

# INTERNATIONAL STANDARD

## NORME INTERNATIONALE



**Series capacitors for power systems –  
Part 4: Thyristor controlled series capacitors**

**Condensateurs série destinés à être installés sur des réseaux –  
Partie 4: Condensateurs série commandés par thyristors**



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Part 4: Thyristor controlled series capacitors**

**Condensateurs série destinés à être installés sur des réseaux –  
Partie 4: Condensateurs série commandés par thyristors**

INTERNATIONAL  
ELECTROTECHNICAL  
COMMISSION

COMMISSION  
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## CONTENTS

|                                                                |    |
|----------------------------------------------------------------|----|
| FOREWORD.....                                                  | 5  |
| 1 Scope.....                                                   | 7  |
| 2 Normative references .....                                   | 7  |
| 3 Terms, definitions and abbreviated terms .....               | 8  |
| 3.1 Terms and definitions.....                                 | 8  |
| 3.2 Abbreviated terms.....                                     | 11 |
| 4 Operating and rating considerations .....                    | 11 |
| 4.1 General.....                                               | 11 |
| 4.2 TCSC characteristics .....                                 | 14 |
| 4.3 Operating range.....                                       | 15 |
| 4.4 Reactive power rating .....                                | 16 |
| 4.5 Power oscillation damping (POD).....                       | 16 |
| 4.6 SSR mitigation .....                                       | 16 |
| 4.7 Harmonics .....                                            | 17 |
| 4.8 Control interactions between TCSCs in parallel lines ..... | 17 |
| 4.9 Operating range, overvoltages and duty cycles .....        | 17 |
| 4.9.1 Operating range.....                                     | 17 |
| 4.9.2 Transient overvoltages .....                             | 18 |
| 4.9.3 Duty cycles.....                                         | 18 |
| 5 Valve control .....                                          | 18 |
| 5.1 Triggering system .....                                    | 18 |
| 5.2 System aspects .....                                       | 19 |
| 5.3 Normal operating conditions.....                           | 19 |
| 5.4 Valve firing during system faults .....                    | 20 |
| 5.5 Actions at low line current.....                           | 20 |
| 5.6 Monitoring.....                                            | 20 |
| 6 Ratings.....                                                 | 20 |
| 6.1 General.....                                               | 20 |
| 6.2 Capacitor rating .....                                     | 21 |
| 6.3 Reactor rating .....                                       | 21 |
| 6.4 Thyristor valve rating .....                               | 21 |
| 6.4.1 General .....                                            | 21 |
| 6.4.2 Current capability .....                                 | 21 |
| 6.4.3 Voltage capability .....                                 | 22 |
| 6.5 Varistor rating .....                                      | 24 |
| 6.6 Insulation level and creepage distance.....                | 25 |
| 7 Tests .....                                                  | 25 |
| 7.1 General.....                                               | 25 |
| 7.2 Test of the capacitor .....                                | 25 |
| 7.2.1 General .....                                            | 25 |
| 7.2.2 Routine tests .....                                      | 25 |
| 7.2.3 Type tests.....                                          | 26 |
| 7.2.4 Special test (ageing test).....                          | 26 |
| 7.3 Tests of the TCSC reactor .....                            | 26 |
| 7.3.1 General .....                                            | 26 |
| 7.3.2 Routine tests .....                                      | 26 |

|       |                                                                                                                    |    |
|-------|--------------------------------------------------------------------------------------------------------------------|----|
| 7.3.3 | Type tests.....                                                                                                    | 27 |
| 7.3.4 | Special tests.....                                                                                                 | 27 |
| 7.4   | Tests of thyristor valves .....                                                                                    | 27 |
| 7.4.1 | General .....                                                                                                      | 27 |
| 7.4.2 | Routine tests .....                                                                                                | 27 |
| 7.4.3 | Type tests.....                                                                                                    | 28 |
| 7.5   | Tests of protection and control system .....                                                                       | 28 |
| 7.5.1 | General .....                                                                                                      | 28 |
| 7.5.2 | Routine tests .....                                                                                                | 28 |
| 7.5.3 | Type tests.....                                                                                                    | 29 |
| 7.5.4 | Special tests – Hardware-in-the-loop (HIL) tests .....                                                             | 29 |
| 8     | Guidance for selection of rating and operation .....                                                               | 30 |
| 8.1   | General.....                                                                                                       | 30 |
| 8.2   | Thyristor controlled series capacitor.....                                                                         | 31 |
| 8.2.1 | AC transmission system .....                                                                                       | 31 |
| 8.2.2 | TCSC operational objectives.....                                                                                   | 32 |
| 8.2.3 | TCSC ratings.....                                                                                                  | 32 |
| 8.3   | Thyristor valves .....                                                                                             | 34 |
| 8.4   | Capacitors and reactors .....                                                                                      | 34 |
| 8.4.1 | General .....                                                                                                      | 34 |
| 8.4.2 | Capacitor considerations .....                                                                                     | 34 |
| 8.4.3 | Reactor considerations .....                                                                                       | 34 |
| 8.5   | Fault duty cycles for varistor rating .....                                                                        | 35 |
| 8.6   | Valve cooling system .....                                                                                         | 36 |
| 8.7   | TCSC control and protection .....                                                                                  | 36 |
| 8.7.1 | General .....                                                                                                      | 36 |
| 8.7.2 | Control .....                                                                                                      | 37 |
| 8.7.3 | Protection.....                                                                                                    | 39 |
| 8.7.4 | Monitoring and recording .....                                                                                     | 39 |
| 8.8   | Precommissioning and commissioning tests.....                                                                      | 40 |
| 8.8.1 | General .....                                                                                                      | 40 |
| 8.8.2 | Pre-commissioning tests.....                                                                                       | 40 |
| 8.8.3 | Station tests .....                                                                                                | 41 |
|       | Bibliography.....                                                                                                  | 43 |
|       | Figure 1 – Typical nomenclature of a TCSC installation .....                                                       | 12 |
|       | Figure 2 – TCSC subsegment .....                                                                                   | 13 |
|       | Figure 3 – TCSC steady state waveforms for control angle $\alpha$ and conduction interval $\sigma$ .....           | 14 |
|       | Figure 4 – TCSC apparent reactance characteristics according to Formula (1),<br>with $\lambda = 2,5$ .....         | 15 |
|       | Figure 5 – Example of TCSC operating range for POD (left) and SSR mitigation (right) .....                         | 15 |
|       | Figure 6 – Valve base electronics (VBE) .....                                                                      | 18 |
|       | Figure 7 – Valve electronics (VE).....                                                                             | 19 |
|       | Figure 8 – Thyristor valve voltage in a TCSC .....                                                                 | 23 |
|       | Figure 9 – Typical block diagram of a real time TCSC protection and control system<br>simulation environment ..... | 30 |
|       | Figure 10 – Example of operating range diagram for TCSC.....                                                       | 33 |

|                                                                                                   |    |
|---------------------------------------------------------------------------------------------------|----|
| Table 1 – Peak and RMS voltage relationships .....                                                | 13 |
| Table 2 – Typical external fault duty cycle with unsuccessful high speed auto-reclosing .....     | 35 |
| Table 3 – Typical duty cycle for internal fault with successful high speed auto-reclosing .....   | 35 |
| Table 4 – Typical duty cycle for internal fault with unsuccessful high speed auto-reclosing ..... | 36 |

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**SERIES CAPACITORS FOR POWER SYSTEMS –****Part 4: Thyristor controlled series capacitors**

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IEC 60143-4 has been prepared by IEC technical committee 33: Power capacitors and their applications. It is an International Standard.

This second edition cancels and replaces the first edition published in 2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) thyristor valve testing requirements refer to IEC 62823;
- b) Formula (1) in Subclause 4.2 has been corrected;
- c) Hardware-in-the-loop (HIL) tests, Subclause 7.5.4, replaces previously specified real time protection and control system test with network simulator.

The text of this International Standard is based on the following documents:

|             |                  |
|-------------|------------------|
| Draft       | Report on voting |
| 33/696/FDIS | 33/702/RVD       |

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

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

- IEC 60143-1:2015,
- IEC 60143-2:2012,
- IEC 60143-3:2015.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at [www.iec.ch/members\\_experts/refdocs](http://www.iec.ch/members_experts/refdocs). The main document types developed by IEC are described in greater detail at [www.iec.ch/publications](http://www.iec.ch/publications).

A list of all parts of IEC 60143 series, under the general title *Series capacitors for power systems*, can be found on the iec website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under [webstore.iec.ch](http://webstore.iec.ch) in the data related to the specific document. At this date, the document will be

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## SERIES CAPACITORS FOR POWER SYSTEMS –

### Part 4: Thyristor controlled series capacitors

#### 1 Scope

This part of IEC 60143 specifies the testing of thyristor controlled series capacitor (TCSC) installations used in series with transmission lines. This document 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 documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 document prevails.

IEC 60050-436, *International Electrotechnical Vocabulary (IEV) – Part 436: Power capacitors*

IEC 60068-2-2, *Environmental testing – Part 2-2: Tests – Tests B: Dry heat*

IEC 60068-2-78, *Environmental testing – Part 2-78: Tests – Test Cab: Damp heat, steady state*

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

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

IEC 60143-1:2015, *Series capacitors for power systems – Part 1: General*

IEC 60143-2:2012, *Series capacitors for power systems – Part 2: Protective equipment for series capacitor banks*

IEC 60143-3:2015, *Series capacitors for power systems – Part 3: Internal fuses*

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

IEC 60255-27, *Measuring relays and protection equipment – Part 27: Product safety requirements*

IEC 61000-4 (all parts), *Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques*

IEC 61000-4-11, *Electromagnetic compatibility (EMC) – Part 4-11: Testing and measurement techniques – Voltage dips, short interruptions and voltage variations immunity tests for equipment with input current up to 16 A per phase*

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 62823:2015, *Thyristor valves for thyristor controlled series capacitors (TCSC) – Electrical testing*

IEC 62823:2015/AMD1:2019

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

### 3 Terms, definitions and abbreviated terms

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

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

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

#### 3.1 Terms and definitions

##### 3.1.1

##### **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

##### 3.1.2

##### **bypass current**

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

##### 3.1.3

##### **temporary overload**

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

SEE: Figure 5 and Figure 10.

##### 3.1.4

##### **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.

##### 3.1.5

##### **thyristor-controlled series capacitor**

##### **TCSC**

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

**3.1.6****valve electronics****VE**

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

**3.1.7****TCSC reactor**

one or more reactors connected in series with the thyristor valve

SEE: Figure 1, item 7.

Note 1 to entry: 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 overvoltage and continuous operating voltage across the thyristor valve.

**3.1.8****valve blocking**

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

**3.1.9****valve base electronics****VBE**

electronic unit, at earth potential, which is the interface between the control system of the TCSC and the thyristor valves

**3.1.10****capacitor current**

$I_C$

current through the series capacitor

SEE: Figure 2.

**3.1.11****line current**

$I_L$

power frequency line current

SEE: Figure 2.

**3.1.12****rated current**

$I_N$

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

**3.1.13****valve current**

$I_V$

current through the thyristor valve

SEE: Figure 2.

**3.1.14****capacitor voltage**

$U_C$

voltage across the TCSC

SEE: Figure 2.

### 3.1.15

#### 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 1 to entry: The protective level can 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.

### 3.1.16

#### rated TCSC voltage

$U_N$

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

### 3.1.17

#### apparent reactance

$X(\alpha)$

TCSC apparent power frequency reactance as a function of thyristor control angle ( $\alpha$ )

SEE Figure 4.

### 3.1.18

#### nominal frequency

$f_N$

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

### 3.1.19

#### rated capacitance

$C_N$

capacitance value for which the TCSC capacitor has been designed

### 3.1.20

#### physical reactance

$X_C$

power frequency reactance for each phase of the TCSC bank with thyristors blocked and a capacitor internal dielectric temperature of 20 °C

$$X_C = 1 / (2\pi f_N \times C_N)$$

### 3.1.21

#### boost factor

$k_B$

ratio of  $X(\alpha)$  divided by  $X_C$

Note 1 to entry:  $k_B = X(\alpha) / X_C$

### 3.1.22

#### rated reactance

$X_N$

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

### 3.1.23 conduction interval

 $\sigma$ 

that part of a cycle during which a thyristor valve is in the conducting state,  $\sigma = 2\beta$

SEE: Figure 3.

### 3.1.24 control angle

 $\alpha$ 

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.

### 3.1.25 internal fault

line fault occurring within the protected line section containing the series capacitor bank

### 3.1.26 external fault

line fault occurring outside the protected line section containing the series capacitor bank

## 3.2 Abbreviated terms

|       |                                          |
|-------|------------------------------------------|
| FSC   | fixed series capacitors                  |
| MC    | master control                           |
| POD   | power oscillation damping                |
| RTU   | remote terminal unit                     |
| SCADA | supervisory control and data acquisition |
| SER   | sequence events recorder                 |
| SSR   | sub-synchronous resonance                |
| RMS   | root-mean-square                         |
| BLK   | blocked (mode of operation)              |
| BP    | bypass (mode of operation)               |
| CAP   | capacitive boost (mode of operation)     |
| HMI   | human machine interface                  |

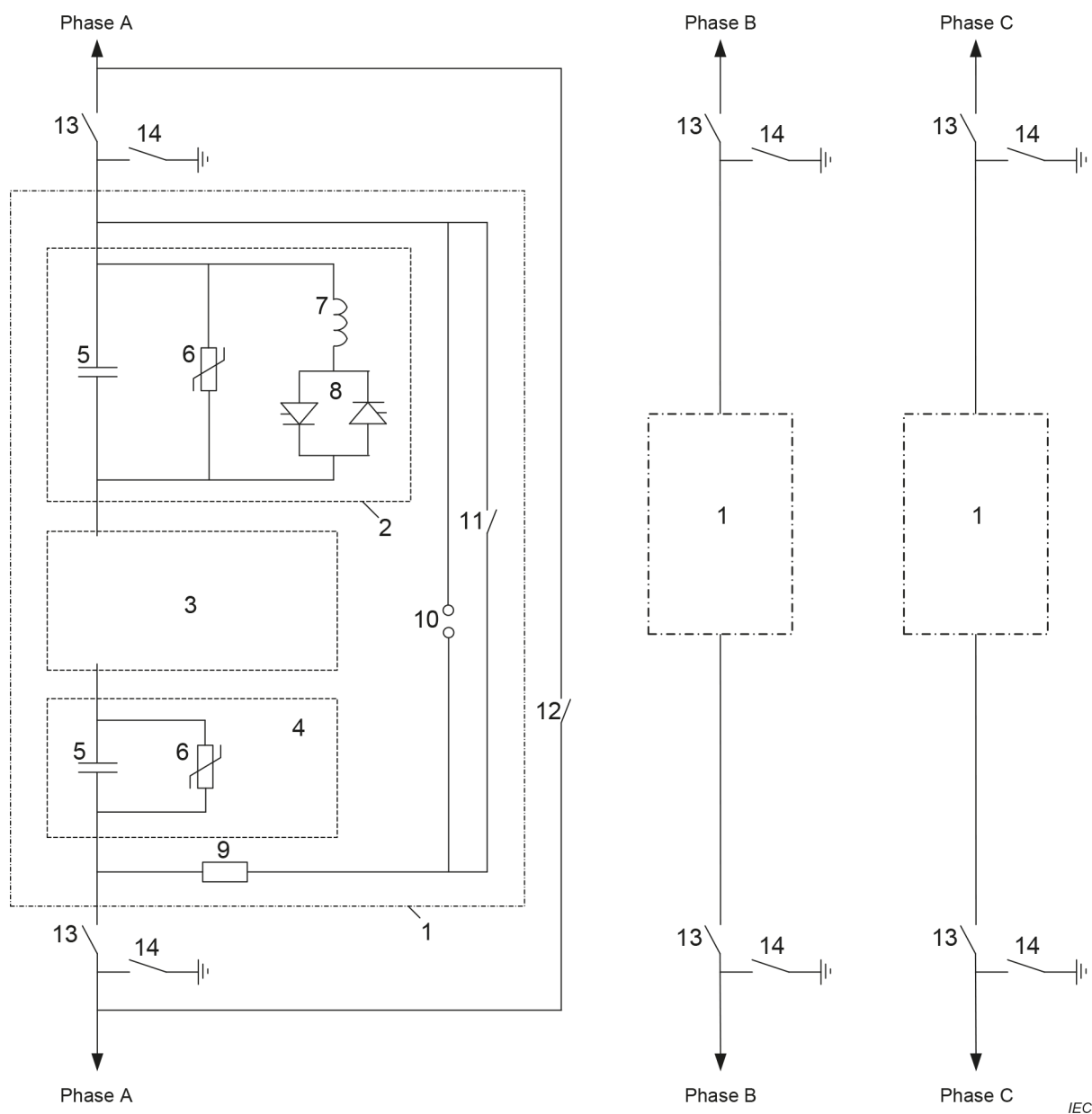
## 4 Operating and rating considerations

### 4.1 General

Transmission line series reactance can be compensated by combinations of fixed series capacitors and TCSC banks (see 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 document (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 with a capacitive boost.



#### Key

- |                                                     |                                    |
|-----------------------------------------------------|------------------------------------|
| 1 TCSC bank (1-phase)                               | 8 thyristor valve                  |
| 2 controllable subsegment                           | 9 current limiting damping circuit |
| 3 additional controllable subsegments when required | 10 bypass gap                      |
| 4 additional FSC segment when required              | 11 bypass switch                   |
| 5 capacitor units                                   | 12 external bypass disconnector    |
| 6 varistor                                          | 13 external isolating disconnector |
| 7 TCSC reactor                                      | 14 external grounding switch       |

**Figure 1 – Typical nomenclature of a TCSC installation**

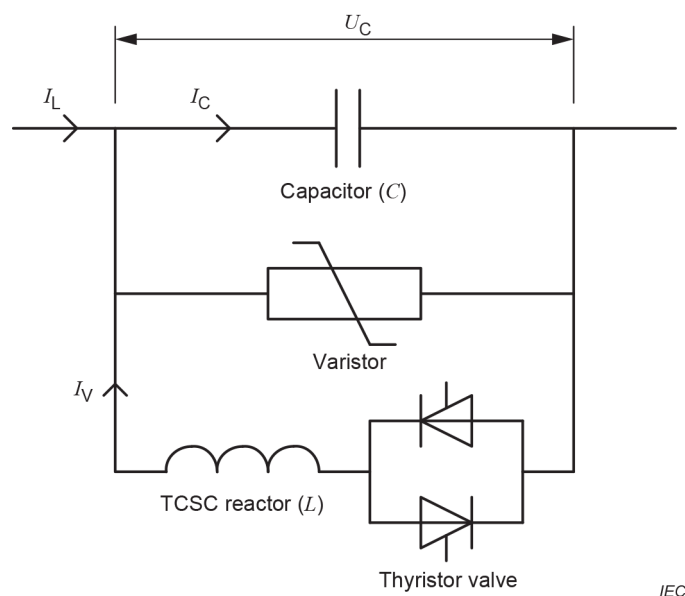


Figure 2 – TCSC subsegment

The definition of control angle ( $\alpha$ ) 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 waveform 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 distort the capacitor voltage ( $U_C$ ). The distorted waveform means that the capacitor 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<br>$k_B$ | Normalized discharge frequency, $\lambda$<br>p.u. | Power frequency RMS voltage<br>p.u. | Power frequency peak voltage<br>p.u. | Total RMS voltage<br>p.u. | Total peak voltage<br>p.u. |
|-----------------------|---------------------------------------------------|-------------------------------------|--------------------------------------|---------------------------|----------------------------|
| 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                       |

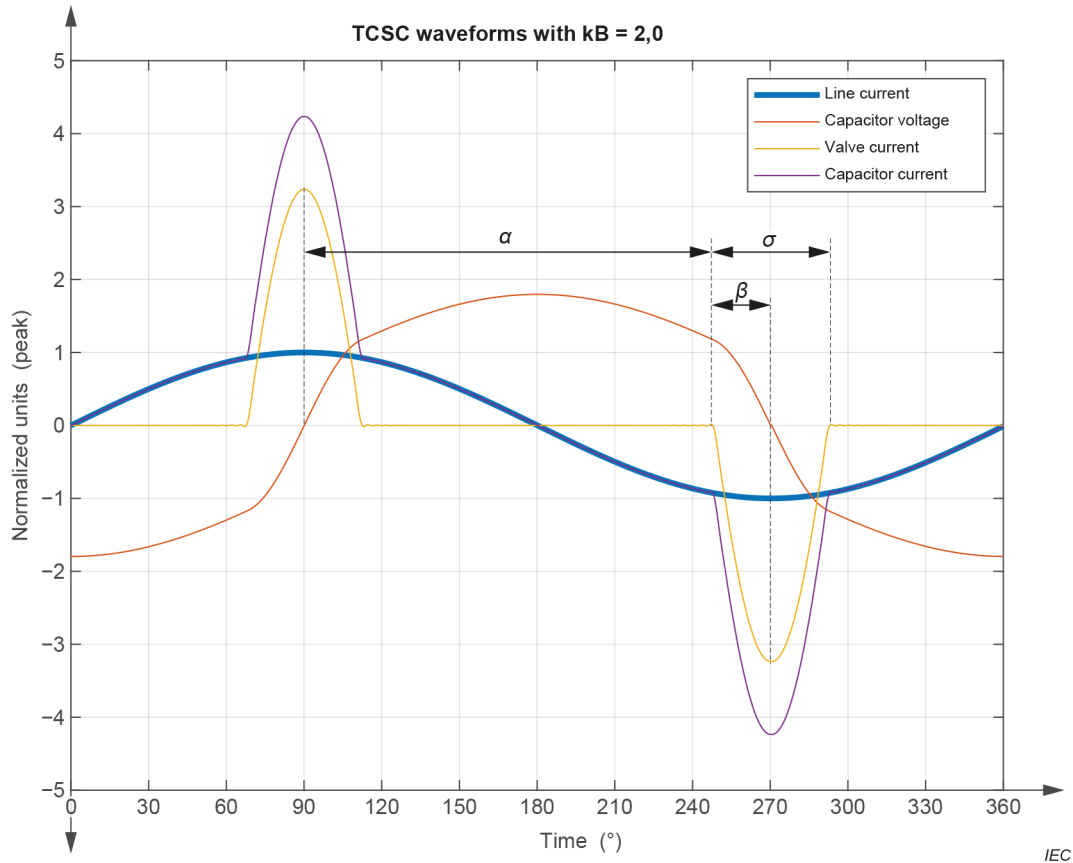


Figure 3 – TCSC steady state waveforms for control angle  $\alpha$  and conduction interval  $\sigma$

#### 4.2 TCSC characteristics

TCSC characteristics are determined from the series capacitor ( $C$ ) and reactor ( $L$ ) circuit parameters shown in Figure 2. The steady state apparent reactance  $X(\alpha)$  as a function of thyristor control angle ( $\alpha$ ) can be calculated from Formula (1), see [1]<sup>1</sup>.

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

where

$\beta$  is half the conduction interval ( $\pi - \alpha$ );

$\alpha$  is control angle from capacitor voltage zero;

$\lambda$  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.

<sup>1</sup> Numbers in square brackets refer to the Bibliography.

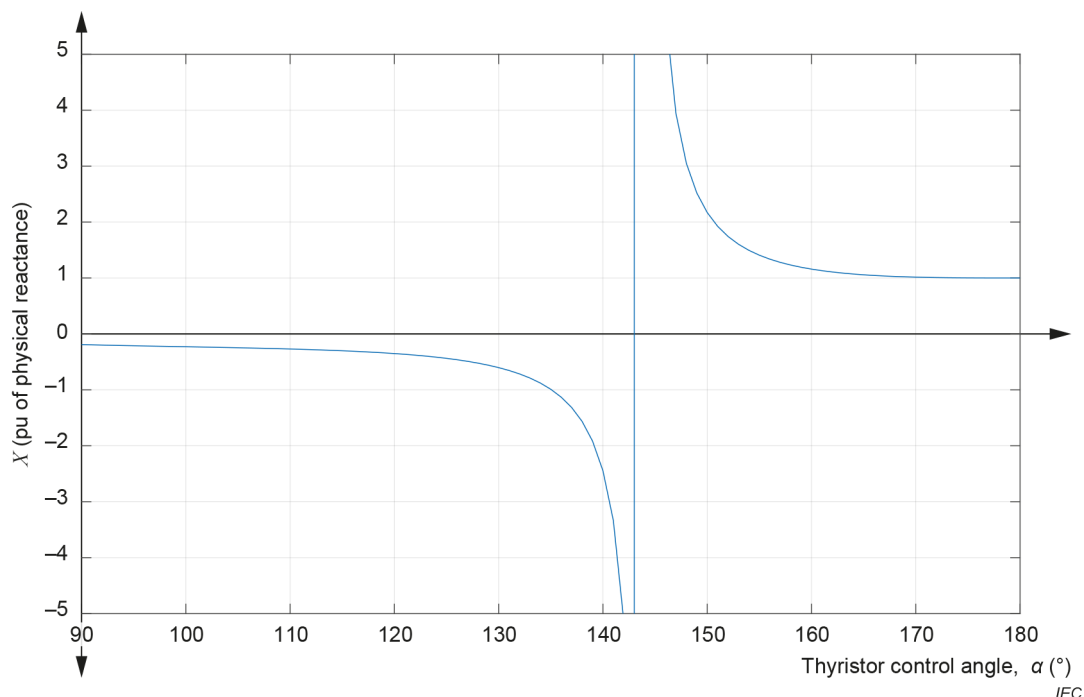
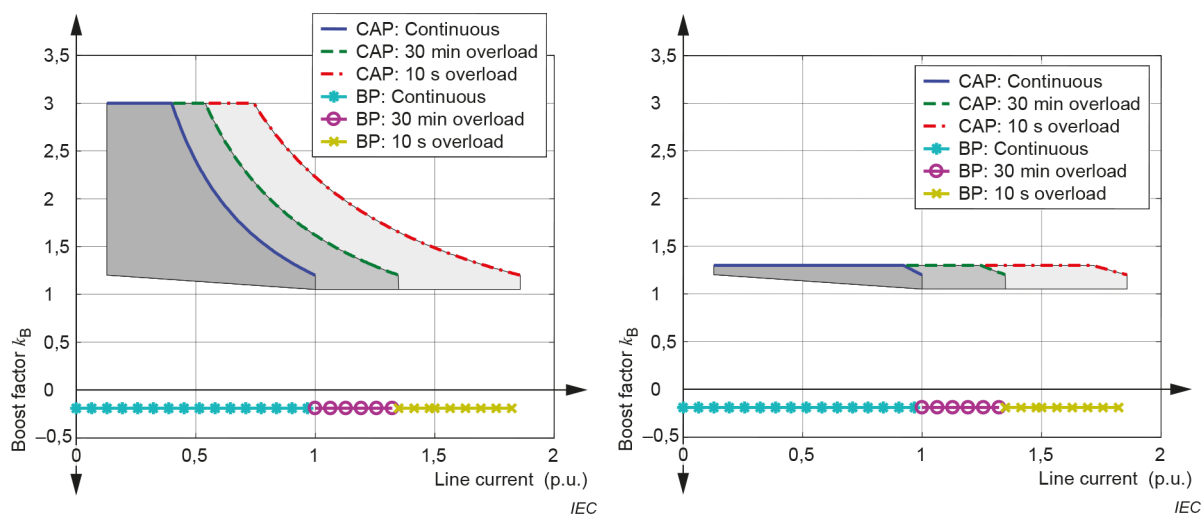


**Figure 4 – TCSC apparent reactance characteristics according to Formula (1), with  $\lambda = 2,5$**

### 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 shall 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.



a) Example of TCSC operating range for POD

b) Example of TCSC operating range 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 can 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 Formulae (2) and (3):

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

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

The nominal reactive power rating of the TCSC shall be defined as the reactive power output given by  $Q_{\text{TCSC}}$  in the above expressions with rated boost ( $k_B$ ), line current ( $I_L$ ) equal to the rated line current and  $1/\omega C$  equal to the physical reactance.

#### 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 shall 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 shall 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 shall 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 applications where TCSC is used for SSR-mitigation or power oscillation damping purposes, the TCSC normally operates with the nominal boost factor and only temporarily operates during system disturbances 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 are suggested to be performed by using the entire network considering the difficulty of computing correct harmonic network equivalents.

#### **4.8 Control interactions between TCSCs in parallel lines**

In situation where two TCSCs are located on parallel lines, there is a risk for control interactions between the TCSCs during system disturbances. To reduce the risk for harmful interactions between parallel connected TCSCs, 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 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 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

### 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 (TE) subsystem, as shown in Figure 6.

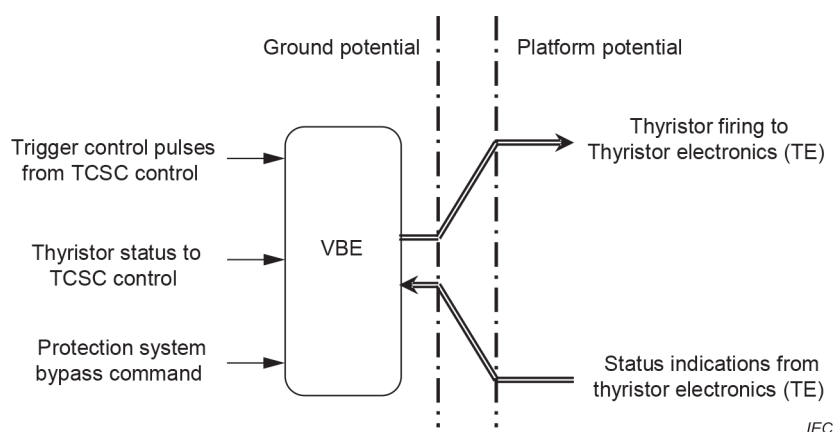


Figure 6 – Valve base electronics (VBE)

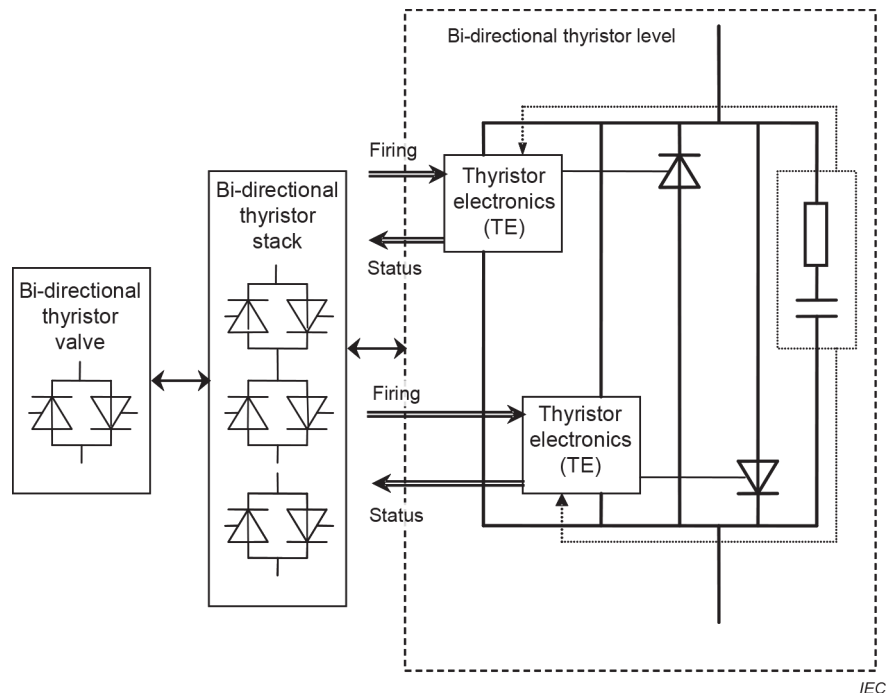


**Figure 7 – Valve electronics (VE)**

The TCSC control system generates trigger pulses that are transferred to the VBE. The VBE distributes firing pulses to each individual TE via fibre 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 can 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 to have a well-defined TCSC operating mode (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

## 6.1 General

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

## 6.2 Capacitor rating

Capacitors for the TCSC shall be designed, manufactured and tested in accordance with the 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 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.

## 6.3 Reactor rating

The TCSC reactors shall be designed, manufactured and tested in accordance with the applicable requirements of IEC 60076-6:2007, Clause 9. The actual reactor current waveforms related to operation in capacitive boost mode shall be included in the equipment specification for the reactor. The rated current of the reactor shall be based on the higher current between the following operating modes:

- the square root sum-of-squares of the power frequency and the harmonic current components in capacitive mode,
- the current when the TCSC is in bypass mode considering the rated line current of the TCSC.

The insulation level between the reactor terminals shall be based on the protective level of the TCSC bank as outlined in IEC 60143-1.

## 6.4 Thyristor valve rating

### 6.4.1 General

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.

### 6.4.2 Current capability

#### 6.4.2.1 General

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.

#### 6.4.2.2 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 the line fault cases specified. Consideration shall be given to the case where 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 depend 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 the 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 shall 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.

#### 6.4.2.3 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 the initiation of the bypass operation, in addition to the fault current from the line.

#### 6.4.3 Voltage capability

##### 6.4.3.1 General

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, see Formula (4).

$$U_{PL} = K_1 \hat{U}_N = \sqrt{2} K_1 U_N \quad (4)$$

where

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

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.

Independently of the required operating range, the thyristor valve shall 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 can be lower than the protective level of the series capacitor.

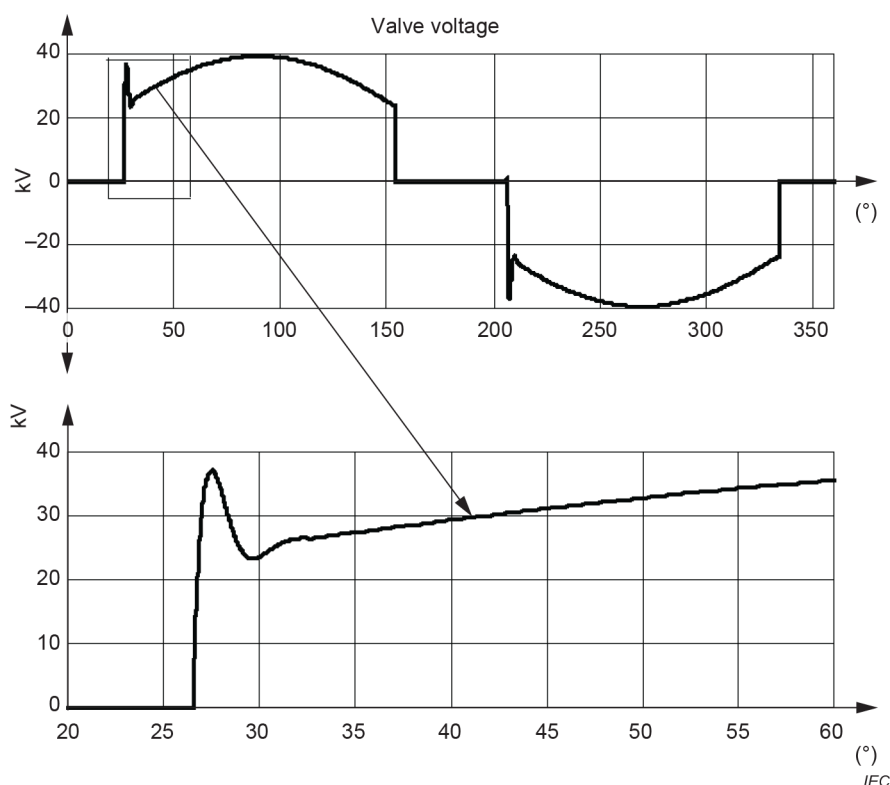


**Figure 8 – Thyristor valve voltage in a TCSC**

In the operating range curves shown 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,  $U_{\text{max,turn-off}}$ , 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  $U_{\text{max,turn-off}}$ .

Overvoltage protection at turn-off of the valve can 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  $di/dt$ , generating protective firing when the current derivative exceeds the design level.

#### **6.4.3.2 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;
- safety factors used in the thyristor valve tests (see IEC 62823).

#### **6.4.3.3 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.

### **6.5 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 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 can be exposed to. If energy injection does take place during system faults, then this energy injection shall be considered in the varistor rating.

Reinsertion of a series capacitor causes a DC offset in the capacitor voltage, which can cause energy injection into the varistor. Energy injection due to reinsertion against a swing current shall 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.

## 6.6 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 IEC 60143-1:2015, Clause 6. 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 p.u., the creepage distance shall be linearly increased with ( $U_{C30}/1,35$ ).

## 7 Tests

### 7.1 General

TCSC equipment shall be subjected to the type tests specified in this document. 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 shall 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 can be used to demonstrate the sufficiency of certain aspects of the design.

Thyristor valves shall be tested according to IEC 62823. All other TCSC main circuit equipment for which tests are not specified in this document shall be tested according to IEC 60143-1, IEC 60143-2 and IEC 60143-3.

### 7.2 Test of the capacitor

#### 7.2.1 General

The routine, type and special tests of the capacitors should be carried out in accordance with IEC 60143-1 and IEC 60143-3 taking into account the rated current and voltage determined as mentioned in 6.2 above.

The following tests stated in 7.2.2 and 7.2.3 shall be performed.

#### 7.2.2 Routine tests

The following routine tests shall be carried out:

- a) capacitance measurement (IEC 60143-1:2015, 5.3);
- b) capacitor loss measurement (IEC 60143-1:2015, 5.4);
- c) voltage test between terminals (IEC 60143-1:2015, 5.5);
- d) AC voltage test between terminals and container (IEC 60143-1:2015, 5.6);
- e) test on internal discharge device (IEC 60143-1:2015, 5.7);
- f) sealing test (IEC 60143-1:2015, 5.8);
- g) discharge test of internal fuses (IEC 60143-3:2015, 5.1.2).

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.

### 7.2.3 Type tests

The following type tests shall be carried out:

- a) thermal stability test (IEC 60143-1:2015, 5.9);
- b) AC voltage test between terminals and container (IEC 60143-1:2015, 5.10);
- c) lightning impulse test between terminals and container (IEC 60143-1:2015, 5.11);
- d) cold duty test (IEC 60143-1:2015, 5.12);
- e) discharge current test (IEC 60143-1:2015, 5.13);
- f) disconnecting test on internal fuses (IEC 60143-3:2015, 5.2.3);
- g) voltage test after opening the container (IEC 60143-3:2015, 5.2.4).

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.

### 7.2.4 Special test (ageing test)

The ageing test will be carried out only after a contractual agreement between the manufacturer and purchaser. This test will be carried out in accordance with IEC 60143-1:2015, 5.2.4.

## 7.3 Tests of the TCSC reactor

### 7.3.1 General

The routine, type and optional tests for the TCSC reactor should be carried out in accordance with relevant subclauses of the reactor standard IEC 60076-6:2007, Clause 9, taking into account the rated current and voltage determined as mentioned in 6.3 above.

The following tests stated in 7.3.2 and 7.3.3 shall be performed.

### 7.3.2 Routine tests

The following routine tests shall be carried out.

- a) measurement of winding resistance (IEC 60076-1);
- b) measurement of inductance (IEC 60076-6:2007, 9.10.5);
- c) measurement of loss and quality factor (IEC 60076-6:2007, 9.10.6);
- d) winding overvoltage test (IEC 60076-6:2007, 9.10.7).