IEEE Std 1031-2000
(Revision of
IEEE Std 1031-1991)

IEEE Guide for the Functional Specification of Transmission Static Var Compensators

Sponsor

Substations Committee
of the
IEEE Power Engineering Society

Approved 30 January 2000

IEEE-SA Standards Board

Abstract: This guide documents an approach to preparing a specification for a transmission static var compensator. The document is intended to serve as a base specification with an informative annex provided to allow users to modify or develop specific clauses to meet a particular application.

Keywords: filters, harmonics, static var compensators, static var system, TCR, thyristor valves, TSC, TSR

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

Published 21 April 2000. Printed in the United States of America.

Print: ISBN 0-7381-1944-X SH94815
PDF: ISBN 0-7381-1945-8 SS94815

IEEE Standards documents are developed within the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE that have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. 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.

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.

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 all 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 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.

Introduction

(This introduction is not a part of IEEE Std 1031-2000, IEEE Guide for the Functional Specification of Transmission Static Var Compensators.)

This document is a revision of IEEE Std 1031-1991, Guide for a Detailed Functional Specification and Application of Static Var Compensators. The guide has been renamed and provides an example and general information that may be considered when developing a technical specification for a transmission static var compensator (SVC).

This guide is not a tutorial, and application of its contents in preparing a technical specification shall be done with sufficient technical knowledge and understanding. This guide may not include all topics necessary for every SVC application and does not address any commercial conditions applicable to specific projects.

This guide was prepared by a task force of Working Group I4, FACTS Controllers in Substations, of the High Voltage Power Electronic Stations Subcommittee for the IEEE PES Substations Committee. Members of the task force were:

Michael H. Baker, *Chair*
Dan Lorden, *Vice Chair*

Maan Al-Eshaiker
Jacques Allaire
Mike Bahrman
Charles Clarke
Gerhard Juette
Vladimir Kahle
William O. Kramer
Lawrence M. Laskowski
Robert Menzies
Al J. Molnar
Mark A. Reynolds
Rao S. Thallam
Duane R. Torgerson
David Young

The members of Working Group I4 were

Michael H. Baker, *Chair*
B. Damsky, *Vice Chair*

Charlie Antonopulos
Hubert Bilodeau
Septimus Boshoff
Thomas W. Cease
Rajiv Chopra
Cord Crichton
Laszlo Gyugyi
Narain G. Hingorani
Mike Holm
Tceza Iravani
Gerhard Juette
H. Peter Lips
Wayne Litzenburger
Jeffrey Mayer
Al J. Molnar
Philip R. Nannery*
Steven J. Swencki
Shigeru Tanabe
Rao S. Thallam
Duane R. Torgerson

*Chair Emeritus

The following members of the balloting committee voted on this standard:

Hanna E. Abdallah
William J. Ackerman
Raymond Allustiarti
Thomas M. Barnes
George J. Bartok
Michael J. Bio
Kenneth L. Black
John Burger
John W. Chadwick, Jr.
Simon R. Chano
D. Mason Clark
Thomas F. Clark
John R. Clayton
Richard Cottrell
Richard Crowdis
Frank A. Denbrock
William K. Dick
W. Bruce Dietzman
Ahmed Elneweihi
Gary R. Engmann
Dennis R. Falkenheim
Dave Finley
David L. Harris
Gary R. Hoffman
Farshad Hormozi
John J. Horwath
George G. Karady
Richard P. Keil
Mark J. Kempker
Hermann Koch
William O. Kramer
Thomas W. LaRose
Lawrence M. Laskowski
M. A. Lebow
David S. Lehman
H. Peter Lips
Jinxi Ma
Rusko Matulic
Gary L. Michel
Al J. Molnar
Jovan M. Nahman
Philip R. Nannery
Arun Narang
Benson P. Ng
Robert S. Nowell
Michael W. Pate
Carlos O. Peixoto
Mark A. Reynolds
Paulo F. Ribeiro
David Shafer
Rao S.Thallam
Bill Thompson
Duane R. Torgerson
John Vithayathil
Georg Wild
Peter S. Wong
Tim Wu

When the IEEE-SA Standards Board approved this standard on 30 January 2000, it had the following membership:

Richard J. Holleman, *Chair*
Donald N. Heirman, *Vice Chair*
Judith Gorman, *Secretary*

Satish K. Aggarwal
Dennis Bodson
Mark D. Bowman
James T. Carlo
Gary R. Engmann
Harold E. Epstein
Jay Forster*
Ruben D. Garzon
James H. Gurney
Lowell G. Johnson
Robert J. Kennelly
E. G. “Al” Kiener
Joseph L. Koepfinger*
L. Bruce McClung
Daleep C. Mohla
Robert F. Munzner
Louis-François Pau
Ronald C. Petersen
Gerald H. Peterson
John B. Posey
Gary S. Robinson
Akio Tojo
Hans E. Weinrich
Donald W. Zipse

*Member Emeritus

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

Robert E. Hebner

Noelle D. Humenick
IEEE Standards Project Editor

Contents

IEEE Guide for the Functional Specification of Transmission Static Var Compensators

1. Overview

1.1 Scope

This document provides general guidelines toward the preparation of a functional specification of transmission static var compensators (SVCs) using conventional thyristor technology. Many clauses will be useful for compensator systems using gate turn-off (GTO) thyristor technology [static compensator (STATCOM)] or other semiconductor devices, or SVCs associated with high-voltage dc (HVDC) converter stations, or industrial and distribution applications.

General terms and conditions forming the commercial part of a specification for a particular project are outside the scope of this document.

1.2 Purpose

Starting at Clause 4, this document presents technical clauses that may be used as the basis of a functional SVC specification. The wording deliberately uses “should” rather than “shall” because this document is a guide, not a specification. The user of this guide might wish to make this adjustment when converting clauses into a specification. Annex B of this document contains supplemental information intended to further develop specific clauses. Further information is referenced by the same subdivision numbering used in the main text.

1.3 Application

The guide should be considered a general purpose resource and does not include all details needed for a specific application. Likewise, because transmission SVCs are typically designed to address a specific application, not every part of this guide may be applicable. The user of this guide should evaluate how, and to what extent, each clause applies to the development of an SVC specification.

Clause 3 gives definitions such as a static var compensator (SVC), a static var system (SVS), and associated other reactive elements. This guide applies to the SVC.

2. References

This guide should be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

Accredited Standards Committee C2-1997, National Electrical Safety Code®,NESC®.[1, 2]

ANSI Std C63.16-1993, American National Standard Guide for Electrostatic Discharge Tests Methodologies and Criteria for Electronic Equipment.

BS EN 61803: 1999, Determination of power losses in high-voltage direct current (HVDC) convertor stations.[3]

IEC 60815-05: 1986, Guide for the selection of insulators in respect of polluted conditions.[4]

IEC 61954-09: 1999, Power electronics for electrical transmission and distribution systems—Testing of thyristor valves for static VAR compensators.

IEEE Std 18-1992, IEEE Standard for Shunt Power Capacitors.[5]

IEEE Std 80-1986 (Reaff 1991), IEEE Guide for Safety in AC Substation Grounding.

IEEE Std 139-1988 (Reaff 1999), IEEE Recommended Practice for the Measurement of Radio Frequency Emission from Industrial, Scientific, and Medical (ISM) Equipment Installed on User's Premises.

IEEE Std 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.

IEEE Std 693-1997, IEEE Recommended Practices for Seismic Design of Substations.

IEEE Std 1303-1994, IEEE Guide for Static Var Compensator Field Tests.

IEEE Std C37.90.1-1989 (Reaff 1994), IEEE Standard Surge Withstand Capability (SWC) Tests for Protective Relays and Relay Systems.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide the following technical terms and definitions apply. The IEEE Standard Dictionary of Electrical and Electronics Terms shall be referenced for terms not defined in this clause.

---

[1] The NESC is 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/).

[2] National Electrical Safety Code® and NESC® are both registered trademarks and service marks of the Institute of Electrical and Electronics Engineers, Inc.

[3] EN publications are available from the European Committee for Standardization (CEN), 36, rue de Stassart, B-1050 Brussels, Belgium (http://www.cenorm.be).

[4] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 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.

[5] IEEE 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/).

3.1.1 commercial operation: The acceptance, by the user, of the static var compensator (SVC) from the supplier.

3.1.2 contract start: The date a contract to supply a static var compensator (SVC) becomes effective, and the user has given notice to proceed.

3.1.3 control range: The total inductive plus capacitive range of reactive current or megavar variation of the static var compensator (SVC), at the point of connection.

3.1.4 lagging operation: Inductive megavars absorption of the static var compensator (SVC), similar to a shunt reactor.

3.1.5 leading operation: Capacitive megavars generation of the static var compensator (SVC), similar to a shunt capacitor.

3.1.6 mechanically switched capacitor (MSC): A shunt-connected circuit containing a mechanical power-switching device in series with a capacitor bank and sometimes also a damping reactor.

3.1.7 mechanically switched reactor (MSR): A shunt-connected circuit containing a mechanical power switching device in series with a reactor.

3.1.8 point of common coupling (PCC): The busbar from which other loads sensitive to voltage may be connected as well as the static var compensator (SVC) and any disturbing load it is required to compensate.

3.1.9 point of connection: For a static var compensator (SVC) with a dedicated transformer, the high-voltage (HV) bus to which the whole is connected. For an SVC connected to an existing transformer, or direct connected at low voltage, the busbar to which it is connected.

3.1.10 reference voltage: The point on the voltage/current (V/I) characteristic where the static var compensator (SVC) is at zero output (i.e., where no vars are absorbed from, or supplied to, the transmission system at the point of connection).

3.1.11 response time: The duration from a step change in control signal input until the static var compensator (SVC) output reaches 90% of required output, before any overshoot.

3.1.12 settling time: The duration from a step change in control signal input until the static var compensator (SVC) output settles to within ±5% of the required output.

3.1.13 slope: The ratio of the voltage change to the current change over the full (inductive plus capacitive) linearly controlled range of the static var compensator (SVC) at nominal voltage, expressed as a percentage.

3.1.14 STATCOM (static compensator): A static synchronous generator operated as a shunt-connected static var compensator (SVC), whose capacitive or inductive output current can be controlled independently of the ac system voltage.

3.1.15 static var compensator (SVC): A shunt-connected static var generator or absorber whose output is adjusted to exchange capacitive or inductive current to maintain or control specific parameters of the electrical power system (typically bus voltage).

3.1.16 static var system (SVS): A combination of different static and mechanically switched var compensators whose outputs are coordinated.

3.1.17 thyristor-controlled reactor (TCR): A shunt-connected thyristor-controlled inductor whose effective reactance is varied in a continuous manner by partial conduction of the thyristor valve.

3.1.18 thyristor-switched capacitor (TSC): A shunt-connected thyristor-switched capacitor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

3.1.19 thyristor-switched reactor (TSR): A shunt-connected thyristor-switched inductor whose effective reactance is varied in a stepwise manner by full- or zero-conduction operation of the thyristor valve.

3.1.20 voltage/current (V/I) characteristic: The relationship between the steady-state current of the static var compensator (SVC) and the voltage at its point of connection.

3.2 Acronyms and abbreviations

BIL	basic impulse level
CT	current transformer
EMI	electromagnetic interference
ETT	electrically triggered thyristors
FACTS	flexible AC transmission systems
GTO	gate turn-off
HV	high-voltage
HVDC	high-voltage direct current
LTT	light-triggered thyristors
LV	low-voltage
MSC	mechanically switched capacitor
MSR	mechanically switched reactor
PCC	point of common coupling
PT	potential transformer
RI	radio interference
RMS	root-mean-square
STATCOM	static compensator
SVC	static var compensator
SVS	static var system
SWC	surge withstand capability
TIF	telephone influence factor
TNA	transient network analyzers
TSC	thyristor-switched capacitor
TSR	thyristor-switched reactor
TVI	television interference
V/I	voltage/current

4. SVC project description

This specification is for the design, manufacture of equipment, construction, installation, test, commission, warranty, training, and placement into commercial operation of an SVC at _______ substation connected to the _______ busbar.

The purpose of the SVC is to regulate the voltage of the _______ kV busbar. The nominal ratings of the SVC are _______ Mvar leading at _______ kV to _______ Mvar lagging at _______ kV.

A regional and local site location map is shown in Figure ___. A proposed one-line diagram of the _______ substation after installation of the SVC is shown in Figure ___. The area for the SVC facility is shown in Figure ___. The points of electrical interconnection of the supplier-furnished SVC and the user-furnished facilities are shown on the following figures:

Figure ___

_______ (power circuit)
_______ (grounding)
_______ (station service)
_______ (control and protection)

and, for turnkey projects

_______ (fencing)
_______(site sub-surface and geotechnical data)
_______ (other)

The design and layout of the SVC facility should provide for future expansion requirements as shown in Figure ___.

See Annex B for additional discussion of the SVC specification.

5. Scope of supply and schedule

5.1 Scope of supply

The equipment, materials, and services to be furnished by the supplier include, but are not limited to, the following:

a) SVC thyristor valve and valve cooling equipment
b) High-voltage (HV) ac equipment, transformer, switchgear, circuit breaker, disconnects, potential transformers (PTs), current transformers (CTs), surge arresters, and grounding transformers
c) Reactors, capacitors, and harmonic filters
d) SVC station services
e) SVC yard control, protection, alarm and monitoring systems
f) Special maintenance equipment and tools
g) Training program for operation and maintenance personnel
h) Spare parts
i) Testing and commissioning services
j) Documentation including instruction manuals

For turnkey supply, the following are added:

k) Civil works for the SVC, including the switchyard, fencing, drainage, access, and parking
l) SVC building, including grounding
m) SVC foundations and structures to mount busbars, including grounding and ground mat connections

5.2 Equipment, materials, and services furnished by the user

The nonelectrical data to be supplied by the user is given in Clause 6; the electrical data is in Clause 7, Clause 8, and Clause 9.

The user should furnish the following equipment, materials, and services:

a) Site for the SVC available ___ calendar days after contract start

b) Source of water for construction

c) Source of temporary station service power for construction at _______ kV, available ___ calendar days after contract start

d) _______ sources of permanent station service power for the SVC at _______ kV, available ___calendar days after contract start

e) Existing facilities and equipment

5.3 Schedule

Project completion is ___ calendar days after contract start. The supplier's project schedule is due ___ calendar days after contract start and should include such details as dates for commencement and completion of work on several controlling features of the project, dates for user-furnished services, dates on which supplier-furnished drawings will be provided and approval given, and dates and length of time of any required power outages.

Design review meetings should be held between the user and supplier to review and discuss progress of the design and supply of the SVC. The first design review should be held within ___ calendar days after contract start. Subsequent design reviews should be held every ___ calendar days.

6. Site and environmental data

The SVC should be designed to meet all rating and performance requirements specified in this document while operating in the following site and environmental conditions:

a) Site elevation above sea level ___________ m
b) Maximum ambient dry-bulb temperature ___________ °C
c) Maximum ambient wet-bulb temperature ___________ °C
d) Minimum ambient air temperature ___________ °C
e) Maximum daily average ambient air temperature ___________ °C
f) Minimum daily average ambient air temperature ___________ °C
g) Ice loading conditions ___________ kg/m^2
h) Maximum ground snow depth ___________ m
i) Maximum frost depth ___________ m
j) Maximum steady wind velocity ___________ m/s
k) Wind gust factor or maximum wind gust ___________ m/s
l) Seismic zone and withstand data ___________
m) Isokeraunic level ___________ days/yr
n) Dust concentration (or pollution level per IEC 60815-05: 1986) ___________ mg/cm^2
o) Salt concentration ___________ mg/cm^2
p) Solar radiation level ___________ W/cm^2
q) Earth resistivity ___________ Ohm-m

7. Power system characteristics

The following ac power system characteristics apply at the point of connection prior to SVC installation. Normal SVC operation is required within the parameter values and durations given.

a)	Nominal ac system voltage, line-to-line	___________	kV
b)	Maximum continuous ac system voltage, line-to-line	___________	kV
c)	Minimum continuous ac system voltage, line-to-line	___________	kV
d)	Maximum short-term ac system voltage, line-to-line	___________	kV
e)	Maximum duration of item d)	___________	s
f)	Minimum short-term ac system voltage, line-to-line	___________	kV
g)	Maximum duration of item f)	___________	s
h)	Continuous negative-sequence voltage component	___________	%
i)	Continuous zero-sequence voltage component	___________	%
j)	Nominal ac system frequency	___________	Hz
k)	Maximum continuous ac system frequency	___________	Hz
l)	Minimum continuous ac system frequency	___________	Hz
m)	Maximum short-term ac system frequency	___________	Hz
n)	Maximum duration of item m)	___________	s
o)	Maximum rate of change of frequency (df/dt)	___________	Hz/s
p)	Minimum short-term ac system frequency	___________	Hz
q)	Maximum duration of item p)	___________	s
r)	Lightning impulse protective level (BIL)	___________	kV peak
s)	Switching impulse protective level	___________	kV peak
t)	Maximum three-phase fault current	___________	kA
u)	Minimum three-phase fault current	___________	kA
v)	Maximum single-phase fault current	___________	kA
w)	Minimum single-phase fault current	___________	kA
x)	Harmonic impedance sectors (for performance)	See Figure	___________
y)	Harmonic impedance sectors (for rating filter components)	See Figure	___________
z)	Background harmonic voltage (or current) spectrum (for rating filter components)	See Figure	___________

8. Main SVC characteristics

8.1 SVC rating

These clauses define the ratings of the compensator equipment.

a) The SVC should regulate the _______ kV bus voltage to a reference voltage of _______ kV (1.0 per unit), continuously adjustable between _______ per unit and _______ per unit.

b) The nominal capacitive reactive power output of the SVC at point A should be _______ per unit on 100 MVA base at 1.0 per unit ac bus voltage and nominal system frequency, and 20 °C ambient temperature. Refer to the voltage/current (V/I) characteristic on Figure 1.

c) The nominal inductive reactive power output of the SVC at point B should be _______ per unit on 100 MVA base at 1.0 per unit ac bus voltage (see Figure 1).

d) The nominal slope of the characteristic should be adjustable in steps of not greater than _______% between _______% and _______%, on a basis of _______ MVA (see Figure 2).

e) The SVC should continue to generate reactive power during a temporary undervoltage down to the value given in Clause 7 f) for the duration given in Clause 7 g) (point C on Figure 1); the SVC may be tripped if the undervoltage persists for more than _______ s.

f) The SVC should continue to absorb reactive power during a temporary overvoltage in a controlled manner up to the value given in Clause 7 d) for the duration given in Clause 7 e) (point D on Figure 1); the SVC may be tripped if the overvoltage persists for more than _______ s.

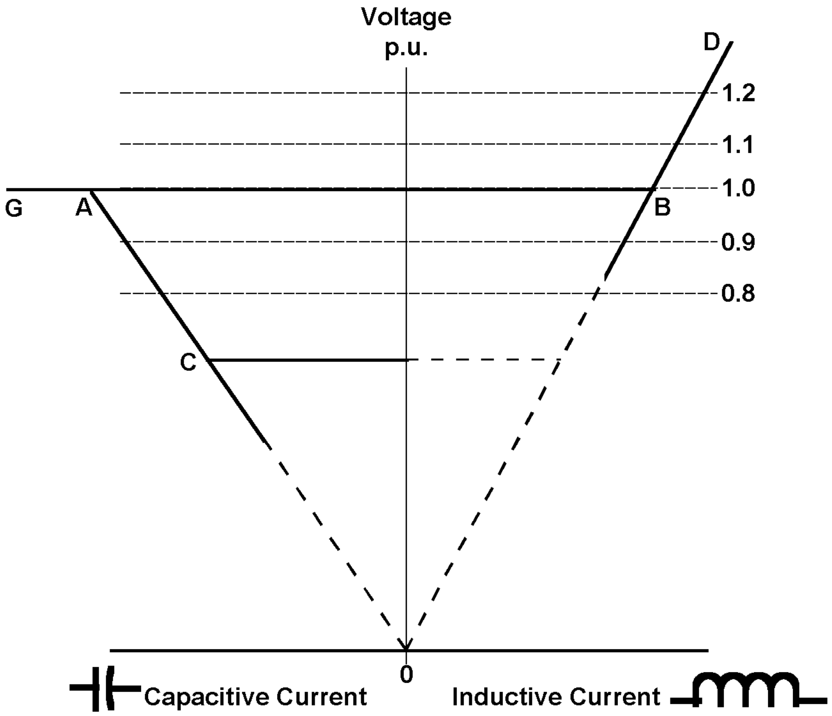


Figure 1—V/I characteristics of the SVC to define ratings at nominal voltage

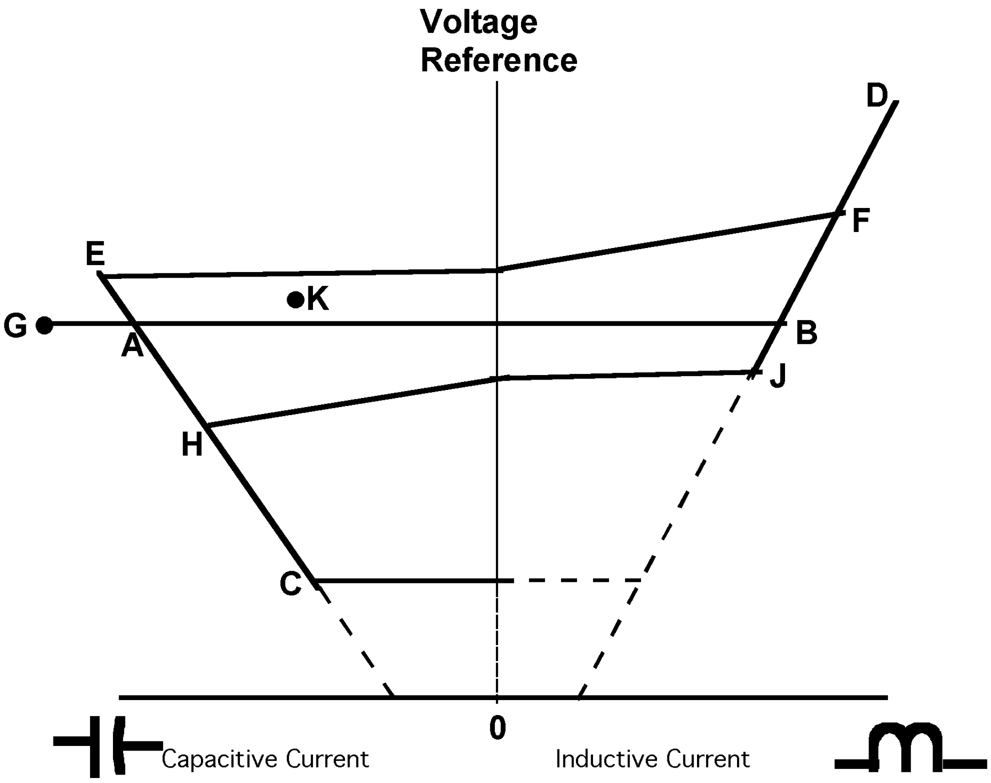
g) (Optional) The short-time capacitive reactive power output of the SVC should be _______ Mvar at _______ per unit ac bus voltage for _______ s (Figure 2, point G), following 1 h operation at or below the level specified under 8.1 b).

h) (Optional) Continued controllable conduction of the SVC to absorb reactive power should be possible up to _______ per unit ac bus voltage for _______ s, following 1 h operation at or below the level specified under item 8.1 c).

i) The SVC should be capable of repeating short-term operation as defined in any one of 8.1 e), 8.1 f), or 8.1 g) every _______ min.

j) The compensator transformer and all bus equipment such as filter branches, thyristor-switched capacitor (TSC) branches, thyristor-switched reactor (TSR) branches, thyristor-controlled reactor (TCR) branches, capacitor bank branches, and reactor bank branches [whether at HV or low-voltage (LV)] should be rated to withstand the specified continuous and short-term operation, and to withstand or be protected against voltage and current stresses that exceed these conditions.

k) All equipment in the SVC system should be capable of sustaining a fault unconstrained by the transformer impedance. Taken with its normally connected transformer, all SVC equipment should sustain, without damage, any internal fault no matter what fault level is available on the HV system(s).



A is defined by 8.1 b), giving the nominal capacitive susceptance, OA.
B is defined by 8.1 c), giving the nominal inductive susceptance, OB.
C is defined by Clause 7 f).

Below point C the SVC should normally block TSC branches and await a recovery of voltage before resuming normal action.

D is defined by Clause 7 d). It is on an extension of line OB.
E is an extension of line OA at maximum voltage reference and minimum slope.
F is an extension of line OB at maximum voltage reference and maximum slope.
G is defined by 8.1 g).
H and J give minimum voltage settings for continuous operation at maximum and minimum slope, respectively.
K is a most severe operating condition, chosen to define filter component ratings.

Figure 2—Detail of SVC characteristic (exaggerated scale)

8.2 Control objectives

8.2.1 SVC functions, with priority

The desired function(s) and the priority in which the SVC should respond to them are

a) Control of three-phase average or positive sequence of the fundamental voltage in steady state and post fault, with slope in the range of _______% to _______%.

b) Control of phase voltage based on
    1) Individual phase voltages
    2) Positive and negative sequence voltages
c) Control of voltage with superimposed reactive power control. The reactive power returns SVC output slowly to a preset steady-state value, so that its megavar capacity to support voltage is held in reserve.
d) Voltage control with superimposed damping control based on active power, speed, or frequency measurements to damp oscillations or to enhance the power transfer capability.
e) The SVC should not trip during the dead time of _______ ms during automatic reclosing operations.

8.2.2 Response

The change of measured system voltage should reach 90% of the desired total change within _______ ms of the initiating control signal of voltage reference. The maximum overshoot should not exceed _______% of the ordered change and the settling time should not exceed _______ ms, after which the voltage should be within _______% of the ordered value. This response is required when the system three-phase fault MVA is at the minimum value defined in Clause 7 (see Figure 3).

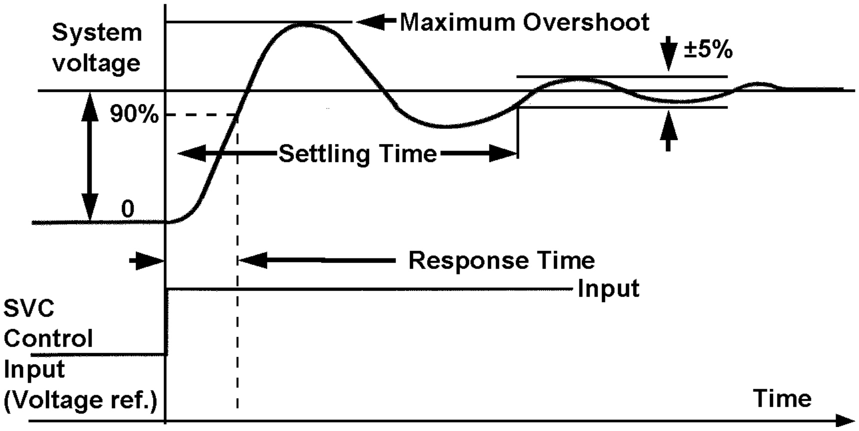


Figure 3—Response of the SVC

8.3 Harmonic performance

The SVC system should be designed to avoid resonance between its shunt capacitor banks, filter branches, and the ac system, and to limit the harmonic distortion imposed on the connected transmission system.

8.3.1 Filter performance

The maximum voltage distortion generated by the SVC should not cause the values shown in Table 11.1 of IEEE Std 519-1992 to be exceeded.

These requirements should be met for the following:

- The continuous range of system and environmental conditions stated in Clause 6 and Clause 7
- Variation in tolerance of total filter capacitance, including permissible fuse failures
- Variation in tolerance for SVC parameters, such as transformer winding unbalances, valve firing variations, and unequal reactor and capacitor reactance between phases

These performance requirements may be exceeded for system conditions outside the continuous normal envelope specified in Clause 7.

8.3.2 Filter component rating

The harmonic filter components (and other SVC components) should be rated to carry the harmonic currents caused by the background harmonic distortion of the system and the harmonic currents produced by the SVC itself. Unless otherwise specified, individual harmonic currents from the system and the SVC should be added quadratically (root sum of squares).

The rated voltage of capacitors should be not less than the arithmetic sum of the normal continuous power-frequency voltage and the largest of the individual harmonic voltages.

8.4 Telephone and radio interference

8.4.1 Telephone interference

Limits for telephone interference should be given, where applicable, as follows:

- The $I \times T$ product should be less than _______, where $I \times T$ is defined as the square root of the sum of the squares of harmonic current (I_n) and the corresponding weighting factor from the "C-message" weighting factors established by subclause 6.9.1 of IEEE Std 519-1992.
- The $kV \times T$ product, otherwise known as telephone influence factor (TIF), should be less than _______, where $kV \times T$ is defined as the square root of the sum of the squares of harmonic voltage (V_n) and the corresponding weighting factor from the "C-message" weighting factors established by subclause 6.9.1 of IEEE Std 519-1992.

8.4.2 Radio interference

The potential for higher frequency emissions should be limited to avoid interference with any properly licensed or authorized radio, television, microwave, or other equipment in service. In addition, the radio frequency emissions produced by the SVC should not exceed _______ μV/m over the range of 150 kHz to 1 MHz, when measured 500 m from the SVC station perimeter, except where overhead lines leave the station. The measurements should be made in accordance with IEEE Std 139-1988, based on quasi-peak detector readings.

8.5 Audible noise

The supplier should design and construct the SVC to limit the audible noise interior and exterior to the facilities. Audible noise limits outside the SVC building typically apply at the substation fence line. Inside the building, they apply at a specified distance (typically 3 m) from the emitting source and include the following:

a) Station fence __________ dB(A)
b) Within compressor areas __________ dB(A)
c) At a distance of _____ m outside of compressor area enclosure(s) __________ dB(A)
d) At a distance of _____ m outside of mechanical equipment areas __________ dB(A)
e) Maintenance workshop __________ dB(A)
f) Control rooms __________ dB(A)
g) Relay rooms __________ dB(A)
h) Other accessible rooms __________ dB(A)

The supplier should also be responsible for establishing existing audible noise levels prior to construction of the facilities and for preparation of a report. The final report should record audible noise levels prior to and after construction.

8.6 Loss evaluation

The bidder should supply the estimated or warranted total losses (kW) calculated in accordance with the equations in 8.6.1 through 8.6.7. It should be assumed that ambient temperature is _______ °C, the busbar voltage is _______ per unit, and the slope setting is _______ %. The SVC may not operate at these conditions, but they provide a common base for evaluation.

For each operating point, losses are calculated for the parts of the SVC in operation or connected, whether conducting current or not. If more than one combination of SVC parts might operate at a given output, both values should be given and separately summated, with explanation, and the average taken forward to the summation.

Losses in switchgear, busbars, cables, clamps, connectors, etc., are excluded. Losses associated with harmonic currents are also omitted from loss calculations for evaluation (though they should be considered to determine ratings of cooling plant and the like).

Losses in the equipment described in 8.6.1 through 8.6.7 should be included in the calculations.

8.6.1 Thyristor valves

See Annex C.

8.6.2 Transformer losses

The transformer losses are a function of the transformer resistance and the root-mean-square (RMS) fundamental current in the transformer and core and stray losses.

Transformer losses are normally measured on test at full load and no load. The no load losses should be stated at nominal voltage and no load, and should be taken as being consumed at all times.

The full load losses should be used to calculate an equivalent resistance of the transformer. Losses of the transformer at each SVC operating point required in 8.6.7 should then be calculated using this resistance and the predicted transformer current for that SVC output.

8.6.3 Reactor losses

The reactor losses are calculated from the rms fundamental phase current I.

$$P_{\mathrm{reac}} = 3 \times R_{\mathrm{reac}} \times I^2 \qquad (1)$$

R_{reac} is the fundamental frequency resistance. The reactor resistance values should be verified from the test report for the reactors. Tests of quality factor, Q, should be made with as many connections, clamps, shields, etc., as possible in position.

This calculation applies to TSC and filter reactors, TCRs, mechanically switched reactors (MSRs), and TSR reactors.

8.6.4 Capacitor bank losses (TSC, MSC, and filters)

In the test reports for each capacitor unit, the dissipation factors (tan delta) are given. An average value for all capacitor units is used to calculate the capacitor bank losses. The formula used is

$$P_{\mathrm{cap}} = Q_{\mathrm{cap}} \times DF \tag{2}$$

where

Q_{cap} is the actual capacitor kvar, and
DF is the capacitor dissipation factor, which should include the losses in capacitor fuses.

8.6.5 Resistor losses

The resistor losses are calculated

$$P_{\mathrm{res}} = 3 \times R_{\mathrm{res}} \times I^2 \tag{3}$$

where

R_{res} is the resistor resistance, and
I is the fundamental RMS phase current through the resistor.

8.6.6 Auxiliary system power

The power used by the auxiliary systems for pumps, fans, and building cooling and heating systems together with the power needed by each thyristor level is deduced for each specified condition of the ambient temperature and reactive power flow. Nominal auxiliary supply voltage is assumed.

8.6.7 Total loss evaluation

The losses for each equipment in operation (8.6.1 through 8.6.6) are summed for each load level (state whether capacitive or inductive) required and should be evaluated as follows:

Point 1 - _______ Mvar: $_______/kW × Calculated losses _______ kW = $ _______
Point 2 - _______ Mvar: $_______/kW × Calculated losses _______ kW = $ _______
. - _______ . . . . . .
. - _______ . . . . . .
. - _______ . . . . . .
Point n - _______ Mvar: $_______/kW × Calculated losses _______ kW = $_______
Total evaluation of losses = $_______ (4)

The $/kW values take into account the percentage of time the SVC is expected to operate at or near that Mvar output. The sum of the above loss values should be added to the first cost of the equipment to determine the total evaluated cost.

In addition, the supplier should provide a curve for the total operating losses over the entire steady-state operating range at a system voltage of _______ per unit.

8.7 SVC availability and reliability

8.7.1 Definitions

The following definitions apply.

a) Forced outages are outages caused by faults in the SVC equipment that result in loss of part or all of the essential functions of the SVC.

b) Scheduled outages are outages necessary for preventive maintenance to assure continued and reliable operation of the SVC. They may result in the temporary loss of part or all of the SVC.

c) Outage duration is the elapsed time in hours from the instant the SVC is out of service to the instant it is ready to be returned to service.

   The following will be included in outage duration:

   1) The down time required to determine the cause of an outage or to determine which equipment or units of equipment to repair or replace.
   2) The time required by system operators to disconnect and ground equipment in preparation for repair work and to remove grounds and reconnect equipment after repairs are complete. Delays caused by unavailability of qualified user personnel are not accumulated in the outage duration.
   3) Partial outage. If partial SVC output is available, the duration of equivalent outage should be calculated as the product of the derated condition duration and the proportion of the nominal output range that cannot be achieved during this period.

d) Annual availability is the annual equivalent availability for forced outages, both total and partial, in percent and is defined with duration in hours

$$\left[1-\sum\frac{\text{Duration of equivalent event}}{8760}\right]\times 100 \tag{5}$$

8.7.2 Required availability and reliability

Reliability performance is required of the SVC, as follows:

a) The annual availability for forced outages for the SVC should be at least _______%.

b) There should be less than _______ (number) forced outages of the SVC per year.

c) The bidder should state the expected or guaranteed average number and duration of scheduled outages per year.

d) The bidder should guarantee the quoted availability performance for ___ years from commercial operation. The supplier should be notified of major outages. During the guarantee period, the user should maintain records of the number and duration of forced and scheduled outages, hours of operation, and any other relevant data and should make those records available to the supplier upon request.

   If the actual performance is below the values stated in 8.7.2 a) and 8.7.2 b), the supplier should provide corrections and modifications to meet the availability guarantees at no extra cost to the user. The availability guarantee should then continue until ___ consecutive years of operation within the guaranteed values have been achieved.

e) Maintenance intervals should occur regularly for inspection and, where necessary, repair. The bidder should suggest the maintenance interval suitable for its equipment and should describe any condition monitoring offered.

9. Main components—required functions and features

All materials that will become a part of the completed work should conform to the specifications given in Clause 2.

9.1 Thyristor valves

9.1.1 Overall performance

The thyristor valves should be designed to ensure operation according to the overall performance requirements.

9.1.2 Value access

The design of the thyristor support structure should permit access by the user for visual inspection, routine maintenance, and component replacement.

9.1.3 Design robustness

The thyristor valve should be designed with individual thyristors and other components applied in a conservative manner with regard to their basic design parameters, as follows:

a) The thyristor valve should withstand maximum overvoltage and overcurrent stresses due to system faults and switching.

   TCR and TSR valves should be controllable up to the voltage given in Clause 7 b). TSC valves should be capable of blocking up to the voltage given in Clause 7 d).

b) The thyristor valve design should include an appropriate allowance for unequal voltage distribution across individual thyristors in the valve due to stray capacitor and component tolerances.

c) The SVC should be designed to prevent, or alternatively, to withstand, false firing events, i.e., the firing of any valve at an incorrect time in the cycle or when not ordered. The bidder should describe the details of prevention or withstand inherent in its design.

d) Each thyristor valve should be able to operate within component ratings, generally with at least one failed thyristor. The number of possible failed thyristors should be selected by the supplier, demonstrated to the user, and be consistent with the availability requirements of the SVC.

9.1.4 Maintenance

Thyristor monitoring and maintenance requirements are as follows:

a) A monitoring means to identify any thyristors that have failed should be provided.

b) The thyristor valves should be designed to allow easy replacement of failed thyristors. Other TSC, TCR, etc., or filter branches should be capable of continued service while a thyristor is being changed or during similar maintenance.

9.1.5 Valve protection

The bidder should state the methods of overvoltage protection of the valves and the voltage levels at which these protections operate, as follows:

a) TCR and TSR valves should be protected against overvoltage by a forced-firing system.

b) TSC valves should not be fired under overvoltage, and interlocks and latches should be provided to avoid false firing.

9.1.6 Testing

The bidder should submit a test program for the thyristor valves, including type tests and routine tests in the factory.

9.2 Thyristor valve cooling system

9.2.1 Liquid cooling (If applicable)

a) A closed-loop recirculating system should provide full heat rejection capacity with redundancy for pumps, heat exchangers, and fans, appropriate to the SVC availability requirements. The cooling system should be able to maintain full capacity at maximum ambient temperature and maximum SVC reactive power output. The cooling system should be able to operate at the lowest ambient temperature and zero output specified, and the bidder should describe how this operation is done.

b) Replacement of certain cooling equipment (e.g., pumps, fans, cooler unit), if defective, should be possible while the cooling system still operates.

c) A purifying loop to maintain liquid resistivity should be provided. The bidder should state the design value of liquid resistivity and describe methods of detecting and responding to abnormal conditions.

d) The quantity of deionising material should be sufficient for a period longer than the specified maintenance interval operation without replacement. Deionising materials should be replaceable without cooling system shut down. Instructions for frequency of inspection and change should be given.

   The bidder should describe the necessary maintenance actions and their frequency.

e) Maintenance of closed loop systems and make up for loss of liquid should not be required more than once a year.

9.2.2 Air cooling (if applicable)

a) An air cooling system should provide full heat rejection with redundancy in blowers, filtering, monitoring, and heat exchangers (if required). The cooling system should permit work on a defective unit without shutting down the system.

b) The bidder should describe the air filtering system and details of monitoring of the status of blowers, filters, and other components.

9.2.3 Cooling system protection

The cooling system should monitor its own operation and the condition of the cooling medium.

a) For liquid-cooled systems, the protection system should include, as a minimum, the following warning alarms:
   1) Depleted demineralizer (deionizing) cell
   2) Low water resistivity
   3) Low coolant level
   4) Primary pump stopped
   5) Primary fan stopped
   6) High coolant temperature

    7) Failure of pump cycling scheme

b) For liquid-cooled systems, the protection system should include, as a minimum, the following shutdown alarms, at different measured values than in 9.2.3 a):
    1) High temperature
    2) Low coolant level
    3) Both pumps stopped or blocked flow
c) For air-cooled systems, the protection system should include, as a minimum, the following warning alarms:
    1) Blower transfer
    2) High exhaust air temperature
    3) High differential pressure across the filter
    4) Low air flow.
d) For air-cooled systems, the protection system should include, as a minimum, the following shutdown alarms:
    1) Excessive exhaust air temperature
    2) Loss of air flow

9.3 Control equipment and operator interface

9.3.1 Control equipment

The control systems should achieve the functional objectives given in 8.2. The accuracy of voltage should be within ±_______% of the reference voltage. The accuracy of linearity of the slope delivered by the SVC should be ±_______% of the slope setting of current, expressed as a percentage of nominal current at maximum output.

The valves and controls should be designed to avoid any "cross-talk" interference between antiparallel thyristor pairs.

When TSC switching is included, the bidder should detail the method of coordination between TCR and TSC switching in and out in order to achieve smooth net output change. Depending on the control principle (e.g., regulator loop with measured current feedback), the deadband may also be frequency-dependent.

9.3.2 Operator interface

a) The control interface should provide for local and remote control points. Only one control point should be active at any one time and as determined by a master control point, but it should be possible to view plant status, control settings, and other SVC parameters at all control points.
b) The local control point should be near the SVC control hardware. It should permit the following control functions to be carried out at the local control point only, during commissioning and maintenance:
    1) Start and stop sequences
    2) Change of reference voltage and slope settings
    3) Alarm acceptance and, where appropriate, reset
c) Each control point should indicate as a minimum:
    1) Starting or stopping sequence in progress

2) Reference voltage and slope settings
3) The control point selected
4) Any other settings such as supplementary stabilizing signals
5) SVC “on” indication
6) SVC “off” indication
7) Three-phase high-side line currents of the main transformer
8) Total reactive power generated or absorbed by the compensator
9) Primary voltage, single phase
10) Secondary voltage, single phase
11) SVC branches in/out (where applicable)
12) Status and alarm information as follows (list)

9.4 Monitoring and protection

9.4.1 Monitoring

The central control unit should monitor its own operation and the operations of the various SVC components. Two levels of protection should be provided: warning and shutdown. The first-level alarm (warning) indicates that a problem exists, but that the equipment or its proper operation is not in immediate danger. The second-level alarm (shutdown) initiates a reduction in output range or a shutdown of the SVC due to equipment problems that might cause damage if left uncorrected.

The first-level alarms include the following as a minimum:

a) Auxiliary power supply failure; back-up supply in use
b) Cooling system fan or pump failure; back-up pump or fan is available
c) Cooling system problems (e.g., low water resistivity, primary pump stopped)
d) Capacitor failures can exist, but within an acceptable quantity
e) Loss of redundant thyristors
f) Branch availability
g) Loss of signal-measuring controlled busbar voltage, with the control continuing to maintain the last SVC operating point, unless the regulated busbar voltage is also the source of synchronizing voltage.

The second-level alarms include the following as a minimum:

a) Loss of all control power
b) Loss of cooling system rated capabilities
c) Loss of source of synchronizing voltage
d) Excessive number of capacitor failures
e) Excessive overcurrent in a thyristor valve
f) Loss of thyristors in excess of redundancy margin

The central control unit should also have a built-in protective system for self-monitoring.

9.4.2 Protection

General principles apply as follows:

a) The protection relays and equipment should receive their primary input from current transformers, potential transformers, etc., that are either supplied as part of the SVC equipment or, where indicated, provided by the user. Redundant protective functions should be included and demonstrated, but common PTs and CTs are acceptable.

b) All protection equipment and systems should be properly coordinated to prevent incorrect operations of the protection equipment or systems during normal SVC operation, including anticipated abnormal conditions on the transmission system of the user, as specified. Fail-safe principles should be applied throughout.

c) Security monitors or dependability monitors should be clearly indicated in the system requirements.

9.4.3 Component protection

The following is a list of the possible required protection. Additional protection may be provided if deemed necessary.

a) Main transformer
    1) Overcurrent
    2) Overtemperature (e.g., liquid, hotspot)
    3) Differential
    4) Ground fault
    5) Gas accumulation
    6) Sudden pressure relay

b) Main reactors
    1) Overcurrent

c) Capacitor banks (or filters)
    1) Overcurrent
    2) Unbalance
    3) Neutral unbalance

d) Bus
    1) Overcurrent or current differential
    2) Ground fault

e) Thyristor valves
    1) Overcurrent
    2) Overvoltage
    3) High junction temperature

f) Master control
    1) Loss of control power
    2) Loss of synchronization signal

9.5 Reactors

Dry, air-cored reactors for outdoor use are preferred.

The magnetic field strength at any point where personnel have access during operation should not exceed _______ mT.

All structural and fence metalwork, including foundations, should be designed to avoid, as far as possible, metallic loops and parallel circuits in which induced currents can run.

9.6 Capacitor banks

Shunt capacitor banks should include capacitor units and protective fuses, suitably connected in series and parallel groups, and an unbalance protection scheme in each capacitor bank to indicate possible capacitor failure.

9.7 Power transformers

The transformer should be designed to carry 100% reactive current. Taps (on load or off load) are not required. The winding insulation class should be consistent with system data (see Clause 7).

The transformer should be capable of carrying the harmonic currents and sustaining the voltage levels associated with the SVC under all normal operating conditions without loss of life. The transformer should be capable of carrying a certain level of dc consistent with the SVC design.

Tests should be made in accordance with the latest revision applicable of IEEE or IEC standards for power transformers.

To ensure minimum harmonic generation, the saturation flux density of the transformer should be higher than the maximum flux density reached during normal operation, and the bidder should state the margin by which it is exceeded. The bidder should also state the steel quality to be used and its reasoning for selecting the margin. This maximum flux density is obtained at the highest secondary voltage during any reactive power generation, highest reference voltage, minimum slope, and minimum continuous frequency.

9.8 Disconnect and grounding switches

Grounding equipment for maintenance and repair should be supplied with each separate circuit (e.g., TCR, TSC, filter) that can be out of service while the remainder of the SVC continues in operation. Grounding equipment for the SVC secondary bus system and for the transformer should also be supplied.

Where it is required that an SVC circuit be isolated, disconnect switches should be supplied.

Disconnect switches and links should be adequately sized to carry the maximum steady-state current that can flow in it (square root of the sum of the squares of the fundamental and harmonic currents), and the momentary currents due to faults.

9.9 Auxiliary power supplies

The SVC equipment should include all the power supplies necessary for its operation, including step-down transformer, ac distribution boards, batteries, battery chargers, etc. The power supplies should be sufficient to supply all pumps, fans, valves and valve controls, and building cooling and heating systems.

10. Spares

The basic supply of the SVC should include a full complement of essential spare parts, which are to be furnished at the same time and as part of the SVC supply. It is the supplier's responsibility, based on the particular design for the SVC, to provide adequate spare parts to meet the reliability and availability requirements specified.

10.1 Spares strategy

A strategy for spare parts should be developed to demonstrate that the complement of spare parts will be adequate to meet the reliability requirements specified.

a) The spares strategy should be based on a tabulation of all of the components in the SVC, down to the level of the lowest "replaceable module." (In other words, all components suitable for unit replacement at the first level of maintenance should be included in the tabulation, but individual devices that would not be replaced except as part of a shop or bench repair of a replaceable component should not be in this tabulation.)

b) Each component in the tabulation should be identified for its importance to the operation of the SVC, according to the following classification:
    1) Category A: SVC operation is not possible until this component has been repaired or replaced (e.g., main step-down transformer, shunt reactor).
    2) Category B: SVC operation can continue (or resume) at reduced rating, but further failures may lead to an SVC outage (e.g., TCR, TSC, MSR, MSC).
    3) Category C: SVC operation can continue on an emergency basis, but a critical function has been lost or bypassed. Some risk of further complications or equipment damage exists until the function is restored (e.g., one of two pumps out of service, protective relaying, UPS, or cooling alarm sensors not in service).
    4) Category D: Operation can continue without serious impairment (e.g., building services such as lighting or heating).

c) The tabulation should include the failure rate or the expected replacement rate of the component over a 10-year period.

d) The tabulation should include the manufacturer's name and model number, suggested source, and estimated delivery cycle.

Each device should either be:

- Included on an inventory list of all site spares. The inventory list should show the description, quantity, and storage location of each spare, assuming that any time that a spare is used, the item is reordered.
- Provided with a contingency plan to obtain a replacement on short notice, if a spare is not being kept on hand.

10.2 Spare parts storage

The spare parts for the SVC should to be stored on site, and the SVC project should be designed to include suitable storage facilities. Where appropriate, storage arrangements for indoor and outdoor equipment should be seismically qualified.

10.3 Spare parts accounting

An inventory of the spare parts should be prepared at the time when the SVC is turned over to the user and again at the end of the warranty period. Any shortages should be replenished by the supplier so that the spare parts inventory is at its 100% level at the end of the warranty period.

11. Engineering studies

Engineering studies should be performed within the scope of supply. These studies are in addition to the actual SVC design studies and performance tests. The studies should demonstrate that the SVC meets all specified performance criteria. Acceptance by the user does not absolve the supplier's overall responsibility for the proper functioning of the SVC as specified. The bidder should list all engineering studies. Engineering studies should include, but not be limited to, the studies described in 11.1 through 11.3.

11.1 Dynamic performance studies

Transient and dynamic stability studies verify SVC control system performance during system disturbances, such as major faults and load rejection, and evaluate all functions specified.

a) Study of start-up, including transformer energization, shutdown, and other switching events
b) Study of response time and of the SVC's behavior and contribution to the system's recovery from faults
c) Study of SVC protection and protection coordination
d) Insulation coordination (including dynamic overvoltages, lightning, and fault and switching transients) to determine insulation levels, clearance, and arrester ratings
e) Studies to verify the operation of any supplementary controls designed to damp power oscillations following system disturbances if these controls are to be included
f) Studies to evaluate the interaction of the SVC controls with the other nearby control systems, including HVDC controls, generator controls, and controls of other flexible AC transmission systems (FACTS) devices

11.2 Harmonic performance studies

Studies to verify the adequacy of the SVC harmonic filter design through simulation of the power system response to SVC harmonics. The studies should evaluate maximum harmonic levels at the SVC point of common coupling (PCC).

Determination of maximum system harmonic levels should be based on, and the study reports should include, the following:

a) Evaluation of specified system operating conditions, including maximum and minimum system voltage levels, and maximum and minimum reactive power output of the SVC
b) Evaluation with maximum filter component tolerances
c) Evaluation with maximum system voltage unbalance and firing angle unbalance for noncharacteristic harmonic generation
d) Evaluation of possible resonant overvoltages
e) Evaluation of the filter thermal ratings based on specified operating conditions
f) MSR and transformer saturation induced harmonics

11.3 Transient overvoltage studies

Transient overvoltage studies should be performed with the actual controls modeled to verify that the SVC equipment is adequately protected against overvoltages and overcurrents (including excessive valve recovery voltages) resulting from power system transients and credible SVC system maloperations. Verification is required that system harmonics do not affect the SVC controls under steady-state or transient conditions. Concerns that should be evaluated include the following:

a) Faults on the high-voltage and low-voltage bus (single line-to-ground, phase-to-phase, and three-phase)

b) Faults across TCR or TSC

c) The potential for false-firing of any valve under the most severe system conditions

12. Tests

Coordination with field tests in IEEE Std 1303-1994 should be required.

12.1 Factory tests of valves

Refer to the following guidelines or use them to specify SVC thyristor valve factory tests recommended per IEC 61954-09:1999.

12.1.1 Type tests for TSC, TSR, and TCR valves

a) Dielectric tests
    1) Between valve terminals and earth
        i) AC
        ii) Switching impulse
        iii) Lightning impulse
    2) Between phases (for multiple valve units only)
        i) AC
        ii) Switching impulse
        iii) Lightning impulse
    3) Between valve terminals
        i) AC
        ii) Switching impulse

b) Operational tests
    1) Periodic firing and extinction
    2) Positive voltage transient during recovery
    3) Overcurrent with subsequent blocking
    4) Without blocking
    5) Minimum ac voltage
    6) Temperature rise
    7) Nonperiodic firing

c) Electromagnetic interference (EMI) tests
    1) Firing and extinction

12.1.2 Production tests

a) Connection check. To check that all the main current-carrying connections have been made correctly.

b) Voltage-grading circuit check. To check the grading circuit parameters and thereby ensure that voltage division between series-connected thyristors will be correct.

c) Voltage withstand check. To check that the valve components can withstand the voltage corresponding to the maximum value specified for the valve.

d) Check of auxiliaries. To check that the auxiliaries (e.g., monitoring and protection circuits) at each thyristor level and the auxiliaries common to the complete valve (or valve section) function correctly.

e) Firing check. To check that the thyristor(s) in each thyristor level turn on correctly in response to firing signals.

f) Pressure test. To check that no liquid leaks exist (for liquid-cooled valves only).

g) Test on individual valve components. All components of the valve should be subjected to rigorous testing, inspection, and quality assessment.

12.2 Factory tests of controls

SVC control function type tests on a simulator should include the following:

- Verification of each control function
- Verification of control linearity
- Verification of control redundancy
- Verification of the monitoring system
- Verification of the protection system
- Verification of overall system performance for minor and major system disturbances
- Verification of processor loading of all digital controllers
- Verification of SVC parallel operation with other controls in the system and control stability
- Verification of control equipment performance for auxiliary power supply voltage (ac and dc) and frequency variations (ac)
- Climatic test, i.e., verification of control equipment performance for a specified range of ambient temperatures and humidity. If climatic test certificates are available for the conditions specified, no further tests are needed
- Interference tests, i.e., the controls should be tested to operate in the environment of ac substations and suitable surge withstand capability (SWC). Tests should be carried out, or proof of previous testing provided, in accordance with IEEE Std C37.90.1-1989 (covering fast transient burst and a damping oscillatory wave) and ANSI Std C63.16-1993 (electrostatic discharge tests).

Routine production tests of all control functions, and separately of all protection functions, should be made to demonstrate manufacturing quality.

13. Documentation

User should specify the documentation required. Examples are given in Annex B.

14. Training

The supplier should be responsible for providing a training course, at the user's specified location, which will cover the information listed in this clause. The training course can assume that user's personnel are well-acquainted with substation equipment, including control protection and communications, but not versed in power electronics.

The training course should cover the following for operations personnel:

- Description of the system objective and function of the SVCs, including specified performance
- Valves
- Master control and operator interface, access, etc.
- Adjustable settings and reasons for their selection
- Simulator testing of controls
- Protection principles
- Operations manuals (see Clause 13)

The training course should cover the following for maintenance personnel:

- Description of the system objective and function of the SVCs, including specified performance
- Valves
- Valve testing
- Master control and operator interface, access, etc.
- Valve access, and test equipment and procedure
- Valve component replacement procedure
- Master controls operator interface test and replacement procedures
- Valve base electronics test and replacement procedures
- Protection principles and tests
- Cooling equipment and its maintenance
- Cooling controls and their maintenance
- Other specialist equipment (e.g., zero-flux CTs, PTs, and reactors
- Operation and maintenance manuals (see Clause 13)

The manuals should be available as texts for each course.

15. Balance of plant

15.1 Buildings and structures

The building should be of a type and design selected by the supplier to meet the functional requirements of the SVC and of the user.

a) The building should be arranged to house the thyristor valves, SVC controls, and other indoor equipment including spare parts. It should take into account the environmental needs of this equipment and the need to gain access to the equipment for operation and maintenance.

b) The building services should include heating, lighting, ventilation, and air conditioning, as appropriate, for occupied areas or as required to meet the requirements of the installed equipment.

c) The building design should follow all applicable local codes and ordinances.

d) The SVC equipment structures should be designed to meet the requirements of the SVC apparatus [including wind and ice loading, fault-current forces, grounding, lightning protection, and seismic (if applicable)]; and designed in accordance with the equipment supplier's recommendations and nationally recognized standards, such as the National Electrical Safety Code®, (NESC®).

15.2 Fire protection

The building (and especially the thyristor valve hall and control room) should be equipped with a fire detection system. The fire detection system should be designed as follows:

a) The failure of any single fire or smoke detector should produce a warning or trouble alarm, but should not either cause a false "fire detected" alarm or disable the overall fire detection system.

b) The detection of an actual fire should cause the SVC to be shut down and be isolated from the source of primary electrical energy.

c) Adequate safety equipment (including alarm communication panels, breathing equipment, and evacuation equipment) should be provided in accordance with local regulations [e.g., Occupational Safety and Health Administration (OSHA)].

15.3 Site requirements and conditions

15.3.1 Construction surveys

Prior to beginning any phase of survey work, the supplier should submit to the user a proposed plan to demonstrate that the lines and grades established by the supplier will meet the requirements specified.

15.3.2 Site conditions

The user should provide the site for permanent installation and rights of way for access. The supplier should be permitted to use such land for construction purposes.

Other items to consider include the following:

a) Protection of existing installations
b) Geological investigations
c) Electric power for construction purposes
d) Water for construction purposes

15.3.3 Safety and health

The supplier should incorporate a safety and health program and take all reasonable precautions to protect the safety and health of employees and members of the public and to prevent damage to public and private property. The safety and health program should be submitted to the user for approval at least ___ days prior to start of construction operations. The program should consider safety meetings, accident records and reporting, personal protective equipment, excavation, structure erection, equipment, environmental quality protection, and safety issues related to substation and transmission line clearances, hot-line orders, and special work permits.

Annex A

(informative)

Bibliography

[B1] Benmoyal, G., et al., "Behaviour of the Overvoltage Protection on the TSC Branch of Static Compensators Exposed to Harmonics and Replacement Strategy," CIGRE SC 34 Colloquium, Antwerp, Belgium, 1993.

[B2] Bonneville Power Administration and Western Area Power Administration, An annotated bibliography of HVDC Transmission and FACTS devices, 1991-1993.

[B3] Bonneville Power Administration and Western Area Power Administration, An annotated bibliography of HVDC Transmission and FACTS devices, 1994-1995.

[B4] CIGRE Publication 25, Static Var Compensators, Working Group 38-01, (I. A. Erinmez, editor), 1986.

[B5] CIGRE Publication 37, Analysis and Optimization of SVC Use on Transmission Systems, Working Group 38-05, 1993.

[B6] Forrest, J. A. C., "Harmonic Load Losses in HVDC Converter Transformers," IEEE Transactions, Power Delivery vol. 6, no. 1, pp. 153–157, Jan. 1991.

[B7] IEC 61000-4-1: 2000, Electromagnetic compatibility (EMC)—Part 4-1: Testing and measurement techniques—Overview of IEC 61000-4 series

[B8] IEEE Std 857-1996, IEEE Recommended Practice for Test Procedures for High-Voltage Direct-Current Thyristor Valves.

[B9] IEEE Std 100-1996, The IEEE Standard Dictionary of Electrical and Electronics Terms, 6th edition.

[B10] IEEE Std 1158-1991 (Reaff 1996), IEEE Recommended Practice for Determination of Power Losses in HVDC Converter Stations.

[B11] IEEE Std C57.110-1986 (Reaff 1992), IEEE Recommended Practice for Establishing Transformer Capability When Supplying Non-Sinusoidal Load Currents.

[B12] IEEE/PES PSRC Working Group, "Static Var Compensator Protection," IEEE Transactions on PWRD, vol. 10, no. 3, pp 1224–1333, July 1995.

[B13] IEEE Publication 320-2 PWR, Static Var Compensators Planning Operating and Maintenance Experiences, 1990.

[B14] Miller, T. J. E., "Reactive Power Control in Electric Systems," A Wiley Interscience Publication, John Wiley and Son, 1982.

Annex B

(informative)

Notes for a functional specification

This annex provides comment and discussion on the preparation of an SVC specification. Reference should be made throughout this clause to the corresponding specification clauses. For ease of reference, the corresponding clauses from the main text have been referenced. The term “user” may include purchaser and consultant.

B.1 SVC project description, see Clause 4

B.1.1 Purpose of an SVC

The basic action of an SVC is to change the generation or absorption of reactive power rapidly, in response to a control signal. In most applications, the action is to control a given busbar voltage. Sometimes the purpose is to contribute directly to the reactive power balance at a particular point in an electrical system.

In most transmission networks, the voltage at various points is largely dependent on the power and reactive power flows between them. Changing the flows, by changing the supply of available vars at a node in the network, results in a change in the voltages of the network. An SVC, therefore, brings the ability to regulate the voltage of a power system by means of appropriate control of reactive generation and absorption at a point in the system.

Where the user has not determined the final ratings and requires studies as part of the contract to make a final definition, a base rating may be specified for bidding and evaluation. SVCs applied in distribution systems are typically less complex than transmission SVCs in their design, manufacture, operation, and maintenance. Industrial SVCs are typically applied at or near a load center to mitigate voltage fluctuations, flicker, phase unbalance, or other load-related disturbances. This guide does not specifically address industrial and distribution SVCs although many features of the guide may be applicable. Similarly, it does not specifically address a STATCOM, although almost all clauses would be relevant to its application to transmission systems.

The wording of Clause 4 anticipates the normal usage of an SVC as being the control of voltage, but an SVC can improve various aspects of power system quality by suitable control action. The improvement of one aspect will sometimes degrade another, however, and it may therefore be necessary to set priorities and/or limits to control actions and their effects. The following are ten main functional objectives in power system performance for which an SVC may be used; the user is invited to select from these objectives and to insert them in Clause 4, giving the priority required. The specific control functions in Clause 8 will follow from these objectives.

a) Voltage control
    1) Steady state voltage control

       The controlled voltage may be at a different point from the point of connection of the SVC.

    2) Voltage stability

       To increase the capacity of a circuit that is limited by low voltage at the receiving end.

To restore busbar voltage to normal after a system disturbance, e.g., due to a fault or load rejection

3) System stability

To increase capacity that is limited by dynamic stability between machines or machine groups. Transmission capacity in such cases may be limited by voltage excursions on certain busbars, and the action of the SVC may be to limit these excursions to acceptable values.

4) Power oscillation damping

The deliberate adjustment of SVC reference voltage is also possible to increase the overall damping of power system oscillations following a disturbance, usually in the range of 0.2 to 2.0 Hz, on the network close to the SVC. Power or frequency measurements are made, combined, and fed into a supplementary control function, which will produce a modulating output, optimized for gain and phase shift, for the range of frequency oscillations for that part of the network.

b) Reactive power control

5) Coordination of var contributions from other equipment

To control the switching of shunt capacitors and reactors.

6) Fast correction of variable loads

The generation or absorption of vars to counteract the effect on voltage of the variation of power and var demand of loads that are balanced between phases but variable in time (e.g., convertor-fed drives for rolling mills).

7) Fast correction of power factor

The generation and absorption of vars to meet a particular demand of a load or group of loads or to counteract a flicker-generating load.

8) The correction of unbalance

The generation or absorption of vars asymmetrically between the phases to counteract the negative phase sequence components of loads or system components. The action can balance phase voltages by adding reactive loads in two phases to offset an active load in the other phase.

c) Control of non-power frequency effects

9) Harmonic filtering

To reduce the harmonic voltage distortion caused by either the harmonic currents generated by the SVC itself or other system components.

10) Subharmonic filtering

The SVC cannot be expected to contribute to the removal of all subsynchronous currents or resonances. However, it may, by suitable control responses in the appropriate frequency range, either avoid worsening them or provide a counteracting effect.

If more than one objective is selected, it is important that the user specify the priority in which the SVC is to respond to the objectives.

B.2 Scope of supply and schedule, see Clause 5

Transmission SVCs typically include several of the following power circuit elements:

- Interconnecting power transformer
- Switchgear
- Shunt-connected TCRs and/or shunt-connected TSCs
- Shunt-connected TSRs
- Fixed shunt capacitor filter banks.

The user should define whether the SVC will be supplied on a “turnkey” basis or as equipment only. In either case, it is important to describe all equipment and services required of the supplier (i.e., which items are included in 5.1 and which in 5.2).

The physical scope of an SVC supply should carefully describe the interfaces between the SVC supplier and all other entities. For example, the interfaces often include:

- The point of connection at power circuit entry
- The point of interconnection for station service power
- All communications and operator control interfaces
- Infeed of voltage and current signals (e.g., from the PCC if it is outside the scope of supply)
- Other physical interfaces that may exist at the SVC substation fence boundary (e.g., water supply, sewer, driveway)

If any mechanically-switched capacitor (MSC) or MSR is required or already exists, it should be described here. If the equipment is to be installed in an existing building, this requirement should be described here.

The time scales and extent of service and monitoring by the user should be stated.

B.3 Site and environmental data, see Clause 6

It is important to specify all local site and environmental conditions for which the SVC will be designed.

The SVC should be designed to meet ambient environmental and system conditions. Usually, the user has the best information on, and access to, the soil and ground conditions at the site, but surveys sometimes need to be carried out. The user should also understand that unnecessarily onerous ambient design conditions may increase the price of the SVC. With this understanding in mind, the design environmental and system conditions should be clearly specified by the user.

Possible additional information for Clause 6 is as follows:

a) Atmospheric pollution levels can be given as light, medium, heavy, or very heavy, per IEC 60815-05: 1986.

b) If evaporative or once-through cooling water may be used for heat rejection, its availability and chemical content should be given.

c) The SVC should continue to operate correctly, without protective tripping, up to a seismic event defined by appropriate event spectra for the region in question. In many cases only the maximum simultaneous horizontal and vertical acceleration can be specified (IEEE Std 693-1997).

d) The SVC should safely shut down and de-energize during a seismic event beyond the level or outside the spectra defined in c) (IEEE Std 693-1997).

B.4 Power system characteristics, see Clause 7

This clause describes the power system to which the SVC will be connected. The data defines both the normal and extreme conditions at the SVC station for which the SVC will be required to continue in uninterrupted operation.

The following items might be added:

a) Existing surge arrester data
b) Existing local generators and associated torsional modes of frequency
c) Existing circuit breaker and circuit switcher characteristics
d) Existing ac relay characteristics and configuration
e) Existing power line carrier equipment and characteristics
f) Existing fault disturbance and event recorders
g) AC system topology in local vicinity

It may be desirable to specify additional values of the following to represent extreme operating conditions [i.e., the more severe conditions for which the SVC should remain connected (and, therefore, able to respond normally as soon as conditions recover) but not necessarily act normally]. These values and the required response should be given with the data in Clause 7. It is, therefore, implied that, beyond these conditions, the SVC may act to protect itself, as follows:

h) Maximum continuous ac system voltage
i) Minimum continuous ac system voltage
j) Maximum temporary ac system voltage (level and duration)
k) Minimum temporary ac system voltage (level and duration)
l) Maximum continuous ac frequency
m) Minimum continuous ac frequency
n) Maximum temporary ac frequency (level and duration)
o) Minimum temporary ac frequency (level and duration)
p) Maximum rate of change of system frequency (df/dt)
q) Maximum negative sequence voltage component (% of fundamental)
r) Maximum zero-sequence voltage component (% of fundamental)

If the SVC is to be connected to an existing transformer's tertiary winding, it is necessary to describe this transformer and give its full name-plate details and the potential short-circuit current at the tertiary terminals. The busbar voltage that is to be controlled by the SVC action should be identified (see Clause 4). It is necessary to take into account that, because of the inherent coupling between the primary and secondary windings, the control of one busbar may have an adverse effect on the voltage of the other.

Instead of supplying item (X) of Clause 7, the user may prefer to supply system data and require the contractor to perform calculations of the system's harmonic response. The data should include load flow data and any known harmonic responses of individual items.

If known, data of the existing harmonic currents in the system are most valuable. All power systems carry harmonic currents to some degree, and a new filter will act as a sink for them. Estimates of how large such currents might be are necessary whether they are made by the user or the supplier.

B.5 Main SVC characteristics, see Clause 8

The detailed SVC design will depend upon the user's specification of the following:

- Steady-state and short-term (overload) reactive power and voltage ratings
- Control objectives and performance
- Harmonic performance
- Losses
- Reliability and availability requirements

B.5.1 SVC rating, see 8.1

B.5.1.1 From 8.1 a), b), c)

Where an SVC controls the voltage of a busbar different from its connection point, add "the nominal ac bus voltage to which the SVC is connected is _______ kV and 1 per unit refers to _______ kV."

The usual primary requirement of the SVC is that it will support the network voltage in post-fault and/or heavy load conditions in order to increase the power transmission capability. It may also be required to limit voltage variations caused by the daily load cycle and to minimize temporary overvoltage conditions or to achieve other objectives outlined in Clause 4.

It will normally help to clarify the user's requirements and the supplier's responsibility by using the so-called voltage current characteristic of V/I diagram (see Figure 1) to describe and define the steady state and overload operating regions and their impact on SVC component rating. It is recommended that the base ratings (points A and B in Figure 1) be defined at 1 per unit voltage.

System studies are frequently carried out using a per unit system with, commonly, 100 MVA equal to 1 per unit. This value is convenient for the user to adopt when specifying an SVC. The rated line-to-line voltage is normally the base value, equal to 1 per-unit voltage. The rating of an SVC in Mvar is described as the product of rated line-to-line voltage, rated line current, and the $\sqrt{3}$. In per-unit terms, with the rated voltage equal to 1 per unit, the per unit rated Mvar of the SVC is equal to the per-unit rated current on a base of 100 MVA. If the SVC is to achieve rated current at other than 1 per unit voltage, such extra points require definition.

The nominal capacitive and inductive ratings of the SVC are defined respectively as operating points A and B in Figure 1. The continuous operating range of the SVC is typically specified by bounding the allowable continuous capacitive voltage range and the allowable continuous inductive voltage range. A more detailed overvoltage cycle, based on user experience can be specified to ensure bidders design to a common basis.

B.5.1.2 From 8.1d)

Slopes above 5% are rare.

B.5.1.3 From 8.1 e), f)

The short-term operating range of the SVC is typically specified by bounding the allowable short-term capacitive voltage range (for magnitude and duration) and the allowable short-term inductive voltage range.

Point D in Figure 1 covers transient and dynamic overvoltages in the system and typically lies in the range of 1.3 per unit to 1.8 per unit.

The temporary minimum operating voltage of an SVC should be specified; a value of 0.4 or 0.5 has sometimes been specified on the basis that a voltage below that level indicates a severe fault condition for which it is better not to switch on capacitors. Otherwise, temporary overvoltages could be made worse when the fault is cleared and voltage recovers. An example of an operating SVC characteristic is given in Figure B.1.

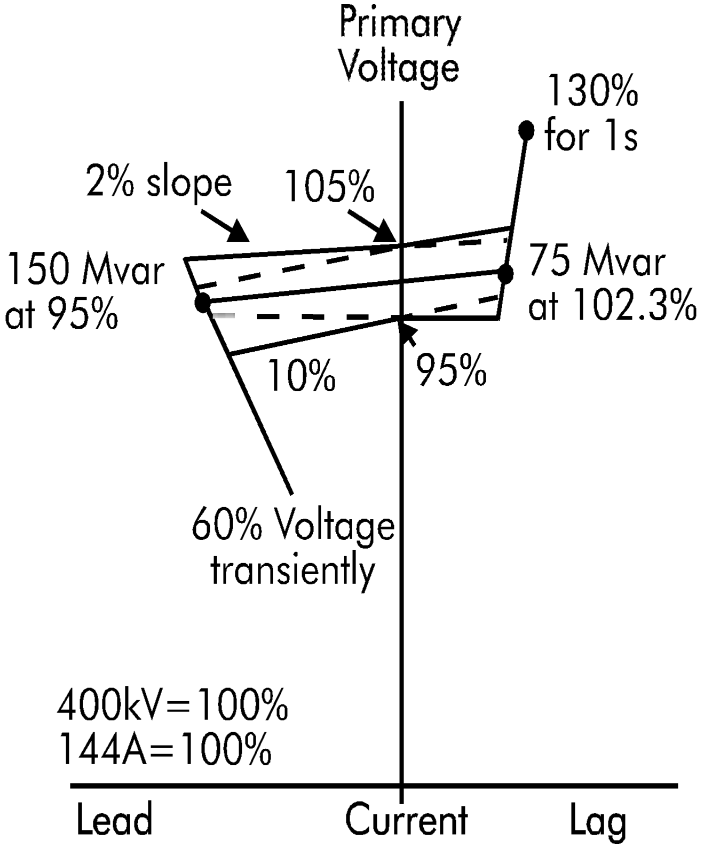


Figure B.1—An Example of an SVC Characteristic

B.5.1.4 From 8.1 h)

The maximum operating voltage of a TCR or TSR is bound by the thyristor junction temperature that will permit blocking for control. If the TCR or TSR is continuously firing (i.e., fully on) no blocking of thyristors occurs. The junction temperature is a function of the through current, but is of no significance unless the thyristor is required to block, i.e., withstand full voltage. Blocking may be required when system voltage has returned below extreme values. Should high junction temperatures persist, continuous firing should be continued for a few cycles longer to allow the thyristors to cool although control will be temporarily lost.

With this possibility in mind, the user may wish to specify a short-term high-voltage situation, so that the SVC may give all possible assistance at times of system stress by specifying an “overload cycle,” such as Figure B.2, where overvoltages and duration periods are specified. The SVC should be able to recover normal control ability at the start of the continuous period shown.

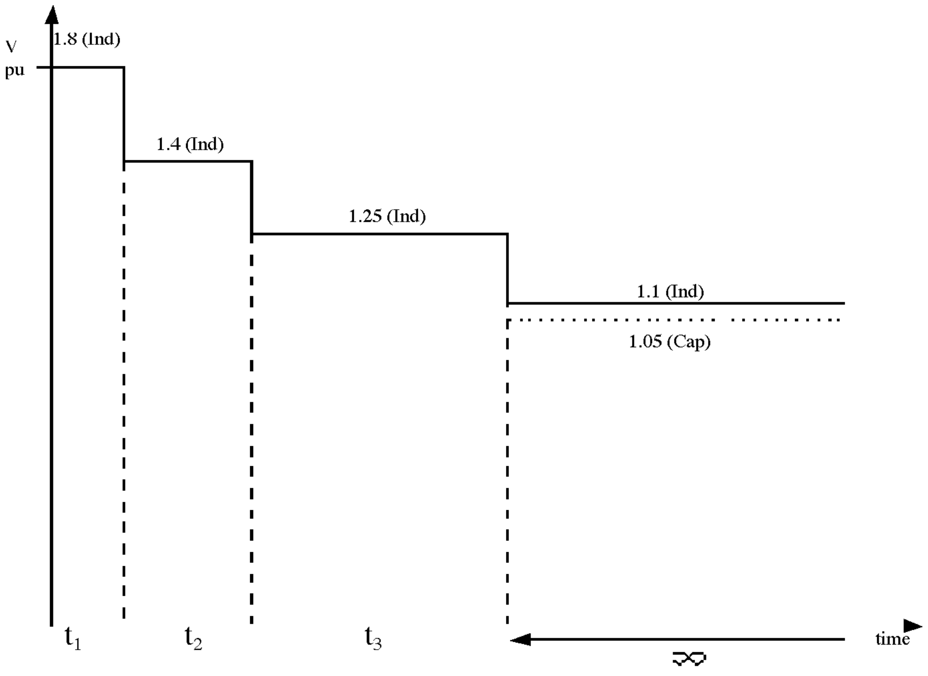


Figure B.2—Overload cycle

Typical values might be

- 1.8 per unit voltage, t_1 = 3 cycles
- 1.4 per unit voltage, t_2 = 12 cycles
- 1.25 per unit voltage, t_3 =1 s

B.5.2 Control objectives, see 8.2

B.5.2.1 SVC functions with priority, see 8.2.1

Select from the menu of 8.2.1 the required functions with priority.

Further functions may refer to the following:

- TSC or TCR switching logic
- Control stability
- Sensitivity to distortion

The measuring transducer, which supplies the signal of the busbar voltage to be controlled, should be compatible with the performance, e.g., response time, required of the SVC. If separately supplied, the transducer should have an appropriate response (usually one cycle) to the total objective.

Normal control action should be based on measurements of the network voltage. Measurements can be done on a single phase basis with additional balancing loops to minimize harmonics or by using a rectified mean of all the voltage signals. There is a choice between deliberately balancing each phase (with the disadvantage of responding to unbalance voltages) and responding to the phase-sequence components.

Further functions that can be specified as follows:

- It may be possible to restrict fault-clearance overvoltages.
- The SVC should offer the most useful performance under switching and fault conditions. It should minimize energization transients when it is switched on. To avoid post-fault overvoltages, it should not connect capacitors (TSCs), nor be sized to counteract them by extending the inductive capability. During the recovery period immediately after a fault is cleared and while the SVC is resynchronizing its controls to the new network conditions, this recovery time should be a minimum, not exceeding two cycles.
- Details should be provided of the synchronizing system to show how it remains functional for up to 1 s during a three-phase fault.

For control accuracy, see 9.3.

The user may also describe any special operating strategy for the potential SVC in the overall system operations of the user. Some concepts are described in B.1.

B.5.2.2 Response, see 8.2.2

The dynamic characteristic of the SVC control system is the response to a step change in the system voltage, so that the SVC remains within its controllable range. Such response time includes the delays in voltage measuring circuits.

An established method of verifying the speed of response of a closed-loop control system is to measure the time to reach 90% of an ordered step-change (see Figure 3). The overshoot may be limited also. Demonstrating this response is difficult for an SVC, because the parameters are three rms phase quantities that do not change together. However, a small step can be injected into the control system as a test. If this test is required, it should be specified.

Once at site and in the commissioning process, a step change to an element of an active power system for such verification may be obtained by switching off a shunt reactor or capacitor, or another SVC. Alternatively, a simulator or model test, using perhaps a voltage reference step applied to the real control system, is a solution at the factory test stage. In either case, a series of steps can be made from part reactive to part capacitive output, or vice versa, where different numbers of reactive elements are switched. In practice there are delays of up to a cycle in measuring three phase MVA output, and these delays should be taken into account.

Many factors affect the response time of an SVC, in particular the slope setting, system impedance, and the number of SVCs connected to the busbar. Increasing system impedance (that is, the system becomes weaker) leads to a faster response and ultimately instability. The user may be expected to specify a response time for the normal range of operating short circuit level, defined in Clause 7. It's important also to define the weakest operating condition so that stability is maintained with a margin, and this condition will define the highest effective loop gain. The user should therefore avoid specifying an unnecessarily short response time for normal operating conditions.

Controls in which the gain setting is adaptive to system strength have been used. A normal range of short circuit MVA of up to 5:1 should be handled by appropriate choice of the slope, and a response time of 50 ms is reasonable. Above that, i.e., at a much weaker short-circuit, the gain is reduced and a response time of 100 ms is advised at normal short-circuit level.

B.5.3 Harmonic performance, see 8.3

If the SVC includes a TCR, then harmonic currents will be generated. A portion of these harmonic currents will flow into the connected transmission system and may cause difficulties to other equipment. Therefore, a TCR type of SVC system is usually provided with harmonic filters to limit the harmonic currents imposed on the transmission system. On the other hand, TSC or TSR systems usually do not produce significant harmonics, and they may or may not incorporate harmonic filters.

The design of the harmonic filters and the selection of their components requires careful study, and these studies are described in Clause 11 of this guide. The purpose of this clause is to describe the engineering considerations which go into specifying harmonic performance for a specific SVC system.

The TCR can be thought of as a current source for harmonic currents. These currents flow out of the TCR and divide between the harmonic filters and the transmission system in inverse proportion to the harmonic impedance of the filter and the transmission system. (See 10.4 of Miller [B14][6] for a further explanation.

It is possible for the sum of the harmonic current in the filter and the harmonic current in the transmission line to be greater than the harmonic current produced by the TCR. This phenomenon is known as current amplification and comes about through parallel resonance (otherwise known as anti-resonance) between the filter and transmission system. (See 5.2.2 of IEEE Std 519-1992 for a further explanation.)

The amount of harmonic currents that a given SVC can impose on the transmission system, without producing unacceptable consequences, will depend on several factors, such as the following:

- Size (rating) of the SVC in relation to the capacity of the transmission system
- Location and nature of other equipment on the transmission system that may incur interference with
- Harmonic impedance of the transmission system
- Presence of existing harmonics on the power system that will add to the harmonics produced by the SVC

The determination of acceptable harmonic limits for the SVC system is best done using the methodology of IEEE Std 519-1992.

NOTE—Even though IEEE Std 519-1992 specifically disclaims applicability to HVDC and SVC systems, the principles described in that standard are suitable for use in specifying the harmonic performance of an SVC.

Although the harmonic distortion produced by an SVC originates as a current source in the thyristor valves, the harmonic performance of the SVC can be specified in terms of either harmonic voltages or harmonic currents, or in terms of both at the point where the SVC is connected to the transmission system, the PCC, the harmonic voltage is related to the harmonic current by Ohm's Law. That is to say

$$V_n = Z_{en} \times I_n \tag{6}$$

where

V_n is the voltage at harmonic "n" at the PCC,

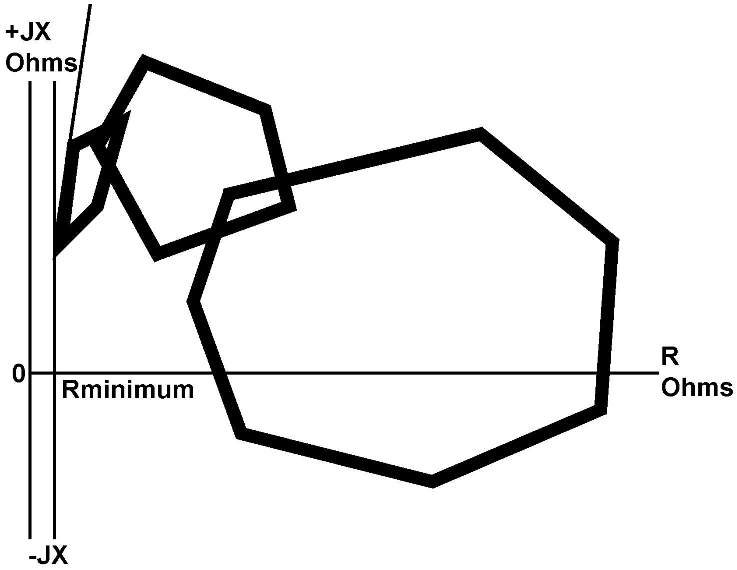
---

[6] The numbers in brackets correspond to those in the bibliography in Annex A.

Z_{en} is the harmonic impedance looking into the transmission system at the PCC, and
I_n is the current injected into the system at harmonic "n."

Users should examine the system viewed from the proposed point of connection of the SVC or other points such as the PCC, for harmonic impedance. Both present and predicted future system conditions should be considered. Plotting the harmonic impedance on an R/X diagram (see Figure B.3) will reveal "search areas" within which the impedance at each frequency can always be found.

An example of the harmonic impedance sectors of Z_{en} is given in Figure B.3.



NOTES:

1—Each box refers to one frequency

2—Units are per unit resistance and reactance.

Figure B.3—Harmonic impedance loci

Although theoretically the system harmonic impedance values at frequencies above fundamental will lie within a circle on the R/X diagram of Figure B.3, to specify that these values can lie anywhere tends to yield an expensive filter. It is preferable to define smaller areas for each frequency, and minimum values of resistance and impedance angle.

The design of a harmonic filter involves a number of considerations, many of which are conflicting. In order to make the supplier aware of the requirements for a particular project, the filter specification should include the following:

a) The required harmonic performance for normal operation.

b) Any permissible deviation from the normal performance, which might be accepted under unusual circumstances, or for a short time, e.g., possible changes from nominal values of frequency per Clause 7, which will change the tuning of the filter. (Relaxing the required filter performance under unusual or rare conditions may result in considerable cost saving in the filters.)

c) The temperature range (see Clause 6) over which the filter should operate. (The capacitance of power capacitors changes slightly with temperature.)

d) The extent to which the filter should perform without one or more capacitor units or filter arms, provided that this condition is alarmed. Internal fused capacitors, where used, should have an unbalance or other protection to remove the bank if internal fuses have operated to the extent that further fuse operation could lead to damage or an undesired operational condition.

e) The presence of any existing harmonic distortion on the transmission system. The harmonic filter in the SVC will act as a “sink” that may attract any existing harmonics to the SVC. Therefore, these harmonics will impose additional duty on the filter and should be accounted for in the rating of filter components.

f) Values to be specified. Harmonics up to about the 50th harmonic may affect other power apparatus connected to the transmission system. Therefore, it is common to specify limits for the following:

V_n is the maximum voltage for any single harmonic below the 50th,

I_n is the maximum current at any single harmonic below the 50th,

THD is the total harmonic distortion including all harmonics to the 50th.

Although no general consensus exists yet for the limits and whether voltage or current distortion is preferable as a design point, IEEE Std 519-1992 presents several tentative suggestions. Alternate clauses might be the following:

— Alternative specification. The maximum voltage distortion at the _______ kV bus should not exceed _______% for any individual harmonic and should not exceed _______% for the rms sum of all the harmonics from the second to the 50th harmonic.

  Individual voltage distortion is typically set between 1% and 3%. RMS voltage distortion is typically set between 2% and 5%.

— Alternative specification. The maximum current distortion at the _______ kV bus should not exceed _______% for any individual harmonic and should not exceed _______% for the rms sum of all the harmonics from the second to the 50th harmonic.

  Individual current distortion is typically set between 4% and 8%. RMS current distortion is typically set between 5% and 10%.

For rating purposes, it is usually too conservative to define the whole of the voltage and current characteristic (see Figure 2, area EFJH) as continuous operating range; therefore the user should define a more limited, practical operating range of the SVC within the characteristic, to be associated with the maximum harmonic stresses on the SVC components. For example, at points E and F in Figure 2, the SVC is unlikely to be generating harmonics. By examining the expected use of the SVC (i.e., normal capacitive output and expected high-voltage reference, e.g., Point K), it is possible to indicate the most severe continuous operating situation. If the highest capacitive output and highest voltage reference are selected for continuous filter component ratings, higher costs should be expected than if the normal voltage reference line (line AB in Figure 2) is used and full output is not continuous.

B.5.4 Telephone and radio interference, see 8.4

B.5.4.1 Limits for telephone interference, see 8.4.1

Although the harmonics produced by power-electronic switching are greatly reduced in magnitude as the frequency increases, any harmonics in the audible band are a concern because they may couple into the telephone system and cause interference. In general, the levels produced by an SVC are not significant. The current standard for limiting the potential for telephone interference is the “C-message” weighting factor curve established by subclause 6.9.1 of IEEE Std 519-1992.

B.5.4.2 Limits for radio interference, see 8.4.2

Because of the very fast switching action of a solid state converter, the potential for directly radiated interference from the SVC does exist. However, actual radio interference problems from SVC installations have been extremely rare. Moreover, a utility type of SVC to which this guide applies will usually be part of an HV substation that has some level of corona discharge, particularly if the substation is a conventional air-insulated installation. Usually the radio interference (RI) produced by the corona discharge from the HV equipment and bus will be greater than the RI produced by the SVC, thereby masking the SVC. Nevertheless, it is prudent to include an RI and television interference (TVI) limit in the SVC specification, typically set between 50 µV/m and 100 µV/m at a distance 500 m away from the SVC station perimeter.

B.5.5 Audible noise, see 8.5

It is helpful if the user makes available (or includes in the scope of supply) an audible noise survey of the situation typically found before the SVC is commissioned.

B.5.6 Loss evaluation, see 8.6

The losses of a static compensator are an important consideration because they can form a major part of the operating cost. This cost should be evaluated against the capital cost of the equipment. Loss evaluation has an important influence on the SVC design. The evaluation procedure has three steps.

a) The user should define the expected normal operating points, in megavar output, of the compensator and the capitalized cost of losses (cost per kilowatt) at each point. A number of such points will exist. The capitalized cost of losses for each point should be weighted according to the percentage of time that the SVC is expected to operate at or near that megavar output. It should be noted that such weights will be different from those used in a system transformer loss evaluation because SVC output is not likely to be proportional to load current.

b) Each bidder calculates and quotes the kilowatt losses at each operating point. The losses will include the electrical power used for pumps, fans, auxiliaries, etc. Multiplying each calculated loss by the specified cost per kilowatt gives the total evaluated cost of losses, which will be added to the equipment price to compare bids. In some instances, the total evaluated cost of losses has had the same order of magnitude as the equipment price. The bidder will normally choose a design that minimizes the total of the equipment cost and the evaluated cost of losses.

c) During project construction, measurements are made at factory testing and the bid calculations reworked. Adjustments to the contract price may be made to reflect a recalculated loss different from that quoted in the bid.

It is widely agreed that measurement of the actual losses of an operating SVC is not practical. Not only are there difficulties in measuring a small quantity in relation to main circuit currents, but measuring heat loss at nominal ambient temperature, harmonic impedance, etc., and finding suitable steady operating conditions either at factory or at site present difficulties. Calculation is, therefore, necessary. Annex C is a recommended procedure to calculate valve losses.

All losses should be determined to a specific condition, e.g., temperature and network operating conditions that should include the system voltage, reference setting, and slope of the SVC. At each operating point all elements should be considered in the loss calculation. Thyristor valves, energized but with zero megavar output, still generate losses and should be included. Zero SVC output may not necessarily coincide with zero transformer current. The total SVC losses are normally between 0.5% and 0.8% of the megavar rating of the SVC. Losses caused by the flow of harmonic currents in the filter components should be excluded from this calculation because they represent a small percentage of the total.

B.5.6.1 Transformer losses, see 8.6.2

The transformer current may not necessarily be zero when the SVC output is zero.

This procedure ignores the losses in a transformer due to harmonic currents (although the transformer design should take them into account). Many SVC designs that use a TCR include a filter on the same busbar, and the filter reduces the harmonic current in the transformer. In other cases, users may wish to specify a calculation of loss due to harmonic currents such as used in HVDC convertors (see Forrest [B6] and IEEE Std 1158-1991 [B10]).

The loss calculation reflects test measurements that can be used to verify it. The total loss at full load is the sum of core, stray, and copper losses. The core losses vary according to the operating voltage of the transformer at the output in question. As an approximation, the nominal-voltage value may be used throughout. The copper loss and stray loss together are calculated from the fundamental current and measured resistance at that frequency, adjusted for conductor temperature. Stray loss is thus modelled by a resistance. The specification requires an estimate of these losses to be used in the evaluation procedure described above and to be verified later from factory tests.

B.5.7 SVC availability and reliability, see 8.7

B.5.7.1 Definitions, see 8.7.1

Alternative definitions are possible. Travel time (within a reasonable maximum) can be deducted from outage time.

B.5.7.2 Required availability and reliability, see 8.7.2

A typical figure for SVC forced outage availability is 98%, and the number of events is five. It is reasonable to specify that such levels for an SVC should be guaranteed, provided that the supplier's recommended spares holding is kept at the site, and the preventive maintenance procedure is followed. It may be necessary to adapt the wording to the calendar year to suit availability records.

Usual guarantee periods are 2 years. Usual maintenance intervals are 12 months.

B.6 Main components—required functions and features, see Clause 9

The specification clauses concerned with thyristor valves and other main components are intended to be functional and general, i.e., not prescribing the precise form, rating, or quantity of the components, but allowing the bidder freedom to propose an optimum solution. Such an approach should encourage innovation and the most cost-effective solution within the user's requirements, without compromising the required reliability or established standards of control, protection, ease of maintenance, etc.

B.6.1 Thyristor valves, see 9.1

The purpose of the thyristor valves is to control (TCR) or switch (TSR) the ac current in a reactor bank or to switch on and off a capacitor bank (TSC). TCR valves control the phase current to provide variable amounts of ac current to the reactor bank, thereby controlling variable inductive vars. TSR valves switch reactor banks in and out to provide blocks of reactive power. TSC valves switch the ac current by allowing either full or zero conduction of current, thereby providing controlled step changes in capacitive vars.

Generally, a single thyristor redundant per phase is sufficient. Small industrial SVCs may have only a single thyristor per phase. In such a case, spare valves are more useful if high availability is needed.

The bidder may be asked to provide a data sheet of ratings of offered thyristors.

B.6.1.1 Valve protection, see 9.1.5

The individual emergency firing protection of TCR valves can be coordinated with the valve surge arrester. If so, the latter should operate first.

Light-triggered thyristors (LTT) and electrically triggered thyristors (ETT) should have built-in overvoltage protection, or the bidder should explain how the consequences of a faulted light source or light guide are handled.

B.6.2 Thyristor valve cooling system, see 9.2

The purpose of the thyristor-valve cooling system is to remove the heat produced by the thyristor valve and to eject it to the environment. Generally, two types of thyristor cooling systems are possible: water cooled or air cooled. In either case, the cooling system should be completely furnished with all necessary interconnecting piping, ductwork, circulating pumps, blowers, heaters, make-up reservoirs, heat exchangers, filters, water treatment plant (if required), instrumentation, automatic controls, alarms, control power systems, and other necessary equipment.

B.6.2.1 Liquid cooling (if applicable), see 9.2.1

The heat transfer from the closed liquid system to the ambient air should take place in a water-to-air or water-to-water heat exchanger as follows:

a) One pump should normally operate and a redundant pump should be standing by. If a pump failure occurs, the second pump should automatically switch in without shutting down the equipment. The pump should change over automatically every month or so to cycle the second pump. A set of alarms should be displayed at the appropriate local and remote control cabinets to alert the operator that a pump problem exists.

   The cooling system should be constructed to permit work on a defective pump unit without shutting down the SVC.

b) The purification system should be designed to maintain the resistivity of the water above 1 MΩ/cm. A resistivity transducer located in the outgoing water from the deionizer should detect the depletion of the material. The second purifying loop will continue to operate in the presence of a primary-loop alarm until its deionizer is depleted.

c) If water-water exchangers are used, the secondary water that is passed through to remove heat should be suitably treated for disposal into the environment. Filters and deionizer material should be designed to allow replacements in a relatively short time without shutting down of the cooling unit. (Normal replacement should not be required more than once every 12 months.)

B.6.2.2 Air cooling (if applicable), see 9.2.2

Either a nonrecirculating (i.e., once through) or a recirculating air system may be provided, depending on the requirement of the thyristor selected by the supplier and on specific site conditions. A once-through air system is one in which outside air is drawn through a filter and then through the thyristor valve, and the heated air is then exhausted to the outside. A recirculated air system is one in which the air is recirculated within the SVC building, and the heated air is cooled with a heat exchanger.

Required design functions and features include the following:

a) Dual blowers with one blower normally operating and the second standing by. If a blower failure occurs, the second blower should automatically switch in without shutting down the equipment; and an alarm should be displayed at the control cabinets to alert the operator that a blower problem exists.

   The cooling system should be constructed to permit work on the defective unit without shutting down the system.

b) Air filtering system (non-recirculated systems). A warning alarm should register at the control cabinet when filter replacement is needed. The filter should be designed so that replacement can take place without outage of the SVC, and under normal conditions should not be required more than once every 6 months.

c) Monitoring. Sufficient gauges and indicators should indicate the status of any part of the unit for both normal operations and maintenance.

B.6.3 Control equipment and operator interface, see 9.3

Overall accuracy of the controlled variables can typically be ±1% for voltage and ±5% for current.

The primary purpose of the control of the SVC is to control system voltage in response to measured system variables, auxiliary inputs for supplementary control, or operator inputs. It is recommended that the voltage and current measurements are included in the SVC scope of supply in order to ensure that they are compatible for the required response of controls.

SVC control contains the following:

a) Alternative modes of operation, as required, including a manual mode for site testing and emergency shutdown by operator
b) Voltage, current, and reactive power measurement
c) SVC control by generating of the appropriate firing pulses to the thyristor valves
d) Orderly start-up and shutdown sequencing
e) Monitoring and protecting the control itself in progress and the components it controls

The controls may also contain one or more of the following:

f) Automatic return to manual mode of operation at the most recent voltage setting on the loss of input voltage measurement signal.
g) Automatic voltage control, operative during start-up to prevent unnecessary switching of the reactive elements.
h) Self-check facility that at regular intervals operates equipment to verify its correct operation.
i) Supplementary control modules for damping and var control.
j) Control system damping with gain supervisor and gain optimizer. On gain supervision, details should be given especially on the onset of instability. The criteria for detection of instability are
   1) Frequency range of the oscillation
   2) Amplitude of the oscillation
   3) Number of consecutive oscillations above an adjustable threshold

This function should also include an adjustable emergency gain.

The user should indicate the type of operator interface that is required, such as

- Computer-screen mimic
- Mosaic panel
- Additional to an existing substation's controls

The choice of interface will be determined by whether maintenance staff is present at site continuously and by the expected location of staff for normal operation and commissioning.

Possible requirements of control system construction are as follows:

- General construction. The control system components should be mounted in free-standing, indoor, metal-clad cabinets with appropriate seismic rating, where necessary.
- Operating environment. Control equipment should be designed to operate properly at the expected maximum allowable ambient indoor air temperature of ___ °C. Supplemental cooling may be provided.
- Circuitry. Printed circuit cards should have built-in test points and indicating lights to facilitate testing and maintenance or, if microprocessor-based, should have some form of self-checking and fault diagnosis, to be described by the bidder.
- Interference tests. The controls should be tested to operate in the environment of ac substations, and suitable SWC (see IEEE Std C37.90.1-1989) tests should be carried out or proof of previous testing provided.

B.6.4 Monitoring and protection, see 9.4

B.6.4.1 Protection, see 9.4.2

In addition to the protective features provided as part of the thyristor valves and control, an independent protection system may be provided to protect the compensator components against all abnormal operating conditions that may occur.

Table B.1 is taken from the IEEE/PES PSRC working group report, see [B12].

Table B.1—Overview of suggested SVC protection methods

Protection zone	Protection device	Protection function	Notes
Transformer	87	Differential	
	50/51	Overcurrent	
	63/49/71	Gas pressure/temperature/ Low-level oil	
	51N	Ground overcurrent	
Low voltage bus	87	Differential	
	50/51	Overcurrent	
	59 ph-ph	Overvoltage	
	59G	Overvoltage (open corner delta)	Ground faults
	51N	Ground overcurrent	Used with grounding transformer

Table B.1—Overview of suggested SVC protection methods (continued)

Protection zone	Protection device	Protection function	Notes
TSC	60C	Unbalance	Cross-connected unbalance measurement
	87	Differential	
	50/51	Overcurrent	Branch faults or limiting reactor overloads
	46	Negative phase sequence	Unbalance
	60	Zero phase sequence	Unbalance in lieu of 46
	59	Overload	Capacitor overvoltage using current measurement
	50N	Ground overcurrent	Branch faults
TCR/TSR	87	Differential	
	50/51	Overcurrent	
	49	Overload	Reactor thermal overload
	46	Negative phase sequence	Reactor branch unbalance
	60	Zero phase sequence	Reactor branch unbalance
	50N	Ground overcurrent	Branch faults
Thyristor valves in TCR/TSR/TSC		Overvoltage	Arresters across each valve for TSC and break-over diodes for TCR/TSR
		Overcurrent	Conventional overcurrent or overload provided in the controls
		Thyristor failure	Monitor thyristors
		Thermal model	
Filters	59N	Neutral voltage shift	Detect failed cans or reactor
	60C	Unbalance	Detect failed cans via cross connection
	50/51	Overcurrent	
	59	Overvoltage	
	87	Differential	Filter differential
	50/51N	Ground overcurrent	Ground fault detection
Cooling		Temperature	Alarm and trip for coolant temperature
		Flow	Alarm and trip for coolant flow
		Resistivity	Alarm and trip for coolant resistivity
		Leakage	Loss of fluid
		Transfer failure or power loss	

B.6.5 Reactors, see 9.5

The purpose of the main shunt reactors is to provide the required lagging var supply.

There is considerable debate regarding the acceptable level of magnetic fields that will not cause adverse effects on personnel. The present recommendation by the National Radiological Protection Board (of the United Kingdom) is that personnel access should be avoided where fields exceed 2 mT. The user should take into account developments in public knowledge of the effects and any relevant legislation.

Design requirements for reactors should include the following:

- Each phase reactor may be divided into two reactors, one on each side of the thyristor valve to limit short-circuit currents resulting when one reactor is shorted or a ground fault occurs.
- The user may attach a standard specification.
- Supporting structural steel work, including foundations, and fences should be designed to minimize currents induced by the magnetic fields of the reactor.
- The purpose of the filter reactors (if required) is to tune the capacitor banks to provide the necessary reduction of harmonics. Subclauses 9.5 and B.6.5 apply to TSC reactors also, if used.

B.6.6 Capacitor banks, see 9.6

The purpose of the capacitor bank(s) is to provide the required leading var supply and also to provide sufficient reduction of harmonic voltages and currents that may be generated by the SVC system. The banks (e.g., shunt capacitors and filter banks) should be designed to avoid resonance with the ac power system regardless of system configuration. Shunt capacitor banks usually include a series reactor for in-rush current limitation.

B.6.7 Power transformers, see 9.7

The purpose of the step-down power transformer (where applicable) is to couple the SVC components to the HV transmission system. Some SVCs may not require step-up transformers because a connection point at a suitable voltage (not usually above 36 kV) exists.

The power transformer is a standard transformer. The design of the transformer should be either three single-phase or one three-phase. Detailed transformer specifications may be included as an attachment.

B.6.7.1 Maximum flux density, see 9.7

Noise, core losses, and harmonic currents increase as the flux level in the transformer core approaches its saturation value.

The saturation flux density is the intersection of the flux density axis and the asymptote of the flux-current characteristic in the saturated region (having a slope equal to the air core reactance). As a general rule, the saturation flux density of the transformer should be at least 5% above the expected highest operating flux density to take account of frequency variation and other effects. The pattern of operation may make high flux density rare, and the user may define some operating condition other than maximum secondary voltage at which this margin should be satisfied.

The maximum flux density depends on the primary leakage reactance of the transformer. For example, in a case considering a maximum capacitive output of 150 Mvar at 1.1 per unit (current of 0.91 per unit/ 150 MVA) and assuming a 15% leakage reactance on the primary side, the minimum voltage at which the transformer saturates is calculated

$$1.05 \times (1.1 + 0.15 \times 0.91) = 1.30 \text{ per unit} \tag{7}$$

B.6.8 Grounding and disconnect switches, see 9.8

The SVC is made up of several major components. As a minimum, the SVC should have a means of being visibly disconnected and grounded from the power system for maintenance or repair. A manual disconnect switch or a removable, metal-clad circuit breaker can provide this function. Grounding devices or provisions for grounding should be provided.

Each of the following major components may be visibly disconnected (e.g., by a switch or a removable link) and grounded, depending on the availability requirements and whether the policy is to maintain a component of the SVC while the other components continue to operate: TCR, TSR, TSC, MSR, MSC, and filter banks.

Tests should be specified in accordance with the latest revision of IEEE or IEC standards for disconnect switches.

B.6.9 Auxiliary power supplies, see 9.9

The user may modify the requirements if an existing power supply is available at site and adequate for the SVC.

B.7 Spares, see Clause 10

A number of approaches to this question exist, and the choice of a particular strategy for a given project is a matter of engineering judgment and part of the overall SVC planning, design, and specification. The main considerations are as follows:

a) The criticality of the SVC to the overall transmission system. Clearly an SVC that is essential to a major portion of the transmission grid cannot be allowed to be out of service for lack of parts. Therefore, a generous allotment of spare parts should be provided.

b) The criticality of each component in the SVC. The different components to the operation of the SVC vary in importance:

    1) Category A. Due to economic constraints, some costly components may not have a spare available. Furthermore, such equipment may have long lead times if a replacement were to be needed. In some cases, it may be prudent to provide a spare despite the cost. (Examples are step-down transformers, shunt reactors, and filters.) Another approach, in the case of a transformer, would be to select the voltage ratio to be the same as that already in use elsewhere on the utility system, where a spare transformer may be available. Another approach is to use single phase transformers with one spare.
    2) Category B. Operation with a major element out of service is often possible.
    3) Category C. Some SVC components are usually provided with back-up devices or equipments, so that the first failure will not cause an SVC outage. These “in-place spares” should be considered when deciding on the overall spare parts strategy. (Examples are redundant thyristors, back-up pumps, and redundant coolers.)
    4) Category D. The failure of some components will not produce an immediate SVC outage. Thus it may be reasonable to limit the spares of these equipments, if replacements can be obtained quickly. (Examples are building service equipments, fault recording equipment, and supervisory equipment.)

    The strategy for some SVC installations may call for an on-site spare for Category A parts and an on-site spare for all Category B or C parts that are not immediately available from other sources. Other strategies may omit spares for all categories for economic reasons. Any parts that are not readily available through normal commercial channels, or whose manufacture is likely to be discontinued during the life of the SVC, should be included in the spares inventory.

c) The likelihood of failure for each component. Today, the failure rates of most electrical components are known, at least approximately. Thus, it is possible to make a quantitative judgment of the likelihood that a particular device will need to be replaced.

d) The availability of a spare device through normal channels. For example, many components in an SVC have other uses as well, so they are available commercially or may even be kept in a central warehouse by the user. If so, there is less need to provide spares specific to the SVC.

e) The uniqueness of the spare devices. The spare devices that are unique to the SVC are best stored on site. Principally this strategy refers to components for the thyristor valves and SVC controls. Storage on site ensures that the devices will be immediately at hand when needed, without the delay needed to draw them from a central stocking area. Therefore, a suitable storage area should be included.

B.8 Engineering studies, see Clause 11

Typically load flow, stability, and voltage control studies including, where necessary, power oscillation damping studies, are done by the user as part of preparing the specification for the transmission system of concern. Different applicable system conditions are considered to determine the optimal location and size of the SVC. The results of these studies are then reflected in the SVC specification in terms of rating and control requirements. In addition, system harmonic impedance calculations and/or measurements for all practical system conditions are often performed including an investigation of the potential for magnification of harmonic voltages elsewhere in the system. The results are then presented in the SVC specification, e.g., in the form of the impedance loci (Figure B.3). This information is important for any SVC harmonic filter design.

The user may wish to defer some of these studies and add them to the scope of supply as listed in Clause 11.

B.9 Tests, see Clause 12

SVC tests to be specified include factory tests, i.e., production tests of all components and field (site) tests of components, subsystems, and the complete SVC.

IEEE Std 1303-1994 should be used when specifying SVC field tests. “Mobile” SVCs, which are designed for service in more than one location, may allow for some of the subsystem tests, now considered field tests, to be done at factory rather than at site in the future. This trend will help reduce commissioning cost, at least for smaller SVCs. The user may also consider staged fault tests.

B.9.1 Factory tests of valves, see 12.1

Factory (type and production) testing of the major components of the SVC, to be performed off site, i.e., at the component factories or test facilities, should be specified per applicable standards as available. Preference between standards and user-specific requirements should be defined. Table B.2 lists the component standards that apply

Table B.2—Component standards

Component	IEEE standards collections	Standards collections of other organizations
Transformer	C57	IEC 60076-1-04: 2000
Circuit breaker		IEC 60056-03: 1987
Reactor		IEC 60289-05: 1988
Capacitor	18-1992	IEC 61070-11: 1991
Protection relays	C37	IEC 60255-20-01: 1984
Thyristor valves		IEC 61956-09: 1999

B.9.2 Factory tests of controls, see 12.2

Special function tests may be requested to confirm the adequacy of the control system for the application at hand. Analog transient network analyzers (TNA) or digital simulators are typically used for these tests. Often, these function tests are also checked against digital simulations performed as part of the SVC control development and design. Development and function testing of the (digital) controls may thus be linked closely with each other or by one process. In any case, a list of control function tests is an important part of any SVC specification, and the user may wish to make specific additions to this clause. For interference testing, the IEC 61000-4 series provides similar test procedures.

B.10 Documentation, see Clause 13

The following documentation is typically produced by the SVC supplier and should be specified as deliverables under the contract:

- Technical reports
- Equipment specifications
- Quality assurance documentation
- Equipment test reports
- One-line drawings, as built
- Three-line drawings, as built
- Control elementary drawings
- Plan and profile drawings, as built
- Civil drawings, as built
- Mechanical drawings, as built
- Architectural drawings, as built
- Operator manuals
- Equipment maintenance repair manuals
- Software and operating system manuals

If computer models of the SVC are required for power system simulation, they should be specified here.

B.11 Training, see Clause 14

The effective use and reliable operation of a static compensator will depend on the people responsible for its operation and maintenance. Their initial training will normally be the responsibility of the supplier within the supply contract, and their continued training updates and the training of new staff will be the responsibility of the user.

Normally, it should be expected that prior to this training the site staff responsible for operation and maintenance will be well versed in the normal practices of an ac station, but will not be experienced in power electronic equipment. The specification clauses should be prepared based on this premise.

The user should consider how continued updates of staff and training of new staff should be handled after the supply contract is concluded. Preparation of a course video is possible, but it should receive specific budgeting and professional attention independent of the supply contract. Amateur hand-held videos, taken from the back of the room during training course lectures, have not been shown to give useful results.

In particular, the user should allow staff to participate in site installation and commissioning of equipment. This opportunity is a unique and valuable way to learn about the equipment and to have access before energization. The training course should be completed prior to this stage of a project.

B.12 Balance of plant, see Clause 15

Several features tend to be common to most installations, whether fixed or relocatable:

- The SVC is frequently located in or as an extension of a substation.
- The thyristor valves, valve auxiliary equipment, and SVC controls will be located in a custom-designed building.
- The other apparatus (e.g., reactors, capacitors, HV circuit breakers, disconnect and ground switches, arresters, bus work) will be conventional.
- The basic construction techniques adopted by the user for conventional HV substations will be suitable for the SVC installation.
- The few cases where special measures are required for the SVC are in the area of the thyristor valve, valve cooling, controls, and grounding. The supplier should describe what is required for its particular system.

B.12.1 Buildings and structures, see 15.1

A wide variety of building types and styles have been successfully used in SVC installations, ranging from the most simple pre-engineered industrial building to masonry buildings with full architectural treatment. In general, each of these approaches has been successful when carefully engineered, and the choice is a matter of the user’s preference (and budget). A few specific aspects should be considered, however:

- Shielding. The switching of the thyristor valves has the potential for producing EMI. Therefore, the supplier should be consulted in case any specific shielding concerns exist regarding the valve hall or control room.
- Circuit security. A number of sensitive circuits are likely to exist between the SVC controls and other apparatus, such as CT and PT and will require shielding or special circuit routing away from sources of electrical noise.

- Health hazard. The inquiry should include any particular requirements regarding health hazards, taking into account local legislation. If risk assessment is necessary, it should be specified here.
- Building services. Although the primary purpose of the SVC building is to house the SVC equipment, equipment should be maintained periodically. Personnel are present, even occasionally in an unmanned station. The level of building services should be integral to the SVC design regarding the building environment, particularly for the extremes of operating temperatures that can be permitted and the level of "creature comforts" that will promote efficient maintenance work (e.g., sanitation, heating, lighting, ventilation, air conditioning).

B.12.1.1 Fire protection, see 15.2

No industry consensus exists as yet about what level of fire protection is appropriate for an SVC installation. A reasoned engineering judgment should be applied on an individual basis. The following factors should be considered:

- Serious fires have occurred in SVC valve halls and in HVDC valve halls that contain similar equipment.
- SVC valves contain little, if any, materials that would support combustion. In other words, some materials in an SVC valve can be made to burn in the presence of an arc, but the flame goes out once the arc is removed.
- Capacitors within thyristor valve grading circuits should have metal caps and open-circuiting pressure switches as protection for internal over-pressure.
- The SVC building and the equipment in the building represent a significant economic investment, and fire protection that is consistent with this investment should be provided.

In view of the above, it seems prudent to recommend that

a) All valve halls and control rooms be equipped with fire detection apparatus that will immediately trip the SVC and isolate it from any source of electrical energy.

b) Whether a fire-suppressing system is to be installed should be a matter of judgment and local practice. Appropriate gas-based systems may be specified in lieu of water systems.

c) As much as possible, the fire detection system should be designed to avoid false operation. Two failure modes exist as follows:

    1) Failure to detect a fire and trip the SVC
    2) False trip of the SVC when there is no fire

d) Large, oil-filled equipment should be treated in a manner that is consistent with the user's other oil-filled apparatus of similar size, cost, and importance (e.g., fire walls, oil containment walls, sumps).

e) It is probably not reasonable to apply fire protection to other outdoor equipment.

Annex C

(normative)

Method of calculating thyristor valve losses

Ideally, the losses in the individual modules or thyristor levels should be measured and the total losses for a valve computed from these measurements. However, electric and/or calorimetric methods to determine losses are, in practice, difficult to undertake, and the following calculation method is intended to replace them to a uniform standard.

C.1 Total losses

Losses are made up of

$$P_{valve} = P_{cvalve} + P_{Tsw} + P_{vd} + P_{sn} + P_{hyst} \tag{C.1}$$

where

P_{vd} is voltage divider losses,
P_{sn} is snubber circuit losses,
P_{valve} is total thyristor valve losses,
P_{cvalve} is thyristor valve conduction losses,
P_{Tsw} is thyristor switching losses (total) = $P_{\mathrm{Tswon}} + P_{\mathrm{Tswoff}}$,
P_{hyst} is reactor hysteresis losses.

C.2 Conduction losses

For each thyristor firing angle, the thyristor currents should be evaluated as follows.

The average thyristor current

$$I_{TAV} = I_{TCR} \times \frac{\sqrt{2}}{\pi} \times [\sin(\pi - \alpha) - (\pi - \alpha)\cos(\pi - \alpha)] \tag{C.2}$$

where

I_{TAV} is thyristor average current,
I_{TCR} is TCR fundamental rms-current for a fully conducting thyristor valve,
α is TCR control angle ($\pi/2$ to π radians).

The RMS thyristor current

$$I_{TRMS} = I_{TCR} \times \sqrt{\frac{(\pi - \alpha) \times [1 + 2\cos^2(\pi - \alpha)] - 1.5\sin[2(\pi - \alpha)]}{\pi}} \tag{C.3}$$

where

I_{TRMS}	is thyristor rms current.

The thyristor valve conduction losses should then be calculated as

$$P_{\text{cvalve}} = 3 \times 2 \times [n \times (U_{TO} \times I_{TAV} + r_T \times I_{TRMS}^2) + R_{busbar} \times I_{TRMS}^2] \quad \text{(C.4)}$$

where

n	is number of series connected thyristors in valve,
U_{TO}	is thyristor threshold voltage,
r_T	is thyristor slope resistance,
R_{busbar}	is dc resistance of valve terminal-to-terminal circuit omitting the thyristors.

C.3 Thyristor spreading losses at turn-on

For a TCR-valve, losses should be calculated as follows.

Turn-on losses assume that the loss is 0.2 Joule per pulse, which, though dependent on the individual thyristor, is a typical value considered acceptable for this calculation.

$$P_{Tswon} = 3 \times 2 \times n \times 0.2 \times freq$$

For TSR and TSC valves, the switching losses use a typical value again and should be assumed as follows.

$$P_{Tsw} = 0.03 \times P_{\text{cvalve}} \quad \text{(C.5)}$$

C.4 Thyristor losses at turn-off

For a TCR valve, turn-off losses should be calculated

$$P_{Tswoff} = 3 \times 2 \times Q_{rr} \times \sqrt{2} \times U_1 \times \sin(\alpha) \times freq \quad \text{(C.6)}$$

where

P_{Tswoff}	is thyristor switch-off losses,
Q_{rr}	is thyristor recovery charge,
U_1	is valve connection voltage (rms fundamental),
$freq$	is system fundamental frequency.

Q_{rr} should be defined as

$$Q_{rr} = k_1 \times (dI_T/dt)^{0.6}$$

where

Qrr is the thyristor recovery charge,

k_1 is a thyristor-type defined parameter that is evaluated by experiment (it relates the stored charge of the thyristor to the turn-off dI_T/dt at the relevant operating junction temperature)

(dI_T/dt) is the derivative of the valve current at zero crossing in A/µs.

The above equation gives the total losses, of which a fraction $(1 - k_Q)$ appears in the thyristors and k_Q in the snubber resistors. The factor k_Q defines the distribution of the recovery charge

$$k_Q = \frac{Q_1}{Q_1 + Q_2} \tag{C.7}$$

where

k_Q is the thyristor parameter.

Equation C.6 is illustrated in Figure C.1.

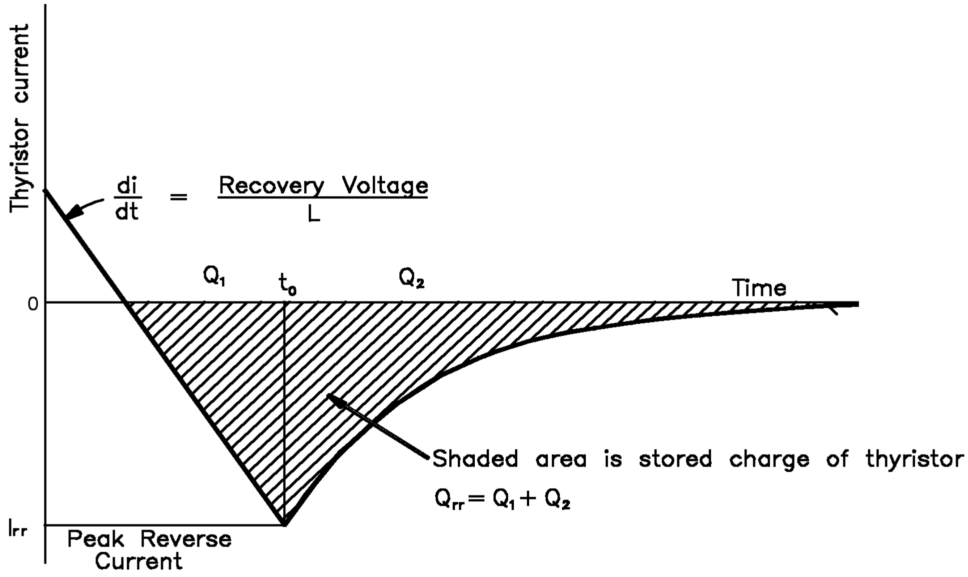


Figure C.1—Thyristor stored charge

C.5 Voltage divider losses

The voltage divider losses are dependent on the voltage that is applied across the thyristor valve. This voltage is dependent on the firing angle as calculated

$$U_{1\alpha} = U_1 \times \sqrt{(2/\pi)\{\alpha - \pi/2 - [1/2 \times \sin(2\alpha)]\}} \tag{C.8}$$

where

$U_{1\alpha}$ is thyristor blocking voltage (rms).

The power losses should then be calculated

$$P_{vd} = 3(U_{1\alpha}^{2})/(R_{vd} \times n)$$

where

R_{vd} is voltage divider resistance (per level).

C.6 Snubber circuit losses

For a TCR, the snubber circuit losses should be evaluated

$$P_{sn} = 3 \times freq \times C_{sn}/n \times [\sqrt{2} \times U_1 \times \sin(\alpha)]^2 \times 2.0 \tag{C.9}$$

where

C_{sn} is snubber circuit capacitance (per level).

C.7 Valve reactor loss

Where used, valve reactor loss consists of three components: resistive loss in the winding, eddy current loss, and hysteresis loss in the magnetic core. If an additional damping circuit is employed across the winding, it also incurs loss.

Reactor winding loss and the reactor core eddy current loss (and/or reactor damping resistor loss) are already accounted for in C.2 and C.6, respectively.

Hysteresis loss should be calculated as follows: A dc magnetization curve for the core material(s) should be determined for the loop of excitation that a valve reactor normally experiences. From the area enclosed by the loop, a characteristic hysteresis loss in joules per kilogram should be determined and applied to the design of the reactor in question, for example

$$P_{hyst} = n_L \times M \times k \times freq \tag{C.10}$$

where

n_L is the number of reactor cores in a valve,
M is the mass of each core,
k is the characteristic loss, in joules per unit mass.