

1534™

IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors

IEEE Power Engineering Society

Sponsored by the
Substations Committee



Published by
The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

20 November 2002

Print: SH95002
PDF: SS95002

WITHDRAWN

Recognized as an
American National Standard (ANSI)

IEEE Std 1534™-2002

IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors

Sponsor

Substations Committee
of the
IEEE Power Engineering Society

Approved 13 June 2002

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, TCSC, thyristor valves

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2002 by the Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 20 November 2002. Printed in the United States of America

Print: ISBN 0-7381-3299-3 SH95002
PDF: ISBN 0-7381-3300-0 SS95002

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

WITHDRAWN

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Associations (IEEE-SA) Standards Board. The IEEE develops its standards through a consensus development process, approved by the American National Standards Institute, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and serve without compensation. While the IEEE administers the process and establishes rules to promote fairness in the consensus development process, the IEEE does not independently evaluate, test, or verify the accuracy of any of the information contained in its standards.

Use of an IEEE Standard is wholly voluntary. The IEEE disclaims liability for any personal injury, property or other damage, of any nature whatsoever, whether special, indirect, consequential, or compensatory, directly or indirectly resulting from the publication, use of, or reliance upon this, or any other IEEE Standard document.

The IEEE does not warrant or represent the accuracy or content of the material contained herein, and expressly disclaims any express or implied warranty, including any implied warranty of merchantability of fitness for a specific purpose, or that the use of the material contained herein is free from patent infringement. IEEE Standards documents are supplied "AS IS."

The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least every five years for revision or reaffirmation. When a document is more than five years old and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

In publishing and making this document available, the IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity. Nor is the IEEE undertaking to perform any duty owned by any other person or entity to another. Any person utilizing this, and any other IEEE Standards document, should rely upon the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
P.O. Box 1331
Piscataway, NJ 08855-1331
USA

Note: Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. The IEEE shall not be responsible for identifying patents for which a license may be required by an IEEE standard or for conducting inquiries into the legal validity or scope of those patents that are brought to its attention.

Authorization to photocopy portions of any individual standard for internal or personal use is granted by the Institute of Electrical and Electronics Engineers, Inc., provided that the appropriate fee is paid to Copyright Clearance Center. To arrange for payment of licensing fee, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923, USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

WITHDRAWN

Introduction

(This introduction is not a part of IEEE Std 1534-2002, 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

- 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

- d) Incorporate equipment ratings during the definition, evaluation, selection, and acceptance of TCSC installations for operational use.
- e) 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:

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

Participants

At the time this recommended practice was completed, the Thyristor-Controlled Series Capacitor Working Group had the following membership:

Duane R. Torgerson, *Chair*

Stan Miske, *Vice Chair*

Wayne Litzenberger, *Secretary*

Bharat Bhargava
Hubert Bilodeau
Todd Campbell
Aty Edris
Carlos Gama

Victor Gor
Richard Haas
Edward Horgan
John Joyce
Lutz Kirschner
Gerald Lee

Ben Mehraban
Nicholas Miller
Jan Samuelsson
Hector Sarmiento
Bo Wikstrom

WITHDRAWN

The following members of the balloting group voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

Hanna Abdallah
Arun Arora
Michael Baker
Hubert Bilodeau
Todd Campbell
Tommy Cooper
Richard Crowdis
Guru Dutt Dhingra
Gary Engmann
Carlos Gama
Philip Hopkinson
Edward Horgan

Farshad Hormozi
Gerhard Juette
George G. Karady
Stephen R. Lambert
Thomas LaRose
Gerald Lee
George Lester
Peter Lips
Wayne Litzenberger
Albert Livshitz
Gregory Luri
Gary Michel
Nicholas Miller

Jeffrey Nelson
Carlos Peixoto
Paul Pillitteri
James Ruggieri
Jan Samuelsson
Michael Sharp
Harinderpal Singh
Rao Thallam
Duane R. Torgerson
Heinz Tyll
John Vithayathil
James Wilson

When the IEEE-SA Standards Board approved this recommended practice on 13 June 2002, it had the following membership:

James T. Carlo, *Chair*

James H. Gurney, *Vice Chair*

Judith Gorman, *Secretary*

Sid Bennett
H. Stephen Berger
Clyde R. Camp
Richard DeBlasio
Harold E. Epstein
Julian Forster*
Howard M. Frazier
Toshio Fukuda

Arnold M. Greenspan
James H. Gurney
Raymond Hapeman
Donald M. Heirman
Richard H. Hulett
Lowell G. Johnson
Joseph L. Koepfinger*

Peter H. Lips
Nader Mehravari
Daleep C. Mohla
William J. Moylan
Malcolm V. Thaden
Geoffrey O. Thompson
Howard L. Wolfman
Don Wright

*Member Emeritus

Also included are the following nonvoting IEEE-SA Standards Board liaison:

Alan H. Cookson, *NIST Representative*
Satish K. Aggarwal, *NRC Representative*

Savoula Amanatidis,
IEEE Standards Managing Editor

WITHDRAWN

Contents

1. Overview.....	1
1.1 Scope.....	1
1.2 Purpose	1
2. References	1
3. Definitions, special symbols, acronyms, and abbreviations.....	2
3.1 Definitions.....	2
3.2 Special symbols	4
3.3 Acronyms and abbreviations	5
4. Service conditions.....	6
5. Operating and rating considerations.....	6
5.1 Introduction	6
5.2 TCSC characteristics.....	9
5.3 Basis for TCSC ratings	10
5.4 Duty cycle	13
5.5 Operational objectives.....	16
6. Thyristor valves (bidirectional)	18
6.1 Current and voltage capability	18
6.2 Valve control.....	23
6.3 Valve cooling system.....	26
6.4 Mechanical design.....	26
6.5 Valve testing.....	27
7. Capacitors and reactors	30
7.1 General.....	30
7.2 Capacitor considerations.....	30
7.3 Reactor considerations.....	30

WITHDRAWN

8. Control and protection	31
8.1 Control.....	31
8.2 Protection.....	34
8.3 Monitoring and recording	35
8.4 Signal transmission and platform power	38
8.5 General requirements.....	39
8.6 Coordination with line protection	40
9. Layout.....	40
9.1 General	40
9.2 Substation yard.....	41
9.3 Platform assemblies	41
9.4 Control building	41
10. Safety.....	42
10.1 Personnel protection	42
10.2 Discharge devices.....	42
10.3 Grounding provisions	42
10.4 Handling and disposal	42
11. Testing and commissioning.....	42
11.1 Introduction.....	42
11.2 Design and production tests and factory control system tests.....	43
11.3 On-site tests.....	44
12. Losses and loss evaluation	46
12.1 Introduction	46
12.2 Ambient conditions.....	46
12.3 Calculation of losses	47
13. Reliability, availability, and maintainability	48
13.1 Introduction	48
13.2 Definitions.....	48
13.3 RAM analysis	49

WITHDRAWN

13.4	Spare parts	49
13.5	Availability and reliability	50
14.	Project scope	50
14.1	Introduction	50
14.2	New TCSC installations	50
14.3	Retrofit to an existing fixed series capacitor installation.....	52
15.	Training	53
15.1	General.....	53
15.2	Off-site training.....	53
15.3	On-site training	54
15.4	Training during commissioning	54
16.	Documentation	54
16.1	Introduction	54
16.2	Purchaser documentation	54
16.3	Supplier documentation	55
	Annex A (informative) Bibliography and annotated bibliography.....	57
	Annex B (informative) TCSC application studies and computer models.....	65
	Annex C (normative) Summary outline of TCSC specification.....	74

WITHDRAWN

IEEE Recommended Practice for Specifying Thyristor-Controlled Series Capacitors

1. Overview

1.1 Scope

This is a recommended practice for specifying 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, training, documentation, 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) provides a summary outline of recommended items that should be considered when preparing a TCSC specification.

1.2 Purpose

This recommended practice is meant to provide 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. References

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

¹IEC publications are available from the Sales Department of the International Electrochemical Commission, Case postale 131, 3, rue de Varembe, CH-1211, Genève 20, Switzerland/Suisse (<http://www.icc.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.

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—Tests C: 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 Capacitors in Power Systems.

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

IEEE Std 1267TM-1999, IEEE Guide for Development of Specification 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.

3. Definitions, special symbols, acronyms, and abbreviations

3.1 Definitions

Some of the definitions used in this recommended practice can be found in IEEE 100TM, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B13]. In some instances, the definition in IEEE 100 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.

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

NOTE—See Figure 1.

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

3.1.3 capacitive range: TCSC operation resulting in an effective increase of the power frequency reactance range of the series capacitor.

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

NOTE—See Figure 3.

²The IEEE standards or products referred to in Clause 2 are trademarks owned by the Institute of Electrical and Electronics Engineers, Inc.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (<http://standards.ieee.org/>).

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

NOTE—See Figure 3.

3.1.6 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.

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

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

3.1.9 reactive power rating: The reactive power rating ($P_Q = 3I_R^2 X_R$) for the TCSC bank as determined from rated reactance (X_R) and rated current (I_R).

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

3.1.11 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.

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

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

NOTE—See Figure 1.

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

3.1.15 thyristor varistor: An assembly of varistor units that limit overvoltages to a given value. In the context of 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.

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

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

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

3.1.19 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. 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

3.2.1 I_C : Current through the series capacitor.

NOTE—See Figure 2.

3.2.2 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.

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) at which the TCSC should be capable of continuous control at rated frequency and rated ambient temperature range.

3.2.6 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.

3.2.7 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.

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

NOTE—See Figure 2.

3.2.9 V_C : Voltage across the TCSC.

NOTE—See Figure 2.

3.2.10 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.

3.2.11 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.

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

3.2.13 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.

3.2.14 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.

3.2.15 $X(\alpha)$: TCSC power frequency reactance as a function of thyristor control angle (α).

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

3.2.17 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 .

3.2.18 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.

3.2.19 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.

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

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

3.2.22 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
BIL	basic impulse level
CCVT	coupling capacitor voltage transformer
EMTP	electromagnetic transient program
ETT	electrically triggered thyristors
FSC	fixed series compensation
GPS	global positioning system
HVDC	high-voltage direct current
LTT	light-triggered thyristors
MC	master control
MTBF	mean time between failure
MTTR	mean time to repair
Mvar	megavar
POD	power oscillation damping
RAM	reliability, availability, and maintainability
RIV	radio influence voltage
RMS	root mean square
RTO	regional transmission organization
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SER	sequence events recorder
SSR	subsynchronous resonance

SVC	static var compensator
TCR	thyristor-controlled reactor
TCSC	thyristor-controlled series capacitor
TE	thyristor electronics
TNA	transient network analyzer
VBE	valve base electronics
VBO	voltage-breakover operation

4. Service conditions

The purchaser should specify the service conditions for operation of the TCSC installation (reference IEEE Std 824-1994) at the specified current, voltage, frequency, and fault sequence ratings, including:

- 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 three basic operating modes: a) thyristors “blocked” (no gating and zero thyristor current), b) thyristors “bypassed” (gating resulting in 360° power frequency thyristor current), and c) “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.

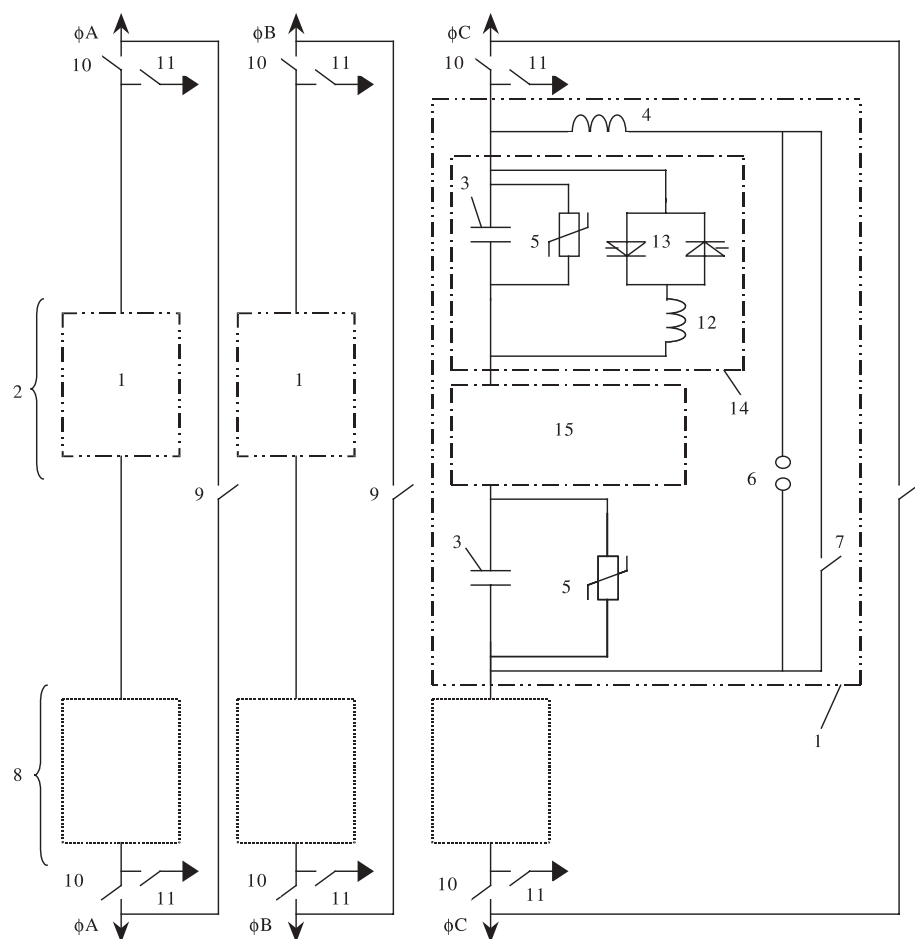


Figure 1—Typical TCSC installation nomenclature

NOTES

- | | |
|--|--|
| 1—Segment (1 ϕ) | 9—External bypass disconnect switch |
| 2—Switching step or module (3 ϕ) | 10—External isolating disconnect switch |
| 3—Capacitor units | 11—External grounding disconnect switch |
| 4—Discharge current limiting reactor | 12—Thyristor reactor |
| 5—Varistor | 13—Bidirectional thyristor valve |
| 6—Bypass gap | 14—Controllable subsegment (1 ϕ) |
| 7—Bypass switch | 15—Additional controllable subsegments when required |
| 8—Additional switching steps when required | |

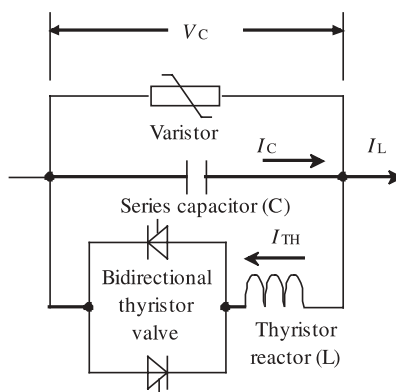


Figure 2—TCSC controllable subsegment

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 seen 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 RMS and peak voltage is not $\sqrt{2}$ 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.

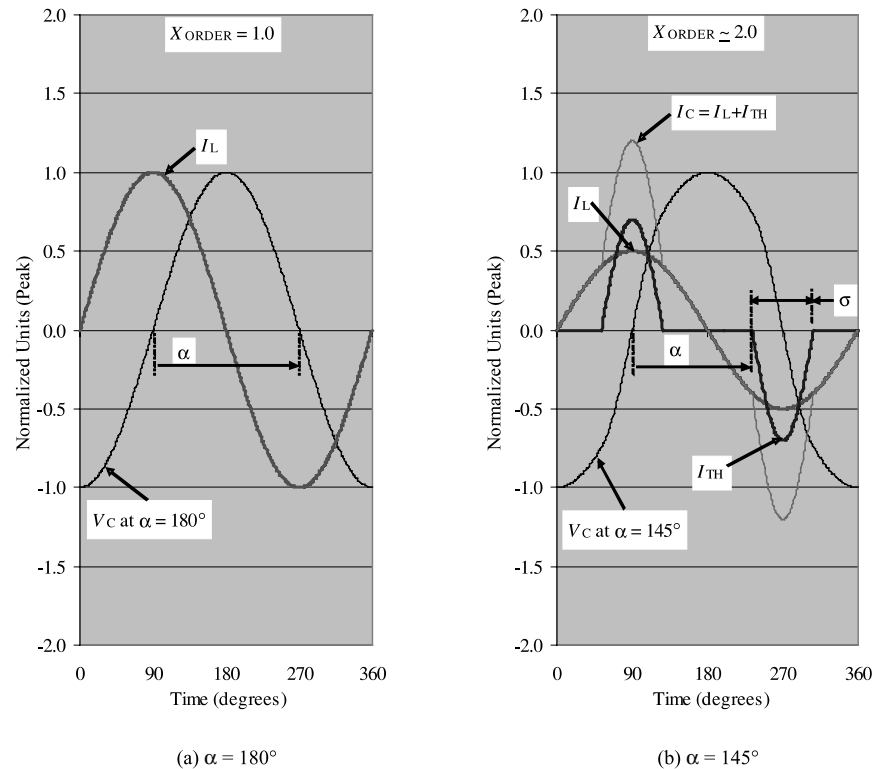


Figure 3—TCSC steady-state waveforms⁴ for control angle α and conduction interval σ

Table 1—Peak and RMS voltage relationships

X_{ORDER}	Power frequency (RMS voltage)	Power frequency (peak voltage)	Total RMS (voltage)
1.0	1.0	1.414	1.0
2.0	2.0	2.56	2.02
3.0	3.0	3.39	3.03

⁴The 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.

5.2 TCSC characteristics

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. [B16])⁵:

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

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,
- λ is $1/\sqrt{LC}$,
- L is the inductance,
- C is the capacitance.

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.

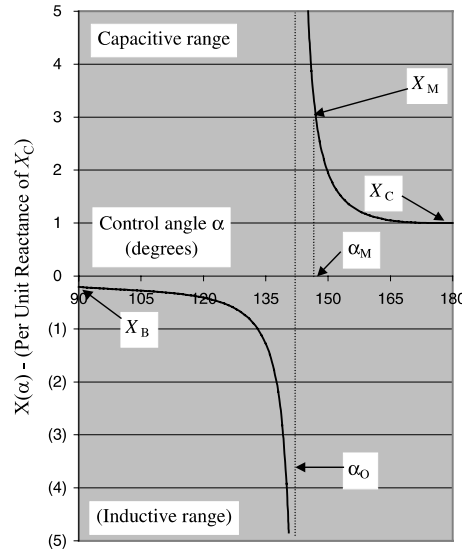


Figure 4—TCSC power frequency steady-state reactance characteristics

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

The transition between the inductive and 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_0 . The exact angle (α_0) 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_0), in practice, steady-state operation with a control angle near α_0 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 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 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 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

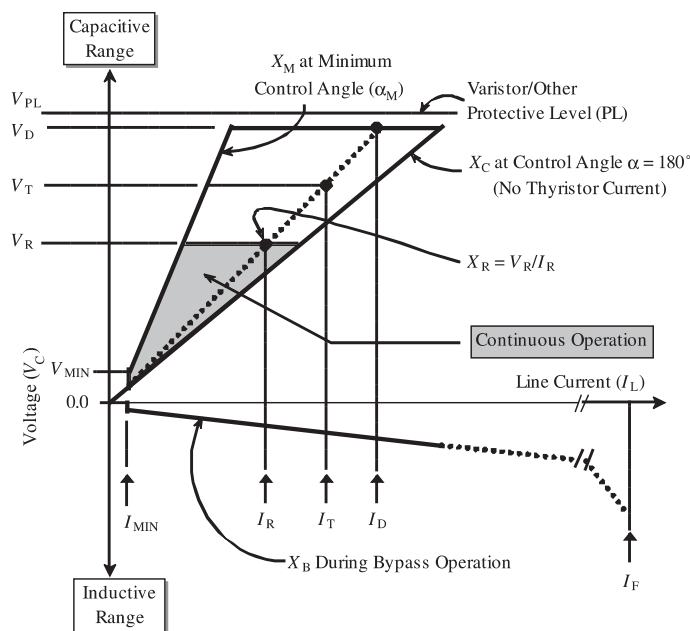


Figure 5—TCSC voltage–current capability curves (single controllable subsegment)

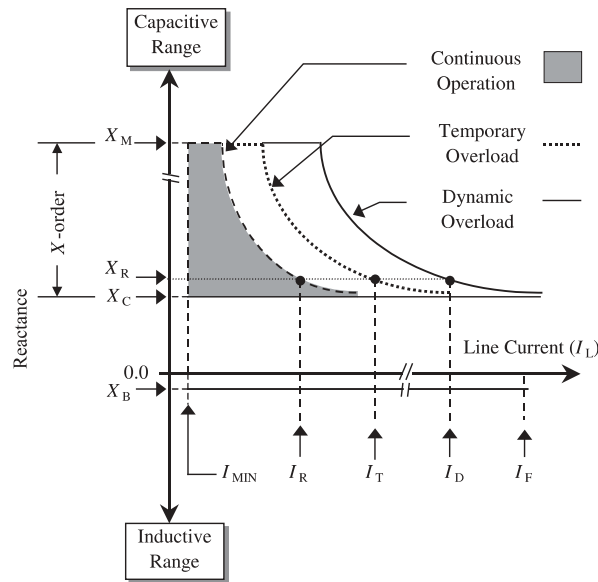


Figure 6—TCSC reactance–current capability curves (single controllable subsegment)

frequency reactance of the capacitor (X_C) as represented by the line labeled “ X_M at Minimum Control Angle (α_M).”

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)]:

$$V_R \cong I_R X_R \quad (2)$$

where

I_R is the maximum continuous power frequency RMS line current at which a reactance of X_R is required,

X_R is the maximum power frequency capacitive reactance that shall be achievable on a continuous basis at a rated line current of I_R ,

V_R is the power frequency RMS voltage across the subsegment for which the equipment is rated for continuous operation.

In some applications, 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 reasonably be expected to be withstood by the capacitors approximately 300 times over 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 (V_{PL}) 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 “ X_B During Bypass Operation” that represents the reactance of the thyristor reactor. The actual operating range extends far to the right, since 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 (360°) 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 following 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 are 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 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) following 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 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.

5.4.2.2 Internal line section faults

Examples of duty cycles for normal internal faults are described in a), b) and c). Internal faults are faults on the power system at locations on the transmission line associated with the TCSC bank specified by the purchaser.

a) Varistor is primary protection with gap bypass:

- 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 junction operating temperature.
- 2) An internal fault occurs. Bypass with the varistor, the thyristor valve, the bypass gap, or bypass switch is permitted. The varistor shall withstand the duty that occurs prior to completion of the bypass. The thyristor valve, the bypass gap, and/or switch shall withstand the resulting capacitor discharge and power frequency fault current. The line circuit breakers interrupt the fault. The thyristor valve shall withstand any prolonged current associated with the transfer of current from the thyristor valve to the bypass switch.
- 3) The line remains open until it is reclosed within the time specified by the purchaser. The TCSC shall reinsert within the time specified by the purchaser. The speed of recovery of the dielectric voltage withstand of the gap shall be consistent with the required reinsertion time. The thyristor valve shall thermally recover sufficiently to achieve the post-fault operational requirements of the purchaser.
- 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) Varistor is the primary protection with thyristor valve bypass:

- 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 junction operating temperature.
- 2) An internal fault occurs. Bypass with the varistor, the thyristor valve, and (optionally) the bypass switch is permitted. The varistor shall withstand the duty that occurs prior to completion of the bypass. The thyristor valve and/or bypass switch shall withstand the resulting capacitor discharge and power frequency fault current (I_F). The line circuit breakers interrupt the fault. The thyristor valve shall withstand any prolonged current associated with the transfer of current from the thyristor valve to the bypass switch.
- 3) The line remains open until it is reclosed within the time specified by the purchaser. The TCSC bank shall reinsert within the time specified by the purchaser. The thyristor valve shall thermally recover sufficiently to achieve the post-fault operational requirements of the purchaser.
- 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.

c) Thyristor valve is the primary protection and fault bypass device:

- 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 junction operating temperature.
- 2) An internal fault occurs. Bypass with the thyristor valve and (optionally) the bypass switch is permitted. The thyristor valve and/or bypass switch shall withstand the resulting

capacitor discharge and power frequency fault current (I_F). The line circuit breakers interrupt the fault. The thyristor valve shall withstand any additional current associated with the transfer of current from the thyristor valve to the bypass switch.

- 3) The line remains open until it is reclosed within the time specified by the purchaser. The TCSC shall reinsert within the time specified by the purchaser. The valve shall thermally recover sufficiently to achieve the post-fault operational requirements of the purchaser.
- 4) The TCSC returns to operation at rated current and with the valve operating in a conduction mode consistent with the objectives specified by the purchaser.

5.4.2.3 Faults of extended duration

In a manner similar to that illustrated for normal faults, the purchaser should define the duration and sequence for extended clearing of faults and the performance requirements of the TCSC bank for such conditions. The emphasis may be on extending the performance requirements for the TCSC bank if it is critical to the power system or conversely, allowing the bank to bypass in a protective mode to limit the stress on the equipment. In any case, the purchaser should define the maximum external fault duration following which the TCSC bank is expected to resume rapidly its operation as a controlled series capacitor. For longer fault durations, the bypass switch is permitted to close. For an internal fault, the bypass switch should be permitted to close for any extended fault and reinsertion delay. High-speed line reclosing is not normally enabled following extended fault clearing.

5.5 Operational objectives

Application studies should be performed during the conceptual, specification, design and operating stages of a series compensation project to resolve technical issues related to steady-state, temporary, and dynamic operating conditions of a TCSC installation (CIGRE Working Group 14.18 [B4]; IEEE FACTS Working Group [B15]). These studies require careful planning and coordination to ensure that the operational objectives of the TCSC are met by the specified equipment. This requires that appropriate computer models for the transmission system and TCSC controller are established and checked to validate study results (see Annex B). Operational objectives that may be the motivation for a TCSC application include the following:

- a) *Subsynchronous resonance (SSR) considerations*: Fixed series compensation inserted into a transmission line may produce a resonant circuit combination that can, under certain conditions, excite mechanical oscillations in turbine generators connected to the system. These mechanical oscillations can, in turn, further excite the electrical system at subsynchronous frequencies that may increase to the level where generators can be damaged. This SSR phenomenon is a significant concern in planning fixed series capacitor installations and requires extensive study efforts to identify potential problems and solutions. An advantage of TCSC technology is that at subsynchronous frequencies, the TCSC will provide a degree of SSR mitigation when operated with an X_{ORDER} greater than 1. The TCSC can help mitigate the resonant SSR series combination that results from fixed series capacitors. Detailed studies of the power system are required to determine an appropriate design for SSR mitigation. Extensive digital computer simulation studies, transient network analyzer (TNA) testing, and field measurements have verified the inherent SSR mitigation features of TCSC installations when properly designed (Cope et al. [B5]; Othman and Angquist [B19]; Pilotto et al. [B22]; Piwko et al. [B23]) and applied.

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 where the power system will include a combination of fixed series capacitors and TCSC, and the combined series compensation exceeds 35%. If the studies indicate that fixed series capacitors with the desired level of compensation will result in an SSR problem, the SSR studies should have the active involvement of the TCSC supplier.

The TCSC can only provide SSR mitigation if the valves are firing on a continuous basis. The degree of mitigation can be a function of the control angle. The result is that, for the TCSC to meet the SSR mitigation objectives, its operating region shall be constrained to an X_{ORDER} equal to or greater than the minimum value determined by power system studies. For example, in Figure 5, if the mitigation of SSR requires that the X_{ORDER} be greater than that depicted as X_R , then the usable range of operation is the segment between X_R and X_{ORDER} equal to 3. Also, it is clear that for this type of application the rated reactance for the TCSC shall be X_R rather than X_C . In an application where SSR mitigation is critical, the operation of the TCSC under low line current condition shall be reviewed. For line currents below which reliable valve firing is not possible, the TCSC shall be bypassed via the bypass switch.

- b) *Power oscillation damping (POD) control*: POD is a specialized subset of closed-loop reactance control that can be realized by modulating the TCSC reactance in response to transmission system conditions to dampen power system oscillations (Gama et al. [B8]). Supplemental input signals, such as frequency or line current, related to the power swings need to be provided to the TCSC controller with the proper gain and phase-angle relationship required for damping. The TCSC installation, if used correctly, can enhance stability and damp interarea power swings on the ac system. The TCSCs that have been applied for power oscillation damping have had a rated reactance that is greater than X_C so that the reactance can be increased and decreased to achieve the desired damping at rated line current.

The current swings of the system interacting with the modulation of the TCSC reactance by the POD create oscillating voltages across the TCSC. The voltage constraints of the TCSC (V_D) override an unacceptable reactance order; therefore, it is imperative that the system studies properly account for this limitation (as discussed in Annex B).

- c) *Transient stability*: The ability to control TCSC reactance rapidly provides a means to enhance system dynamic performance. Typically, a TCSC will have a basic control that will hold a specified reactance order, within the device design limits. Higher-level control inputs to the reactance control can be used to achieve improvements in: 1) transient angle stability, 2) post-contingency current (not necessarily on the line with the TCSC), and 3) transient voltage stability. This may be implemented to control the fundamental frequency reactance of each phase independently or control an average three-phase value within reactance unbalance limits established by design criteria. Capacitive reactance ranges between X_C and X_M can be controlled within the protective limits of time-dependent voltage and current ratings of the TCSC equipment. These transient stabilizing control signals are most commonly implemented as open-loop discrete switching orders (e.g., condition-based discrete actions of the type commonly used in remedial action schemes). Closed-loop (e.g., continuously acting control actions with feedback) implementation is also possible.

Detailed power system load flow and stability studies (see Annex B) are normally required to develop appropriate algorithms and settings for specific applications. It is important that the TCSC be specified to have the necessary dynamic current, reactance, and voltage capabilities as determined in transient stability studies of the power system. It is important to recognize that the TCSC model used in such studies may not have the voltage constraints (V_D) that the actual equipment will have. As with the application of fixed series capacitor banks, the application of TCSC shall address the higher performance requirements of the power system during temporary and dynamic overloads on the power system. As with conventional series capacitors, TCSC equipment has higher temporary and dynamic overload ratings that can provide this performance. These overloads are shown in Figure 7, which illustrates the current through a TCSC during an external fault and disconnection of a parallel transmission line. However, in the case of fixed series capacitors, this additional capability can only be used if the inherent swings of the power system impose overloads on the bank. That is not the case with the TCSC. Since the TCSC can adjust its reactance, the overload capability of the equipment can be used

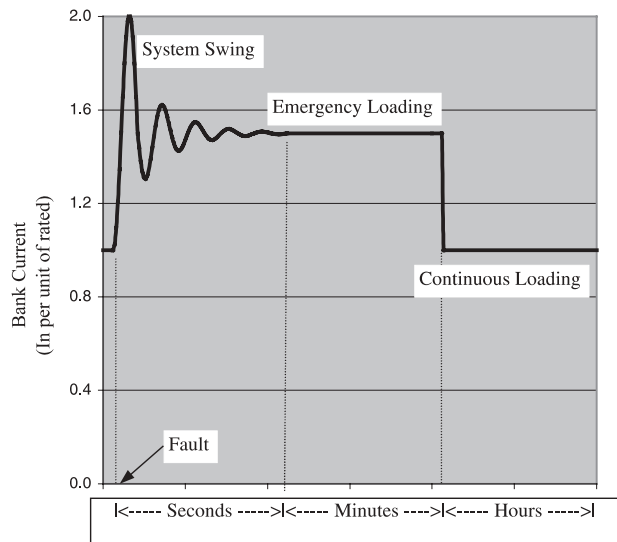


Figure 7—Current capability of TCSC

to the degree defined in Figure 7, even if the line current does not exceed the continuous current rating (I_R).

- d) *Current or power control*: The TCSC can be used to regulate either line current or through power on a continuous or emergency basis. A closed-loop regulator can be used on each phase or an average three-phase value to regulate transmission line current (I_L) (or power) within a limited range dependent on the power transmission system and TCSC operating parameters. These regulators are slow and shall be coordinated with the transient and POD controls.
- e) *Voltage control*: Like static var compensators (SVCs), TCSCs can be used to control the voltage at a specific point in the power system. This voltage control can improve voltage stability and reduce voltage fluctuations, including flicker. A closed-loop regulator can be used to modify the TCSC reactance order in response to a measured voltage signal.
- f) *Phase balancing control*: Phase balancing to compensate for asymmetrical currents as a result of single-phase loads or untransposed lines can be achieved by regulating the control angle for each phase independently, resulting in current balancing. This feature may be realized in the reactance or current control modes. Design of this feature requires detailed three-phase representation of the TCSC and the surrounding power system.

6. Thyristor valves (bidirectional)

6.1 Current and voltage capability

The current and voltage capabilities of the thyristor valve are derived from the TCSC ratings as discussed in 5.3 and illustrated in Figure 5 and Figure 6. These ratings determine the power frequency component of the voltage, V_C , which is being inserted by the TCSC in series with the transmission line, at different amplitudes of the line current power frequency component, I_L . In the design procedure it is assumed that the line current remains sinusoidal (undistorted) at the rated power frequency.

6.1.1 Current capability in normal TCSC operation

The design procedure often starts with selection of the capacitance, C , of the series capacitor bank and the inductance, L , of the TCSC reactor. The angular frequency λ of the resonance circuit in the TCSC