g., overload, bypass, varistor conduction).

b) Archiving:

The purchaser should specify the requirements on the sequence events recorder (SER) and the recording of analog and digital signals during disturbance events.

8.8 Precommissioning and commissioning tests

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8.8.1 Introduction

Testing and commissioning TCSC installations involves a systematic test program that begins with off-site tests and involve specified design tests, production tests, and factory control system tests. The test program continues with on-site precommissioning tests of equipment, station tests, and commissioning tests.

Precommissioning tests involve on-site localized testing and checkout of individual equipment items and subsystems, after their installation to verify proper installation, adjustment, and local manual operation of an individual piece of equipment or apparatus. Testing of transducers, capacitors, reactors, resistors, disconnect switches, circuit breakers, cooling system, fiber optics, grounding switches, switchgear, motor control centers, thyristor valves, and control and protection panels should be included.

The purpose of subsystem tests is to check independently the necessary functional performance of all TCSC subsystems before starting station testing. The TCSC station testing includes tests to verify that subsystems interact and function according to specified requirements. These tests involve high-voltage energization of equipment and require coordination with system operators.

Commissioning tests includes testing the TCSC installation with transmission system power flows up to the rating of the installation. Various transmission system configurations and power flow levels should be configured to test the TCSC installation operational parameters to confirm that specified performance can be achieved. Commissioning tests can involve a period of trial operation followed by acceptance tests and can include staged fault testing.

Testing and commissioning TCSC installations requires planning of test sequences, procedures, and load schedules. Testing and commissioning responsibilities of the purchaser and supplier should be defined in the specification as well as any on-site testing restrictions due to system operational constraints, transmission line outage periods, or other limitations.

Documentation of commissioning test results should include a report describing each test series together with all relevant test data (sequence of event recorder printouts, transient fault recorder recordings, etc.).

8.8.2 Precommissioning tests

Precommissioning tests should be performed on site to validate that individual equipment items have been properly installed and are functionally operating prior to commissioning tests. Precommissioning tests do not require high-voltage energization, but could require station service power (ac and dc).

Precommissioning objectives typically include tests to verify:

a) Equipment is installed in accordance with manufacturers instruction books and station design drawings
b) Wiring, fiber optics, and grounding connections
c) Capacitance, reactance, and resistance parameters
d) Turns ratio and signal polarities
e) Timing checks on circuit breakers and switches
f) Contact resistance of disconnects and circuit breakers
g) AC and dc station service power equipment
h) Cooling system
i) Control, protection, and monitoring equipment
j) Communication interface
k) Remote telecommunications interface and operator interface

8.8.3 Station tests

The TCSC station testing consists of local station tests utilizing many or all of the different subsystems together. Station tests are confined to the local station and do not require scheduling of power transfers on the transmission line, except for station service power needs. Switching and initiation of local sequences shall be from the local and master operator controls. Testing should begin without ac system high voltage connected to the TCSC installation with local operational and emergency trip sequences being tested prior to applying ac system high voltage. These tests give system operators an opportunity to become familiar with switching procedures and operator interfaces before actual equipment energization. When energization tests are performed, the external grounding disconnect switches are opened and the external isolating disconnect switches can be closed.

8.8.4 Commissioning (field) tests

a) Transmission testing:

Transmission tests include testing all performance requirements under normal operating conditions and, as conditions permit, under contingency operating conditions. All specified TCSC installation control modes should be tested. Transmission tests may include:

– Start, insertion, and bypass sequences
– Steady-state operation at minimum line current
– Block and bypass sequences
– Bypass operation
– Reactance range at rated voltage and current
– Temporary and dynamic overload voltage and current
– Power oscillation damping (if specified)

– SSR mitigation (if specified)

b) Trial operation:

Trial operation provides an opportunity for sustained operation of the TCSC installation together with the connected ac system for an extended period of time that should start prior to any warranted operating periods. The purchaser should specify the trial operation period (10-30 days). Trial operation affords the purchaser a first indication of the TCSC installation's availability under real operating conditions. Trial operation should verify that the TCSC installation is capable of reliable operation with the connected ac system for an extended period of time without misoperation. During trial operation, the TCSC installation should be operated under expected operating conditions (e.g. operated by trained purchaser operators and dispatchers without supplier assistance).

During trial operation, the TCSC installation should demonstrate its capability to perform as specified during any disturbances in the ac system or communication system for which the TCSC installation is designed or specified. All disturbances during trial operation should be monitored, recorded, and analyzed to determine the causes and their impact. All alarms should be investigated and proper operation verified. If possible, the TCSC installation and ac network should be operated in various steady-state configurations for extended periods of time.

c) Acceptance tests:

Acceptance tests should include testing of various performance requirements included in the TCSC installation specifications. Acceptance tests verify the overall performance of the TCSC installation and demonstrate that the design is correct and that the as-built installation meets the requirements of the specifications. As staged fault testing involves the introduction of disturbances to the transmission system, the system operator shall typically take responsibility for scheduling, structuring, and performing any such tests.

The supplier should be required to assist in structuring the test plans and have representatives on site to monitor testing procedures. The tests that are performed should be designed jointly between the system operator and the supplier in order to establish that the associated power system and TCSC installation component additions or upgrades meet the minimum specification requirements; can withstand the duty imposed by disturbances; provide a safe working environment; and do not degrade the transmission system stability or reliability. Successful completion and documentation of acceptance tests should result in customer acceptance of the TCSC installation and include the following:

– Steady-state ratings
– Temporary and dynamic overload tests
– Power oscillation damping performance (if specified)
– SSR mitigation performance (if specified)
– Staged fault tests (if specified)
– Harmonic and interference performance (if specified)
– Audible noise performance (if specified)
– Electrical losses performance report
– Cooling system performance

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