



IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors

IEEE Power & Energy Society

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IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors

Sponsor

**Substations Committee
and the
Transmission and Distribution Committee
of the
IEEE Power & Energy Society**

Approved 11 September 2009

IEEE-SA Standards Board

Abstract: Recommended practices for specifying thyristor-controlled series capacitor (TCSC) installations used in series with transmission lines are provided. Ratings for TCSC thyristor valve assemblies, capacitors, and reactors as well as TCSC control characteristics, protective features, cooling systems, testing, commissioning, training, documentation, operation, and maintenance are addressed.

Keywords: power oscillation damping, series capacitors, subsynchronous resonance, thyristor-controlled series capacitor (TCSC), thyristor valves

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Introduction

This introduction is not part of IEEE Std 1534-2009, IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors.

This introduction provides some background on the rationale used to develop this recommended practice. This information is meant to aid in the understanding and usage of this recommended practice.

This recommended practice describes rating considerations for thyristor-controlled series capacitor (TCSC) installations used in series with a transmission line. It is intended for the following persons:

- a) Individuals or organizations that use TCSC installations and acquire these stations from suppliers.
- b) Individuals or organizations that influence how TCSC installations are acquired from suppliers.
- c) Suppliers interested in providing TCSC installations to purchasers.

This recommended practice is designed to help organizations and individuals to do the following:

- a) Incorporate equipment ratings during the definition, evaluation, selection, and acceptance of TCSC installations for operational use.
- b) Determine how TCSC installations should be evaluated, tested, and accepted for delivery to end users.

This recommended practice is intended to satisfy the following objectives:

- a) Promote consistency between organizations when acquiring TCSC installations from suppliers.
- b) Identify issues that differentiate TCSC installations from conventional series capacitor installations and provide useful practices for rating TCSCs during acquisition planning.
- c) Provide useful practices on evaluating supplier capabilities to meet purchaser requirements.

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1. Overview

1.1 Scope

This recommended practice specifies thyristor-controlled series capacitor (TCSC) installations used in series with transmission lines. ~~and should be used together with IEEE Std 824-1994 when specifying TCSC installations~~ The document addresses issues that consider ratings for TCSC thyristor valve assemblies, capacitors, and reactors as well as TCSC control characteristics, protective features, cooling systems, testing, commissioning, operation, and maintenance. ~~This document does not provide recommended practices for the development of TCSC computer models. However, this document does present issues that need to be considered when developing TCSC computer models as discussed in Annex B (informative). Annex C (normative)~~

1.2 Purpose

This document provides assistance and guidance to planning, substation, ~~apparatus~~, commissioning, and operation engineers in the course of specifying TCSC installations. Users of this document should tailor these recommendations to their specific project requirements.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~This recommended practice shall be used in conjunction with the following publications. When the~~

~~following publications are superseded by an approved revision, the revision shall apply:~~

IEC 60068-1-~~1998~~, Environmental Testing, Part 1: General and Guidance.¹

IEC 60068-2-2-~~1974~~, Basic Environmental Testing Procedures, Part 2: Tests—Tests B: Dry Heat.

IEC 60068-2-3-~~1969~~, Basic Environmental Testing Procedures, Part 2: Tests—Test CA: Damp Heat, Steady State.

IEC 61000-4-2-~~2001~~, Electromagnetic Compatibility (EMC)—Part 4-2: Testing and Measurement Techniques— Electrostatic Discharge Immunity Test.

IEEE Std 693TM-~~1997~~, IEEE Recommended Practice for Seismic Design of Substations.^{2,3}

IEEE Std 824TM-~~1994~~, IEEE Standard for Series Capacitor Banks in Power Systems.

IEEE Std 1031TM-~~2000~~, IEEE Guide for the Functional Specification of Transmission Static Var Compensators.

IEEE Std 1267TM-~~1999~~, ~~IEEE~~, [IEEE Trial-Use](#) Guide for Development of Specifications for Turnkey Substation Projects.

IEEE Std C37.90.1TM-~~2002~~, IEEE Standard for Surge Withstand Capability (SWC) Tests for Relays and Relay Systems Associated with Electric Power Apparatus.

IEEE Std C57.16TM-~~1996~~, IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air-Core Series-Connected Reactors.

~~¹IEC publications are available from the Sales Department of the International Electrochemical Commission, Case postale 131, 3, rue de Varembe, CH-1211, Geneva 20, Switzerland/Suisse (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.~~

3. Definitions, special symbols, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. ~~The IEEE 100™, The Authoritative Standards Dictionary: Glossary of IEEE Standards Terms Seventh Edition [B13], & Definitions~~ should be referenced for terms not defined in this clause.⁴ In some instances, the definition in ~~The IEEE 100 Standards Dictionary: Glossary of Terms & Definitions~~ may be either too broad or too restrictive. In such a case, an additional definition or note has been included. Definitions used in this standard should be used together with those found in IEEE Std 824-1994™ when specifying TCSC installations.

~~Some of the definitions used in this recommended practice can be found in~~

bidirectional thyristor valve: An arrangement of thyristor valves capable of conducting current in two directions.

NOTE—See Figure 1.⁵

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⁴The IEEE Standards Dictionary: Glossary of Terms & Definitions is available at <http://shop.ieee.org/>.

⁵Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

bypass current: The current flowing through the bypass switch, protective device, thyristor valve, or other devices, in parallel with the series capacitor.

capacitive range: Thyristor-controlled series capacitor (TCSC) operation resulting in an effective increase of the power frequency reactance range of the series capacitor.

conduction interval (α): That part of a cycle during which a thyristor valve is in the conducting state.

NOTE—See Figure 3.

control angle (α): The time expressed in electrical angular measure from the capacitor voltage (VC) zero crossing to the starting of current conduction through the thyristor valve.

NOTE—See Figure 3.

dynamic overload: The power frequency line current (I_D) and voltage (V_D) at which the TCSC should be capable of continuous control for a short duration (typically 10 s) at rated frequency and ambient temperature range.

platform control power: Energy source(s) available at platform potential for performing thyristor valve firing, protection, and control functions.

platform-to-ground cooling/air-handling insulator: An insulator that encloses cooling/air handling paths between platform and ground level.

reactive power rating: The reactive power rating ($P_Q = 3I_R^2 X_R$) for the [thyristor-controlled series capacitor](#) (TCSC) bank as determined from rated reactance (X_R) and rated current (I_R).

temporary overload: The power frequency line current (I_T) and voltage (V_T) at which the [thyristor-controlled series capacitor](#) (TCSC) should be capable of continuous control for a short duration (typically 30 min) at the rated frequency and ambient temperature range.

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

thyristor electronics (TE): Electronic circuits at thyristor valve potential(s) that perform control functions.

thyristor reactor: One or more reactors connected in series with the thyristor valve.

NOTE—See Figure 1.

thyristor valve enclosure: A platform-mounted enclosure containing thyristor valve(s) with associated valve cooling and electronic hardware.

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

valve blocking: An operation to prevent further firing of a thyristor valve by inhibiting triggering.

valve deblocking: An operation to permit firing of a thyristor valve by removing valve--blocking action.

valve base electronics (VBE): An electronic unit that provides an interface ~~between~~[among](#) the control equipment, at earth potential, and the thyristor electronics (TE).

voltage-breakover operation (VBO): An operation that is designed to turn on a thyristor valve based on a protective voltage level that appears across the thyristors. The protective level is normally set at a specified voltage level and coordinated with the capacitor bank varistor protective level. The voltage breakover operation can be used for the primary protection of the capacitor and can operate during external as well as internal faults.

3.2 Special symbols

I_C : Current through the series capacitor.

[NOTE—See Figure 2.](#)

[\$I_D\$: The power frequency line current at which the TCSC should be capable of continuous control for a short duration \(typically 10 s\) at the rated power frequency and ambient temperature range.](#)

[\$I_F\$: The line current that the TCSC might experience during a major power system disturbance for which protective control actions are allowed \(bypass breaker closed\).](#)

[\$I_L\$: Power frequency line current.](#)

NOTE—See Figure 2.

I_{MIN} : The ~~power frequency~~ minimum line current (I_L) at which the TCSC should be capable of continuous control ~~for a short duration (typically 10 s)~~ at rated ~~power~~ frequency and rated ambient temperature range.

~~3.2.3 I_F : The line current that the TCSC might experience during a major power system disturbance for which protective control actions are allowed (bypass breaker closed).~~

~~3.2.4 I_L : Power frequency line current.~~

~~NOTE—See Figure 2.~~

~~3.2.5 I_{MIN} : The minimum line current (I_L)~~

I_R : The RMS line current (I_L) at which the TCSC should be capable of continuous control of the rated reactance (X_R) at rated voltage (V_R), power frequency, and ambient temperature range.

I_T : The power frequency line current at which the TCSC should be capable of continuous control for a sustained period (typically 30 min) at the rated frequency and ambient temperature range.

I_{TH} : Current through the bidirectional thyristor valve.

NOTE—See Figure 2.

V_C : Voltage across the TCSC.

NOTE—See Figure 2.

V_D : The power frequency voltage across each phase of the TCSC at which the TCSC should be capable of continuous control for a short duration (typically 10 s) at the rated reactance (X_D), current (I_D), frequency, and ambient temperature range.

V_{MIN} : The minimum TCSC RMS voltage (V_C) at which the TCSC should be capable of continuous control at rated power frequency and rated ambient temperature range.

V_{PL} : The voltage protective level of the varistors or other protective device.

V_R : The power frequency voltage across each phase of the TCSC that can be continuously controlled at rated reactance (X_R), current (I_R), frequency, and ambient temperature range.

V_T : The power frequency voltage across each phase of the TCSC at which the TCSC should be capable of continuous control for a short duration (typically 30 min) at the rated reactance (X_T), current (I_T), frequency, and ambient temperature range.

$X(\alpha)$: TCSC power frequency reactance as a function of thyristor control angle (α).

X_B : The inductive reactance for each phase of the TCSC at $\alpha = 0^\circ$ with rated continuous current (I_R) and frequency.

X_C : The power frequency reactance for each phase of the TCSC bank with thyristor firing blocked with a capacitor (C) internal dielectric temperature of 25°C .

X_D : The power frequency reactance for each phase of the TCSC at which the TCSC should be capable of continuous control for a short duration (typically 10 s) at the rated current (I_D), voltage (V_D), frequency, and

ambient temperature range.

X_M : The maximum power frequency reactance for each phase of the TCSC at $\alpha = \alpha_M$, which can be continuously controlled at rated frequency and ambient temperature range.

X_{ORDER} : The ratio of $X(\alpha)$ divided by X_C .

X_R : The power frequency reactance for each phase of the TCSC that can be continuously controlled at rated continuous current (I_R), continuous voltage (V_R), frequency, and ambient temperature range.

X_T : The power frequency reactance for each phase of the TCSC at which the TCSC should be capable of continuous control for a short duration (typically 30 min) at the rated current (I_T), voltage (V_T), frequency, and ambient temperature range.

3.3 Acronyms and abbreviations

ATP	alternative transient program
EMTP	electromagnetic transient program
FSC	fixed-series compensation
HVDC	high-voltage direct current
LTT	light-triggered thyristors
MC	master control
Mvar	megavar
POD	power oscillation damping
RAM	reliability, availability, and maintainability
RMS	root mean square
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SER	sequence events recorder
SSR	subsynchronous resonance
SVC	static var compensator
<u>TCSC</u>	thyristor-controlled series capacitor
TE	thyristor electronics
TNA	transient network analyzer
VBE	valve base electronics

~~BIL~~	~~-basic impulse level~~
~~CCVT~~	~~coupling capacitor voltage transformer~~
~~ETT~~	~~electrically triggered thyristors~~
~~GPS~~	~~global positioning system~~
~~MTBF~~	~~mean time between failure~~
~~MTTR~~	~~mean time to repair~~
~~RIV~~	~~radio influence voltage~~
~~RTO~~	~~regional transmission organization~~
~~VBO~~	~~-voltage breakover operation~~

4. Service conditions

The purchaser should specify the service conditions for operation of the TCSC installation (~~reference~~ IEEE Std 824) at the specified current, voltage, frequency, and fault sequence ratings, including the following:

- a) Altitude
- b) Ambient temperature
- c) Ice load
- d) Wind velocities
- e) Seismic conditions
- f) Snow depth
- g) Exposure to dust
- h) Exposure to salt, damaging fumes, or vapors
- i) Swarming insects
- j) Flocking birds
- k) Conditions requiring over insulation or extra leakage distance on insulators
- l) Continuous harmonic currents in the power system
- m) Unusual transportation or storage conditions
- n) Untransposed lines

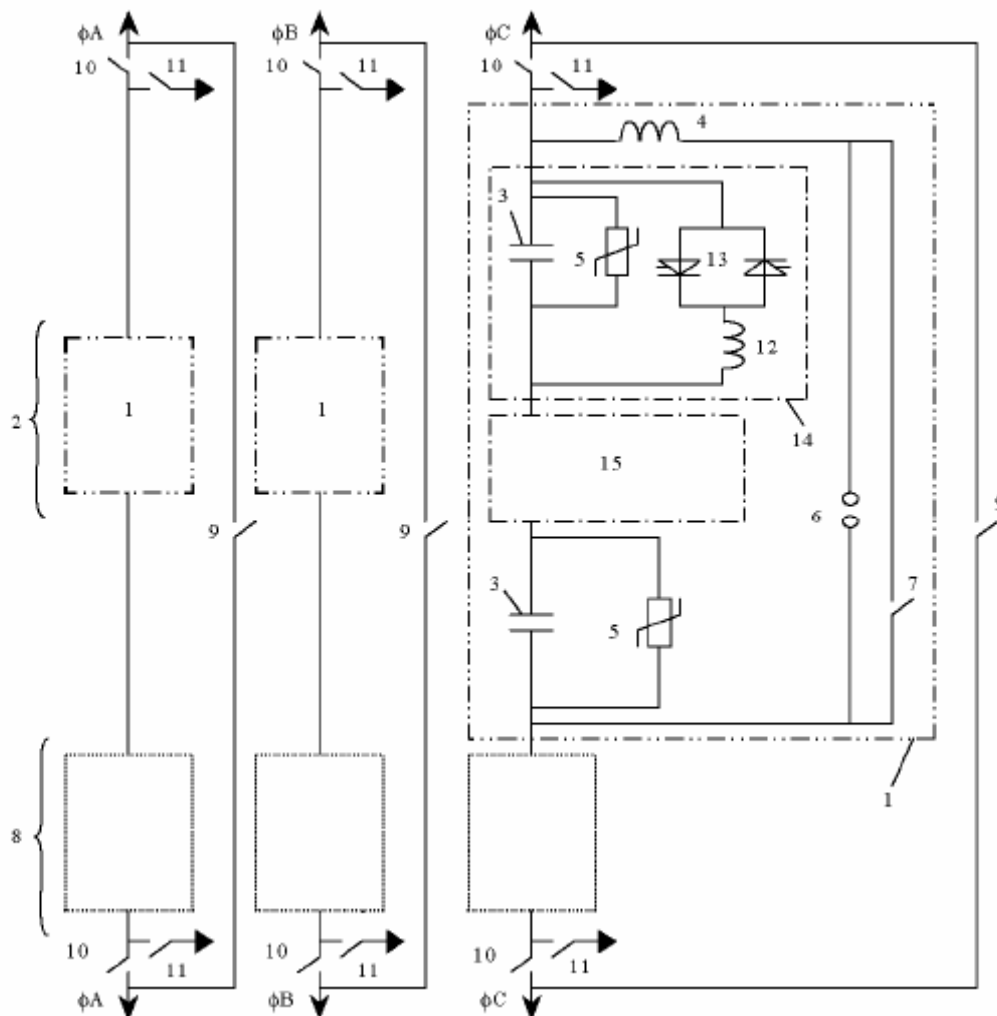
5. Operating and rating considerations

5.1 Introduction

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 standard (see Figure 2) consider the following three basic operating modes: 1) thyristors “blocked” (no gating and zero thyristor current), 2) thyristors [“bypassed”](#) (gating resulting in 360° power frequency thyristor current), and 3) “controlled” operation (periodic gating resulting in thyristor currents at a frequency higher than the power frequency). The “controlled” operation modes discussed in this standard refer to operating conditions that vary the capacitive reactance of the TCSC. “Controlled” operating modes that result in varying the inductive reactance are [identified](#) for reference only.

Steady-state waveforms for the basic TCSC circuit configuration operating in the capacitive range are shown in Figure 3. The capacitor voltage (V_C) is plotted with two different control angles (α). This standard defines the control angle (α) as the electrical angle from the capacitor voltage zero crossing to the start of thyristor conduction. For steady-state conditions, the conduction interval (σ) of the thyristor valve current (I_{TH}) is symmetrical around the capacitor voltage zero crossing with V_C lagging the current ($I_C = I_L + I_{TH}$) that drives the capacitor voltage. Typical capacitor voltage and current waveforms with control angles at 180° and 145° are shown in Figure 3(a) and Figure 3(b), respectively.



- 1 – Segment (1 ϕ)
- 2 – Switching step or module (3 ϕ)
- 3 – Capacitor units
- 4 – Discharge current limiting reactor
- 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 – Thyristor reactor
- 13 – Bidirectional thyristor valve
- 14 – Controllable subsegment (1))
- 15 – Additional controllable sub-segments when required

Figure 1—Typical TCSC installation nomenclature

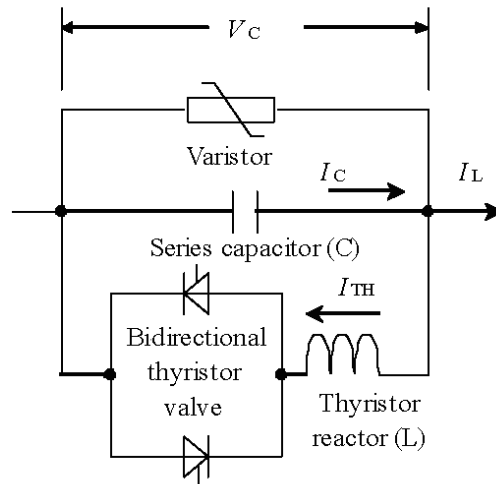


Figure 2—TCSC controllable subsegment

The definition of control angle with reference to voltage zero is selected to be consistent with other power electronic equipment. It should be recognized, however, that most TCSC control systems use the line current waveform as an important control reference.

As ~~can be~~ shown in Figure 3(b), when a subsegment is operating in the capacitive mode, a current in the thyristor branch can boost the power frequency voltage across the capacitor segment, resulting in an effective capacitive reactance greater than the nominal ($X_{\text{ORDER}} \simeq 2.0$). Note that the pulses of current in the thyristor branch cause a distortion of the capacitor voltage (V_C). In a TCSC application, the increased capacitive reactance would increase the line current. Some comments on the units for the magnitudes of the voltages are in order. As ~~previously~~ mentioned, conduction of the thyristor branch distorts the voltage across the subsegment. This distortion means that the voltage includes nonpower

frequency components and that the relationship between root mean square (RMS) and peak voltage is not 2 as is the case for a pure sinusoid. The relationships for these voltage quantities for various X_{ORDER} are shown in Table 1. The values assume one per unit line current and that the power frequency RMS voltage across the subsegment with an X_{ORDER} of one is defined as one per unit.

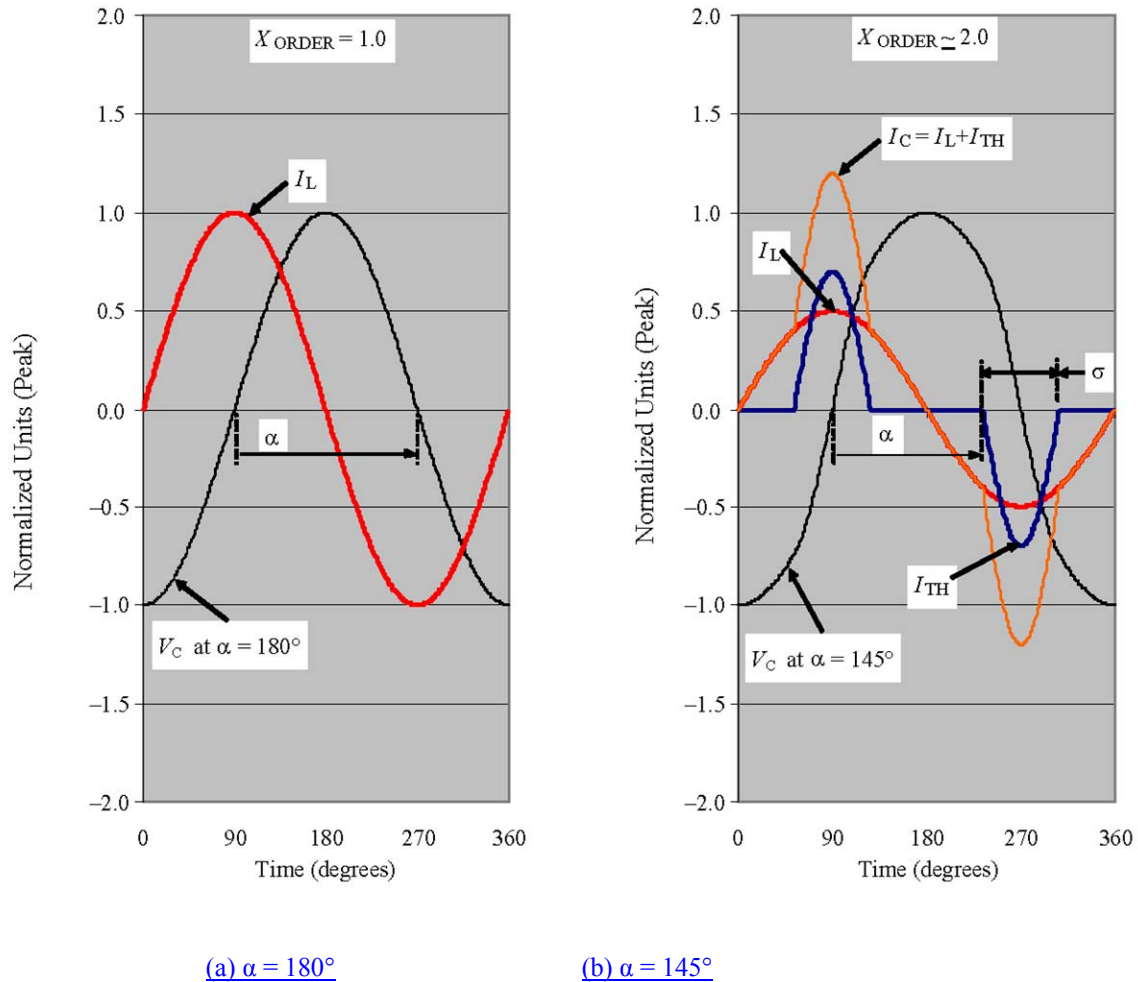


Figure 3—TCSC steady-state waveforms⁶ for control angle α and conduction interval σ

⁶The scales used in these figures are normalized for illustration purposes and are not in per unit of any set of rated parameters for a subsegment.

Table 1—Peak and RMS voltage relationships

X_{ORDER}	Power frequency (RMS voltage)	Power frequency (peak voltage)	Total RMS (voltage)
<u>1.0</u>	<u>1.0</u>	<u>1.414</u>	<u>1.00</u>
<u>2.0</u>	<u>2.0</u>	<u>2.560</u>	<u>2.02</u>
<u>3.0</u>	<u>3.0</u>	<u>3.390</u>	<u>3.03</u>

5.2 TCSC characteristics

The characteristics of TCSC are determined from the series capacitor (C) and reactor (L) circuit parameters shown in Figure 2. The steady-state TCSC power frequency reactance [$X(\alpha)$] as a function of thyristor control angle (α) can be calculated from Equation (1), based on an analysis of thyristor current (Christl et al. [B3]; Jalali et al. [B15]).⁷

⁶ The scales used in these figures are normalized for illustration purposes and are not in per unit of any set of rated parameters for a subsegment.

⁷ The numbers in brackets correspond to those of the bibliography in Annex A.

$$X(\alpha) = \frac{-j}{\omega C} \left[1 - \frac{k^2}{k^2 - 1} \times \frac{\sigma + \sin(\sigma)}{\pi} + \frac{4k^2}{(k^2 - 1)} \times \cos^2(\sigma / 2) \times \frac{k \tan(k\sigma / 2) - \tan(\sigma / 2)}{\pi} \right] \quad (1)$$

where

- σ is $2(\pi - \alpha)$
- α is the control angle from capacitor voltage zero
- k is λ/ω
- ω is $2\pi f$
- f is the power frequency (Hz)
- λ is $1/\sqrt{LC}$
- L is the inductance (H)
- C is the capacitance (F)

Equation (1) represents the reactance of the equivalent power frequency reactance of a TCSC controllable subsegment. The equation does not include the other components of impedance that the TCSC has because of the distorted voltage across the subsegment. Because the firing of the thyristor results in a circuit that is not linear, the equation cannot be used to predict performance if the line current is a combination of power frequency and other frequency currents. This equation cannot be used in the analysis of subsynchronous resonance.

The TCSC power frequency steady-state reactance characteristics of Equation (1) for “controlled” operation in the capacitive range ($\alpha_0 < \alpha < 180^\circ$) and inductive range ($90^\circ < \alpha < \alpha_0$) are shown in Figure 4. The magnitude of the inductance in the thyristor branch has some effect on this characteristic.

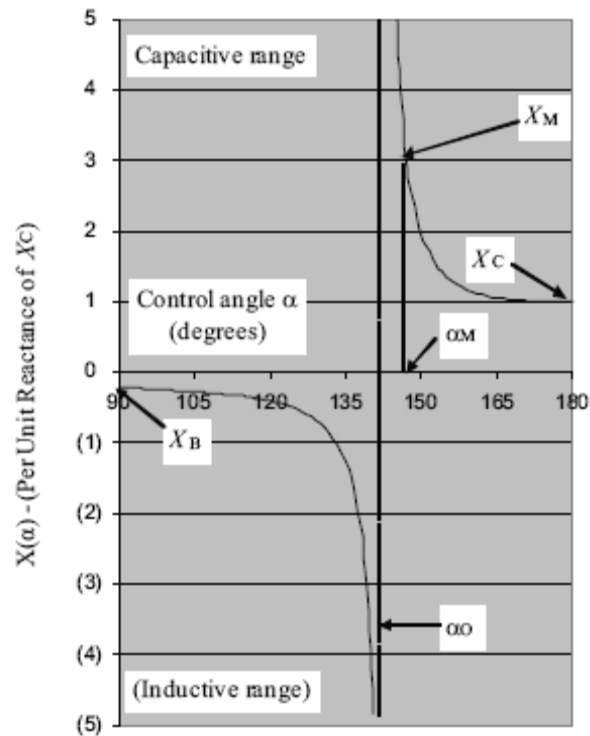


Figure 4—TCSC power frequency steady-state reactance characteristics

In Figure 4, the vertical axis is the per-unit reactance and the horizontal axis is the control angle in degrees.

⁵The numbers in brackets correspond to those of the bibliography in Annex A.

The transition between the inductive and the capacitive region has a resonant condition that can theoretically lead to extremely large values of reactance if the subsegment is in steady-state operation and the control angle approaches α_O . The exact angle (α_O) at which resonance will occur is dependent on the magnitude of the inductance and capacitance of the subsegment. Although it is possible to operate a TCSC during transient conditions at the firing angle (α_O), in practice, steady-state operation with a control angle near (α_O) shall be avoided because it is difficult to control the reactance and the equipment may be subjected to high voltages and currents. It is recommended that the purchaser specify a maximum steady-state capacitive reactance X_{ORDER} for X_M (see 5.3).

5.3 Basis for TCSC ratings

The basis for rating a TCSC is dependent on the supplier applying basic TCSC characteristics (see 5.1 and 5.2) to establish operating parameters that meet specific objectives defined by the purchaser. Operational objectives can include [subsynchronous resonance](#) (SSR) mitigation, power oscillation damping, current (power flow) control, reactance control, special protective features, or combinations of these (see 5.4 and 5.5). TCSC operating parameters associated with a single controllable subsegment are shown in Figure 5 and Figure 6. ~~While~~ Although Figure 5 can be used for establishing TCSC equipment limits, Figure 6 is more useful when specifying power system operating parameters from an application point of view.

Figure 5 shows the basic TCSC equipment operating parameters of a single controllable subsegment. A triangular area of controlled operation is shown with time-dependent voltage and current limits based on practical constraints of the TCSC equipment. Since Figure 5 is a plot of voltage versus line current, straight lines from the origin represent lines of constant reactance. The line labeled “ X_C at Control Angle $\alpha = 180^\circ$ ” represents the TCSC capacitive reactance with essentially no thyristor current, and it is shown to be equal

to the power frequency reactance of the capacitor (C). When the conduction time (σ) of the thyristor valve is increased, the resulting increase in V_C raises the effective power frequency reactance of the TCSC, and the line of constant reactance is rotated counterclockwise on the figure. The range of controlled capacitive reactance of the TCSC (X_{ORDER}) is a function of the TCSC voltage (V_C) and line current (I_L) with typical ranges up to three times the power frequency reactance of the capacitor (X_C) as represented by the line labeled " X_M at Minimum Control Angle (σ_M)."

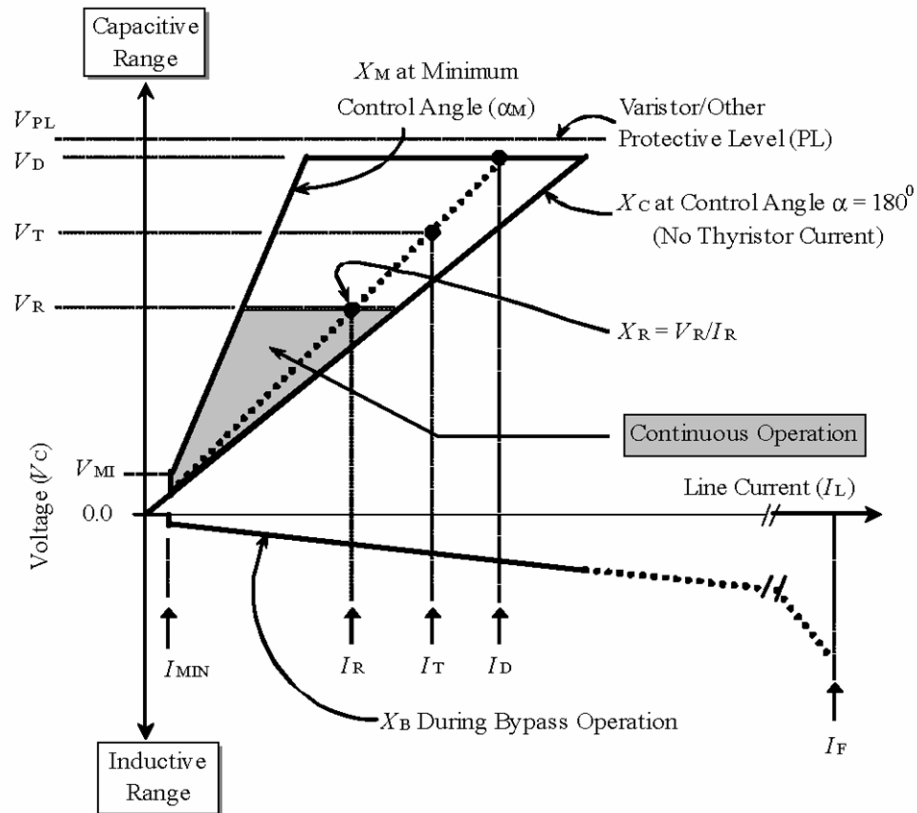


Figure 5—TCSC voltage–current capability curves (single controllable subsegment)

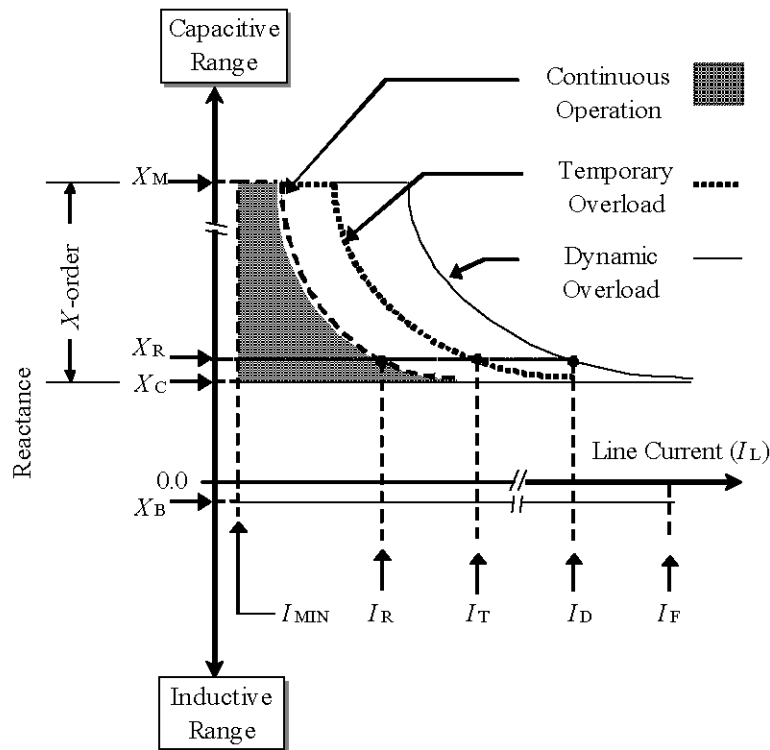


Figure 6—TCSC reactance–current capability curves (single controllable subsegment)

The lines of constant reactance for controlled operation do not extend all the way to the origin because the steady-state firing of a thyristor valve is not possible at very low thyristor valve voltages and currents. All thyristors have a minimum voltage below which firing 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. The results are a TCSC that has a minimum line current (I_{MIN}) and a minimum voltage (V_{MIN}) below which valve firing may not be reliable. This can have ramifications on the application and operation of the TCSC.

The TCSC equipment has voltage and current limitations that constrain the range of operation. The ability of a subsegment to operate with increased reactance is constrained by the ability of the equipment to withstand the associated voltage.

For continuous operation in the capacitive region, the constraint on voltage is established with respect to the rated continuous operating point specified by the purchaser [Equation (2)]:

where

- I_R is the maximum continuous power frequency rms line current (A) at which a reactance of X_R is required
- X_R is the maximum power frequency capacitive reactance (Ω) that must be achievable on a continuous basis at a rated line current of I_R
- V_R is the power frequency rms voltage (V) across the sub-segment for which the equipment is rated for continuous operation

In some applications, the rated continuous operation will be defined by the purchaser for the condition of no thyristor valve conduction. This is likely to be especially true for installations where a TCSC is realized from an existing fixed-series capacitor bank. For this case, X_R will be equal to X_C . However, in the general case, X_R is not equal to X_C . This general case is shown in Figure 5 by the dotted constant reactance line.

For continuous operation, the TCSC is constrained to operate within the continuous voltage (V_R) and line current (I_R) capability of the capacitors, varistors, thyristor reactors, and thyristor valves. In Figure 5, the horizontal line labeled V_R represents one such constraint. Although controlled operation can typically implement an X_{ORDER} anywhere between 1 and 3, if the resulting steady-state voltage (V_C) exceeds V_R , the controller should automatically reduce the X_{ORDER} , within the equipment temporary and dynamic time constraints, until the capacitor voltage is $\leq V_R$. To summarize, the TCSC should be capable of continuous operation within the area bounded by the voltage rating (V_R) of the equipment with X_{ORDER} ranges typically between 1 and 3.

Typical temporary overload capabilities of a TCSC (typically ≤ 30 min) are determined by the area (see Figure 5) limited by the temporary voltage rating (V_T) with X_{ORDER} ranges between 1 and 3. This overload rating is typically 1.35 to 1.5 times the rated voltage (V_R) for the capacitors. IEEE Std 824-1994 indicates that such overloads can be reasonably expected to be withstood by the capacitors approximately 300 times during the life of the capacitors.

The TCSC dynamic overload capabilities (typically ≤ 10 s) are determined by the area (see Figure 5) limited by the dynamic voltage rating (V_D) with controllable voltages that approach the protective level (VPL) of the varistors or other protective device. This upper limit on voltage (V_D) is typically less than twice the rated voltage (V_R) of the capacitors.

Operating the TCSC in the inductive region (see Figure 5) is shown as a straight line labeled “XB During Bypass Operation” that represents the reactance of the thyristor reactor. The actual operating range extends far to the right, because the reactor could be required to withstand power system fault currents (I_F).

For simplicity in this recommended practice, the constant-voltage lines in Figure 5 can be considered to be lines of constant RMS voltage. As can be seen from Table 1, increasing X_{ORDER} results in a proportionate increase in the power frequency RMS voltage. However, the same is not true for the peak voltage where the increasing voltage distortion results in less than a proportionate increase in voltage. Since much of the equipment is more sensitive to peak rather than RMS voltages, this could be a factor in the final design of the equipment. Finally, the constant-voltage line illustrating the protective level is in terms of peak voltage.

Figure 6 presents information similar to that portrayed in Figure 5 except that the vertical axis on the graph is reactance rather than voltage. The region of continuous capacitive reactance operation is shown in the shaded area. The lower reactance boundary is the fundamental frequency reactance (X_C) of the capacitor. The upper reactance boundary (X_M) is typically an X_{ORDER} of less than 3. The curved boundaries represent the TCSC temporary and dynamic time constraints on the X_{ORDER} that are required to limit the voltage across the TCSC to the rated voltage of the capacitors. The left boundary is the minimum line current (I_{MIN}) for which the thyristors can reliably fire.

From an application perspective, the TCSC can be operated anywhere in the region of continuous operation to enhance or control steady-state current (power) flow on the system. The TCSC can be operated in a constant reactance or constant current (power) transfer mode.

Figure 6 shows an expanded area of temporary operation wherein the TCSC can utilize the 30 min temporary overcurrent (I_T) and overvoltage (V_T) capability of the capacitors (typically between 1.35 and 1.5 times V_R). This capability is available to allow the TCSC to maintain its reactance at higher than continuous rated currents or to allow it to increase temporarily its reactance in response to changing power system conditions.

During dynamic conditions (typically ≤ 10 s), the TCSC can operate anywhere within the most expansive boundaries of Figure 6. This is an area of operation that is important in TCSC applications involving power oscillation damping. Care shall be taken in applying the results of power system stability analysis programs when defining the dynamic requirements for a TCSC. Some system stability analysis programs model a TCSC simply as a variable reactance and do not have time-dependent constraints on the maximum voltage as is the case with a practical TCSC (see Annex B).

Also shown in Figure 6 is the horizontal line illustrating TCSC operation in the inductive bypass region (X_B) with continuous (3°) thyristor valve conduction.

5.4 Duty cycle

5.4.1 Introduction

The purchaser should specify the required sequences of faults, dynamic overload, temporary overload, and continuous currents for the TCSC bank. These sequences form the duty cycles that all of the components of the TCSC bank should be designed to withstand. The duty cycle should be consistent with the manner in which the surrounding power system will be operated for both internal and external line faults. The purchaser should define duty cycles for faults of normal and extended duration and for faults of different types (multiple and single phase). The terms “normal” and “extended” refer to the operation of the line relays and line circuit breakers. A normal fault duration is that associated with the correct operation of the primary line relaying and the line circuit breakers. An extended fault duration is the longer time that can occur when the fault is not detected by the primary relays or there is a failure of a line circuit breaker.

The purchaser should specify the power system fault currents, the type of bypass that can occur during internal and external faults, and the desired post-fault control mode(s), reactance range, and voltage across the TCSC bank:

- a) Fault currents should be defined in terms of the parameters of the transmission line in series with the TCSC bank and the equivalent short-circuit impedance at the terminals of that line for the surrounding power system. In applications where the power system parameters can change over time, the purchaser should clearly identify the specific set of parameters for which the equipment is to be designed. The purchaser should specify that the supplier designs the equipment for the worst fault locations on the power system. Consideration should be given to the condition of a parallel line out-of-service that can result in a temporary increase in the TCSC line current.
- b) The duration of internal and external faults should be defined for all fault types. The reclosing time for internal and external faults shall be defined. The type of line reclosing (single phase or three phase) should also be defined whether simultaneous or nonsimultaneous reclosing is applied.
- c) There are four possible means of bypassing the capacitors of a TCSC during a power system fault: thyristor valve, varistors, bypass gap, and bypass switch. The purchaser should specify the desired type of bypass that should be used for various power system fault conditions.
- d) The performance of the TCSC after fault clearing can be critical to the stability of the power system. In addition, the thyristor junction temperature (see Clause 6) can be elevated due to conduction during the fault. Therefore, it is important that the desired post-fault range of reactance and voltage across the TCSC be carefully specified.

5.4.2 Duty cycle sequence

The following [subclauses](#) include examples of duty cycle sequences that should be specified for a TCSC bank. These sequences are different for external and internal line section faults. Presented are possible modes of operation for various overvoltage protection schemes for the TCSC bank. The purchaser should tailor the sequences to the requirements for the specific application. The equipment should be able to execute the specified duty cycle at any ambient temperature within the range specified by the purchaser. Further clarifications on duty cycle sequences are given in Annex C.

5.4.2.1 External line section faults

Examples of TCSC bank duty cycles for external faults of normal duration are described below. External faults are faults on the power system at locations other than on the transmission line associated with the TCSC bank being specified:

- a) A varistor is the primary overvoltage protection:
- 1) The TCSC is initially in the inserted condition with rated continuous current (I_R) and the thyristor valve operating in a conduction mode consistent with the objectives specified by the purchaser that results in the highest thyristor operating junction temperature.
 - 2) An external fault occurs that is cleared within normal clearing time. The varistor is required to withstand the duty associated with protecting the capacitors and thyristor valve during the fault. Bypass with the thyristor valve during all or part of the fault duration is permitted. However, bypass with a bypass gap or switch is not permitted. Within one cycle ~~following~~[after](#) fault clearing, the thyristor valve shall be able to operate in a conduction mode consistent with the power transfer objectives of the purchaser. The only exception is that the varistor and/or the thyristor valve may conduct as required to limit the voltage across the TCSC to the protective level (V_{PL}).
 - 3) The TCSC is exposed to swing current and overload currents followed by post-fault currents that can be greater than I_R as a result of changing power system conditions. The purchaser shall specify the magnitude of the post-fault overload currents. It may be at rated current (I_R) or at the 30 min overload current (I_T) followed by rated current (I_R). During this period, the equipment shall be able to achieve the 10 s and 30 min overload objectives of the purchaser. Consideration shall be given to the energy the varistor can absorb during the swing.
 - 4) The TCSC returns to operation at rated current (I_R) and with the thyristor valve operating in a conduction mode consistent with the objectives specified by the purchaser.
- b) The thyristor valve is the primary protection:
- 1) The bank is initially in the inserted condition with rated continuous current and the valve operating in a conduction mode consistent with the objectives specified by the purchaser that results in the highest thyristor junction operating temperature.
 - 2) An external fault occurs that is cleared within normal clearing time. The thyristor valve shall conduct as required to limit the voltage across the capacitors to less than or equal to the protective level (V_{PL}). Closure of the bypass switch is not permitted. Within a few cycles (time to be specified by the purchaser) after fault clearing, the valve shall be able to operate in a conduction mode consistent with the power transfer objectives of the purchaser. The only exception is that the thyristor valve may conduct as required to limit the capacitor bank voltage to the protective level (V_{PL}).
 - 3) The TCSC is exposed to swing current and overload currents followed by post-fault currents that can be greater than I_R . The purchaser shall specify the magnitude of the post-fault overload currents. It can be at rated current (I_R) or at the 30-min overload current (I_T) followed by rated current (I_R). The equipment shall be able to achieve the 10 s and 30 min overload objectives of the purchaser. Consideration shall be given to the selected protective level (V_{PL}) and the capabilities of the thyristor valve ~~to ensure~~[so](#) that the thyristor valve can insert the capacitors during overload conditions and achieve the desired power transfer objectives. This shall be possible in spite of the additional components of voltage that can appear across the capacitors due to reinsertion by the thyristor valve. Reinsertion during the overload can result in a total voltage across the capacitors and the thyristor valve that approaches twice that associated with the overload current, leading to voltage triggering and failure to reinsert unless counteractive thyristor valve control strategies are implemented. In practice, the reinsertion transients are limited by a metal oxide varistor in parallel with the valve. The voltage-current characteristic of the varistor shall be carefully coordinated with the protective level established by the valve to avoid excessive energy absorption by the varistor. Simulations shall be performed to establish the energy requirements of the varistor for power system faults and swings.
 - 4) The bank returns to operation at rated current (I_R) and with the thyristor valve operating in a conduction mode consistent with the objectives specified by the purchaser.