

IEEE Guide for Specification of Transmission Static Synchronous Compensator (STATCOM) Systems

IEEE Power and Energy Society

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IEEE Guide for Specification of Transmission Static Synchronous Compensator (STATCOM) Systems

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Substations Committee
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IEEE Power and Energy Society

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Abstract: Assisting users in specifying the functional requirements for transmission static synchronous compensator (STATCOM) systems using forced commutated technology based on voltage sourced converter topologies is the purpose of this guide. These systems may be hybrid, and also incorporate thyristor and mechanically switched inductors and capacitors. Reactive power compensation, voltage regulation and control, transient and dynamic stability, and control and protection are the functions included. Accepted engineering practices for the application of STATCOM systems are presented. Specifications, typical application requirements, engineering studies, main component characteristics, system functions and features, factory testing, commissioning, and operations are covered. Informative annexes that allow users to develop or modify specific clauses to meet the requirements of a particular transmission system application are included.

Keywords: functional requirements, high voltage power transmission systems, IEEE 1052™, power system compensation, reactive power supply, static synchronous compensator (STATCOM), static var compensator (SVC), transient and dynamic stability, voltage regulation

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Introduction

This introduction is not part of IEEE Std 1052™-2018, IEEE Guide for Specification of Transmission Static Synchronous Compensator (STATCOM) Systems.

This document is a new guide, based on the revised version of IEEE Std 1031™-2011, Guide for the Functional Specification of Transmission Static Var Compensators. The guide provides an example and general information that may be considered when developing a technical specification for a transmission static synchronous compensator (STATCOM) specification.

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

This guide was prepared by a task force of Working Group I5, Voltage Sourced Converters in Substations, of the High Voltage Power Electronic Stations Subcommittee for the IEEE PES Substations Committee.

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IEEE Guide for Specification of Transmission Static Synchronous Compensator (STATCOM) Systems

1. Overview

1.1 Scope

This guide assists users in specifying the functional requirements for transmission static synchronous compensator (STATCOM) systems using forced commutated technology based on voltage sourced converter topologies. This guide covers specifications, applications, engineering studies, main component characteristics, system functions and features, factory testing, commissioning, and operations of the STATCOM systems. A number of sections in the guide can be used for active filters and for industrial or distribution system applications. However, reactive power compensation, mitigation of load disturbances, or phase unbalance compensation for industrial and distribution system applications are not included in this guide. Commercial terms and conditions for the purchase of the STATCOM systems are also beyond the scope of this document.

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

This guide presents technical information that may be used as the basis of functional specifications for STATCOM systems for transmission systems. For transmission systems, functions covered include reactive power compensation, voltage regulation and control, transient and dynamic stability, main components, control and protection, and accepted engineering practices for the application of STATCOM systems applications. This guide also includes informative appendices that allow users to develop or modify specific clauses to meet a particular system application. The wording deliberately uses “should” rather than “shall”, given that the document is a guide, not a standard specification. The user of this guide might wish to make this adjustment when converting specific sections into a specification. The guide includes the following:

- Newer developments in STATCOM components, particularly control systems
- Information on latest practices for STATCOM applications
- An informative annex to allow users to modify or develop specific clauses to meet a particular system application

1.3 Application

The guide assists the users in understanding the functional requirements for the specification and the implementation of transmission STATCOM systems. This guide may be used as a general purpose resource. In this case, not every part of this guide may be applicable and the user of this guide should evaluate how, and to what extent, each clause applies to the development of a specific STATCOM system specification.

The user of this guide may also refer to IEEE Std 1267™ for additional information on the specification of turnkey projects.¹

2. Normative references

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

Accredited Standards Committee C2-1997, National Electrical Safety Code®.^{2,3}

IEC 60815, Selection and dimensioning of high-voltage insulators intended for use in polluted conditions.⁴

IEC 61000-3-6, Electromagnetic compatibility (EMC)—Part 3-6: Limits—Assessment of emission limits for the connection of distorting installations to MV, HV and EHV power systems.

IEC 61954, Static var compensators (SVC) - Testing of thyristor valves.

IEC 62927, Voltage sourced converter (VSC) valves for static synchronous compensator (STATCOM)—Electrical testing.

IEEE Std 18™, IEEE Standard for Shunt Power Capacitors.^{5,6}

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

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

IEEE Std 1267™, Guide for Development of Specification for Turnkey Substation Projects.

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

IEEE Std 1313.2™, IEEE Guide for the Application of Insulation Coordination.

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

IEEE Std C57.123™, Guide for Transformer Loss Measurement.

IEEE/ANSI Std C63.16™, American National Standard Guide for Electrostatic Discharge Test Methodologies and Acceptance Criteria for Electronic Equipment.

¹Information on references can be found in [Clause 2](#).

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3. Definitions, acronyms and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁷

commercial operation: The acceptance, by the user, of the static synchronous compensator (STATCOM) from the supplier.

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

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

Hybrid STATCOM: A combination of both STATCOM and thyristor switched devices whose outputs are coordinated.

lagging operation: Inductive operation or reactive power absorption of the static synchronous compensator (STATCOM), similar to a shunt reactor.

leading operation: Capacitive operation or reactive power generation of the static synchronous compensator (STATCOM), similar to a shunt capacitor.

mechanically switched capacitor/mechanically switched capacitive damping network (MSC/MSCDN): A shunt-connected circuit containing a mechanical power-switching device in series with a capacitor bank and sometimes also a current limiting reactor (MSC). In typical MSCDN branches the reactor/auxiliary capacitor is paralleled by a resistor.

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

point of common coupling (PCC): The connection point between the STATCOM and the power system at which performance requirements are defined.

point of connection (POC): For a STATCOM with a dedicated transformer, the high-voltage (HV) bus to which the whole is connected. For a STATCOM connected to an existing transformer, or direct connected, the busbar to which the STATCOM is connected.

reference voltage (V_{ref}): The point on the voltage/current (V/I) characteristic where the static synchronous compensator (STATCOM) is at zero output (i.e., where no reactive power is absorbed from, or supplied to, the transmission system where the voltage is controlled).

response time: The duration from a step change in control signal input until the voltage changes by 90% of its final change, before any overshoot.

settling time: The duration from a step change in control signal input until the STATCOM output settles to within $\pm 5\%$ of the required control output.

slope: The ratio of the voltage change to the current change over a defined controlled range of the STATCOM, normally the full (inductive plus capacitive) range at nominal voltage, expressed as a percentage.

⁷*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>

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

STATCOM system: An SVS where the static var device includes a VSC.

STATCOM valve: Electrically and mechanically combined assembly comprised of forced commutated devices (for example, IGBT) assembled in levels, complete with all connections, auxiliary components, and mechanical structures, which can be connected in series with each phase of reactor of a STATCOM.

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

submodule: Part of a STATCOM valve comprising controllable switches and diodes connected in a half bridge or full bridge arrangement, together with their immediate auxiliaries, and storage capacitor, if any, where each controllable switch consists of one or more switched valve device(s) connected in series.

thyristor-switched capacitor (TSC): A shunt-connected capacitor (or capacitor arranged as a filter) in series with a thyristor valve, which is used to switch the capacitor on or off. A current limiting reactor or a damping network is connected in series with the capacitor and the thyristor valve.

thyristor-switched reactor (TSR): A shunt-connected reactor in series with a thyristor valve, which is used to switch the reactor on or off.

voltage/current (V/I) characteristic: The relationship between the current of the STATCOM and the voltage at its point of connection.

VSC (voltage sourced converter): A forced commutated device (for example, IGBT) based self commutated converter that is capable of generating ac voltage from dc capacitor voltages.

NOTE—A number of terms defined in 3.1 are represented in Figure 1 and Figure 2.⁸

3.2 Acronyms and abbreviations

BIL	basic insulation level
CT	current transformer
EMI	electromagnetic interference
EMC	electromagnetic compatibility
ETT	electrically triggered thyristors
FAT	factory acceptance test
FACTS	flexible ac transmission system
HV	high-voltage
HVDC	high-voltage direct current
IGBT	insulated gate bipolar transistor
LTT	light-triggered thyristor

⁸Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

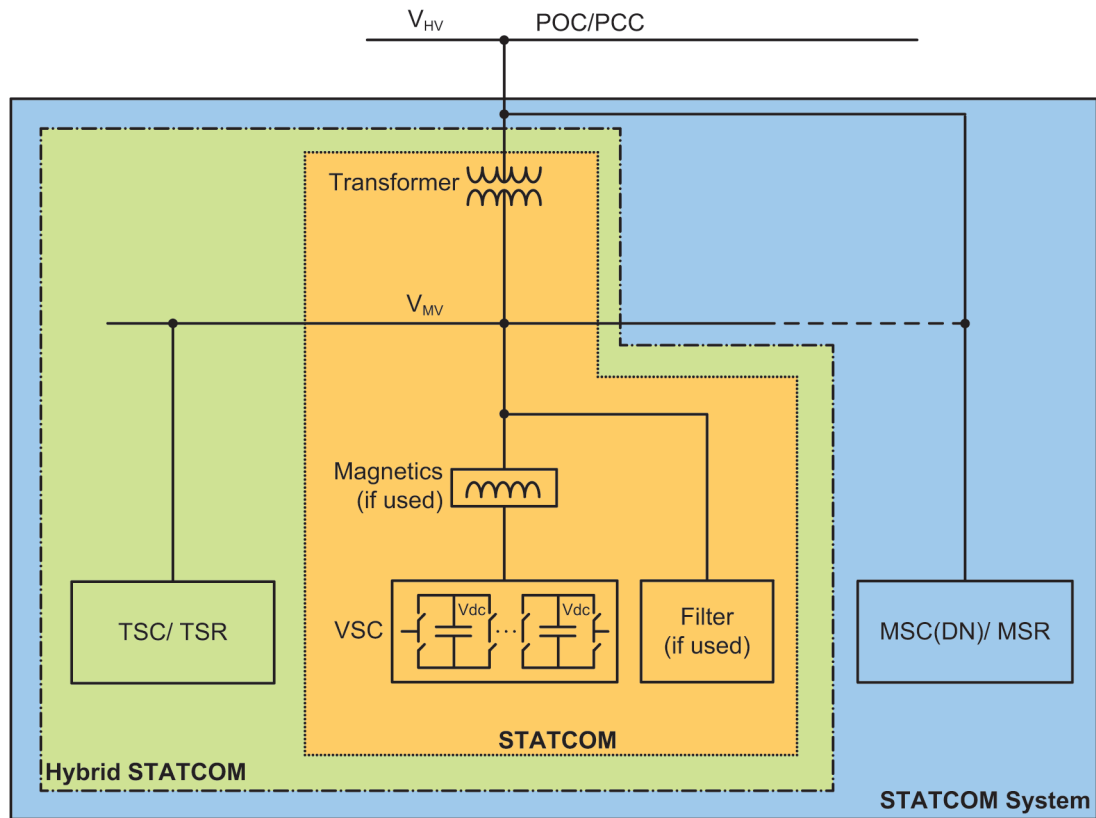


Figure 1—Explanation of STATCOM system nomenclature

LV	low-voltage
LVRT	low-voltage ride through
MSC	mechanically switched capacitor
MSCDN	mechanically switched capacitive damping network
MSR	mechanically switched reactor
PCC	point of common coupling
PLC	power line carrier
POC	point of connection
RI	radio interference
rms	root-mean-square
RTDS	real time digital simulator
SIL	switching impulse level
STATCOM	static synchronous compensator
SVC	static var compensator (thyristor-based)
SVS	static var system
SWC	surge withstand capability
TCR	thyristor controlled reactor

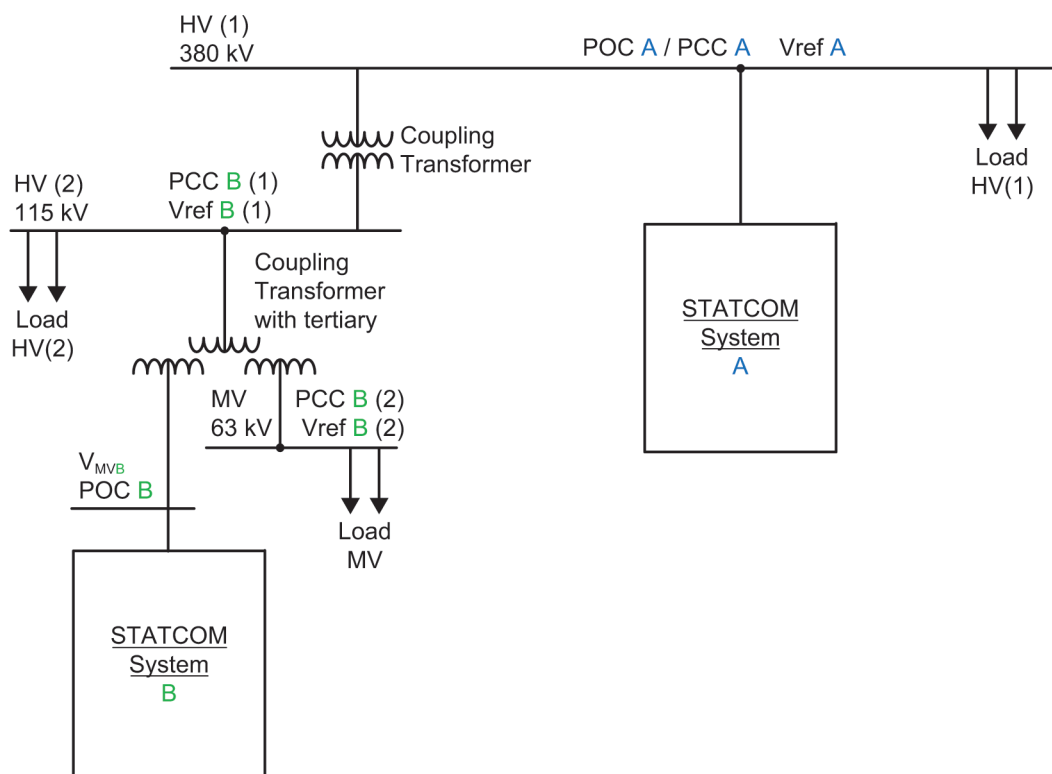


Figure 2—Example of POC, PCC, and Vref for different STATCOM system configurations

TIF	telephone influence factor
TNA	transient network analyzer
TSC	thyristor-switched capacitor
TSR	thyristor-switched reactor
TVI	television interference
V/I	voltage/current
VT	voltage transformer
VSC	voltage source converter

4. STATCOM system project description

The following text may be used as a project description for the technical specification of a STATCOM system:

This specification is for the design, manufacture of equipment, construction, installation, test, commission, warranty, training, and placement into commercial operation of a STATCOM system at _____ substation connected to the _____ busbar. The STATCOM system may consist of a power electronic based voltage source converter (VSC) converter complemented with fixed or thyristor-switched capacitor (TSC) banks and thyristor switched reactor (TSR), allowing asymmetrical operation in the leading and lagging Mvar region as applicable to reach the dynamic range specified. See B.5.1 for further discussion on STATCOM configuration. The purpose of the STATCOM system is to regulate the voltage of the _____ kV busbar. The nominal ratings of the STATCOM system are _____ Mvar leading at 1.0 p.u. voltage to _____ Mvar lagging at 1.0 p.u. voltage.

A regional and local site location map is shown in Figure _____. A simplified system one line diagram showing the sources, interconnected transmission lines, and other system components is attached in Figure _____. A proposed one-line diagram of the _____ substation after installation of the STATCOM system is shown in Figure _____. The area for the STATCOM system facility is shown in Figure _____. The points of physical and electrical interconnection between the supplier-furnished STATCOM system and the user-furnished facilities are shown in the following figures:

- _____ (site location)
- _____ (system one line diagram/substation electrical environment)
- _____ (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 STATCOM facility should provide for future expansion requirements as shown in Figure _____.

See [Annex B](#) for additional discussion of the VSC specification.

5. Scope of supply and schedule

5.1 Scope of supply

The following text and table may be used to define the scope of supply of the supplier and the user in the technical specification of a STATCOM system.

The equipment, materials, and services to be furnished by the supplier and the user are listed in [Table 1](#). Scope of supply of the supplier should include, but is not limited to, the items checked in the “Provided by supplier” column.

Table 1—Scope of supply checklist

	Item	Provided by supplier	Provided by user	Remarks
1	VSC or other devices including controls and cooling equipment			
2	Step down or coupling transformer			
3	HV switchgear: circuit breaker, disconnects, grounding switches			

Table continues

Table 1—Scope of supply checklist (continued)

	Item	Provided by supplier	Provided by user	Remarks
4	LV switchgear (circuit breaker, disconnects, grounding switches) and cables if used for connection to LV bus			
5	Measuring equipment Voltage transformers (VTs) Current transformers (CTs)			
6	Surge arresters			
7	Grounding transformers			
8	Reactors			
9	Capacitors			
10	Harmonic filters			
11	Station services dedicated to VSC			
12	Yard control, protection, alarm, and monitoring systems			
13	Special maintenance equipment and tools			
14	Training program for operation and maintenance personnel			
15	Spare parts			
16	Testing and commissioning services			
17	Documentation including instruction manuals			
18	Civil works for the STATCOM system, including the switchyard, fencing, drainage, access, and parking			
19	VSC building, including air conditioning and grounding			
20	VSC foundations and structures to mount busbars, including grounding and ground mat connections			
21	Fire detection and protection systems (building and components)			
22	Physical security systems			
23	Detailed STATCOM system simulation models			
24	Engineering studies			
25	Others			
26	Site for the STATCOM system			available ___ calendar days after contract start
27	Source of water for construction			
28	Source of temporary station service power for construction			___ kV available ___ calendar days after contract start
29	___ sources of permanent station service power for the STATCOM		X	___ kV available ___ calendar days after contract start
30	Existing facilities and equipment		X	
31	Building permits			

5.2 Schedule

The user should specify the expected project schedule. The paragraphs that follow may be used.

Project completion (Testing and Commissioning) 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 STATCOM. The first design review should be held within ___ calendar days after contract start. Subsequent design reviews should be held according to agreed project schedule.

6. Site and environmental data

Site and environmental data should be provided by the user in the technical specification as they may have a significant impact on the design of the STATCOM system. The text and [Table 2](#) may be used.

The STATCOM system should be designed to meet all rating and performance requirements specified in this document while operating in the site and environmental conditions described in [Table 2](#).

Table 2—Site and environmental data

#	Site characteristic	Value	Unit
1	Site elevation above sea level		m
2	Maximum ambient dry-bulb temperature		°C
3	Maximum ambient wet-bulb temperature		°C
4	Minimum ambient air temperature		°C
5	Maximum daily average ambient air temperature		°C
6	Minimum daily average ambient air temperature		°C
7	Ice loading conditions (thickness)		mm
8	Maximum ground snow depth		m
9	Maximum frost depth		m
10	Maximum steady wind velocity		m/s
11	Wind gust factor or maximum wind gust		m/s
12	Seismic zone and withstand data		
13	Isokeraunic level		days/yr
14	Creepage distance (per IEEE Std 1313.2™) or dust concentration (or pollution level per IEC 60815)		mg/cm ² or pollution level
15	Salt concentration		mg/cm ²
16	Solar radiation level		W/cm ²
17	Ground resistivity		Ω-m
18	Humidity		%
19	Existing ambient noise		dB(A)

7. Power system characteristics

Power system characteristics may have an impact on the design and performance of a STATCOM system and should be included in a technical specification. The text and [Table 3](#) show an example for the specification of power system characteristics.

The following ac power system characteristics apply at the point of connection. Normal STATCOM operation is required within the parameter values and durations given in [Table 3](#).

Table 3—Power system characteristics

#	Power system characteristic	Value	Unit
1	Nominal ac system voltage, line-to-line		kV
2	Maximum continuous ac system voltage, line-to-line		kV
3	Minimum continuous ac system voltage, line-to-line		kV
4	Maximum short-term ac system voltage, line-to-line	See B.5.2.2	kV
5	Maximum duration of item 4	See B.5.2.2	s
6	Minimum short-term ac system voltage, line-to-line	See B.5.2.2	kV
7	Maximum duration of item 6	See B.5.2.2	s
8	Continuous negative-sequence voltage component (used for performance calculation)		%
9	Continuous negative-sequence voltage component (used for rating calculation)		%
10	Continuous zero-sequence voltage component		%
11	Nominal ac system frequency		Hz
12	Maximum continuous ac system frequency		Hz
13	Minimum continuous ac system frequency		Hz
14	Maximum short-term ac system frequency		Hz
15	Maximum duration of item 14		s
16	Maximum rate of change of frequency (df/dt)		Hz/s
17	Minimum short-term ac system frequency		Hz
18	Maximum duration of item 17		s
19	Basic insulation level (BIL)		kV peak
20	Switching impulse level (SIL)		kV peak
21	Power frequency withstand voltage		kV
22	Maximum three-phase fault current -for performance requirements -for rating of STATCOM [see item k) of 8.1] -X/R -Clearing time - normal -Clearing time - backup -Auto-reclose -Phase angle change (maximum) if required	See Annex E	kA kA for ___s cycles cycles s °
23	Existing three-phase fault current		kA
24	Minimum three-phase fault current -for performance requirements -for safe operation		kA kA
25	Maximum single-phase fault current		kA
26	Existing single-phase fault current		kA
27	Minimum single-phase fault current		kA

Table continues

Table 3—Power system characteristics (continued)

#	Power system characteristic	Value	Unit
28	Harmonic impedance sectors for each harmonic number up to the 49th harmonic or system impedance data as R-X values with frequency steps not larger than 1 Hz (for performance and/or STATCOM system component rating)	See Figure B.8 in B.5.4.2	
29	Background harmonic voltage (or current) spectrum (for STATCOM components rating)	See B.5.4.3	
30	Geomagnetic induced current (GIC) for transformer design (optional)	See Annex D	A
31	Power system phase rotation		CCW or CW

8. STATCOM system characteristics

8.1 STATCOM system rating

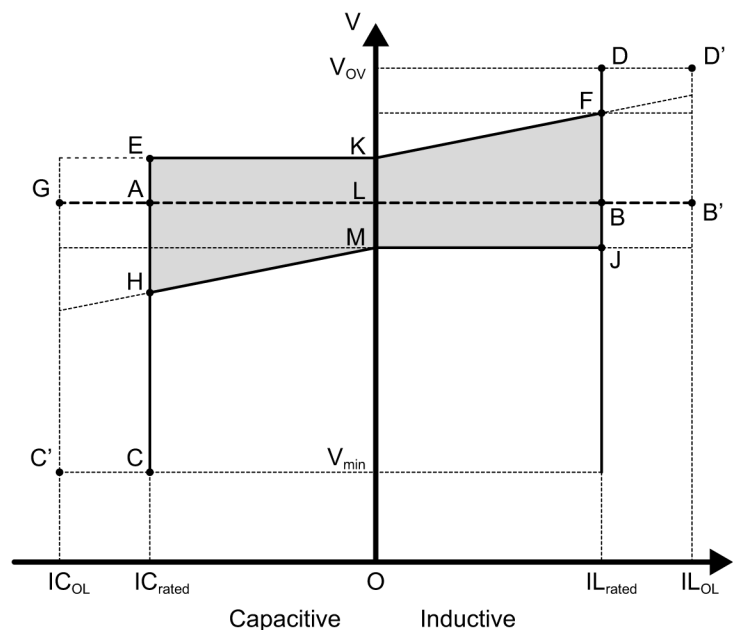
The expected ratings of the STATCOM system should be included in the technical specification. The following text and figures give guidance on how to specify the required ratings.

The output of a STATCOM system can be adjusted continuously over the range illustrated in [Figure 3\(b\)](#). The following items define the ratings of the STATCOM system equipment. More detailed information on the items that follow is added to [Annex B](#).

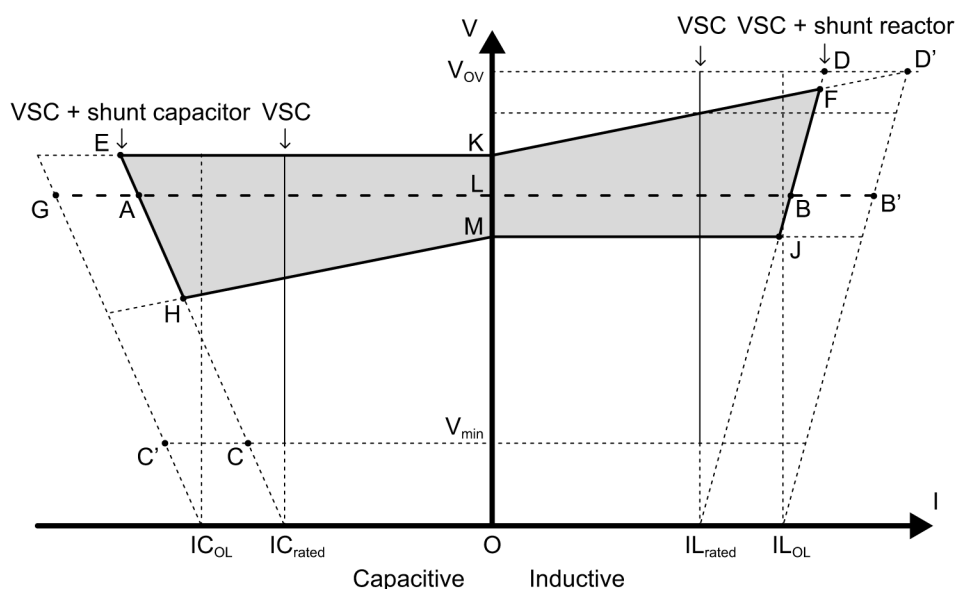
- The STATCOM system should regulate the _____ kV bus voltage to a reference voltage of _____ kV (1.0 per unit), continuously adjustable between _____ per unit and _____ per unit.
- The nominal capacitive reactive power output of the STATCOM system should be _____ Mvar at 1.0 p.u. ac bus voltage and nominal system frequency, and _____ °C ambient temperature. Refer to the voltage/current (V/I) characteristic in [Figure 3\(b\)](#) at point A.
- The nominal inductive reactive power output of the STATCOM system should be _____ Mvar at 1.0 p.u. ac bus voltage and nominal system frequency, and _____ °C ambient temperature. Refer to the V/I characteristic in [Figure 3\(b\)](#) at point B.
- The slope of the characteristic should be adjustable in steps of not greater than _____ % between _____ % and _____ %, on a basis of _____ (A+B (optional G+B)) MVA [see [Figure 3\(b\)](#)].
- The STATCOM system should continue to generate reactive power during a temporary undervoltage down to the value given in [Clause 7](#) (item 6 in [Table 3](#)) for the duration given in [Clause 7](#) (item 7 in [Table 3](#)) [point C optional C' on [Figure 3\(b\)](#)]; the STATCOM system may be tripped (or blocked) if the undervoltage persists for more than _____ s.
- The STATCOM system should continue to absorb reactive power during a temporary overvoltage in a controlled manner up to the value given in [Clause 7](#) (item 4 in [Table 3](#)) for the duration given in [Clause 7](#) (item 5 in [Table 3](#)) [point D on [Figure 3\(b\)](#)]; the STATCOM system may be tripped if the overvoltage persists for more than _____ s.
- (Optional) The temporary capacitive reactive power output of the STATCOM system, associated with the operation of the VSC, should be _____ Mvar at _____ per unit ac bus voltage for _____ s [[Figure 3\(b\)](#), point G], following continuous operation at any operating point in the steady-state operating region. (This temporary capacitive output is the additional capacitive output provided by the STATCOM, as shown on [Figure 3\(a\)](#), point G, and is not achieved by the addition of extra capacitors.)
- (Optional) Continued controllable conduction of the STATCOM system associated with the operation of the VSC to absorb reactive power should be possible up to _____ per unit ac bus voltage for _____ s [[Figure 3\(b\)](#), point B'], following continuous operation at any operating point in the steady-

state operating region. (This temporary capacitive output is the additional inductive output provided by the STATCOM, as shown on [Figure 3\(a\)](#), point B', and is not achieved by the addition of extra capacitors.)

- i) The STATCOM system should be capable of repeating temporary operation as defined in any one of item e), item f), item g), or item h) of [8.1](#) every _____ min.
- j) The coupling transformer and all bus equipment, if used, such as filter branches, capacitor bank branches (thyristor switched or fixed), 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 STATCOM system should be capable of sustaining, without damage, any fault limited by the maximum design short circuit level of the system and the VSC transformer impedance, if a coupling transformer is used.



(a) VI curve of the VSC portion



(b) Example of VI curve of a STATCOM system

- A is defined by item b) of 8.1 giving the capacitive design point for continuous operation
- B is defined by item c) of 8.1 giving the inductive design point for continuous operation
- C, C' is defined by Clause 7 (item 6 and item 7 in Table 3)
- D is defined by Clause 7 (item 4 and item 5 in Table 3). It is an extension of line IL_{rated}-B
- E is an extension of line IC_{rated}-A at maximum reference voltage (K) and minimum slope
- F is an extension of line IL_{rated}-B at maximum reference voltage (K) and maximum slope
- G is defined by item g) of 8.1 giving the capacitive design point for short time operation
- H is an extension of line IC_{rated}-A at minimum reference voltage (M) and maximum slope

Figure 3—Example of VI characteristic of a (a) STATCOM and a (b) STATCOM system

(figure continues on next page)

J	is an extension of line ILrated-B at minimum reference voltage (M) and minimum slope
K	Maximum reference voltage
L	Nominal reference voltage
M	Minimum reference voltage

Figure 3—Example of VI characteristic of a (a) STATCOM and a (b) STATCOM system

8.2 Control objectives

8.2.1 STATCOM system functions and applications, with priority

The technical specification of a STATCOM system should include a description of the required control modes and their priority. More information about the available control functions is available in [B.1.2](#). An example is given as follows.

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

- a) Fixed reactive power mode (FQM)
- b) Voltage control mode (VCM/manual control mode)
 - 1) Control of the positive sequence component of the fundamental frequency voltage in steady state and dynamic operation, with slope in the range of _____% to _____% at _____ MVA base.
 - 2) Control of phase voltages (based on positive and negative sequence voltage). (optional)
- c) Supplementary control functions
 - 1) Gain supervision

To control regulator gain in order to prevent oscillations and excessive overshoot in the STATCOM response, a gain supervision function can be implemented. This function monitors the STATCOM response following a system disturbance. If required, an order to reduce the regulator gain based on frequency range, amplitude, and number of consecutive oscillations of the response will be issued. Gain reduction should be indicated and provisions for reset should be provided either automatically or by the operator.
 - 2) Coordinated reactive power control of external devices (optional)

To optimize the use of dynamic vars versus steady state vars, control of externally connected shunt capacitor or reactor banks can be implemented. Such banks can be connected either locally to a HV bus also connected to the STATCOM unit (see [Figure 4](#)) or remotely several busses removed (see [Figure 5](#)). The location of the banks to be controlled may call for different strategies and interface signals. If applied simultaneously with the supplementary VSC current controller, the two functions require careful coordination. External devices like mechanically switched capacitor (MSC)/mechanically switched reactor (MSR) can be switched ON or OFF to position the steady state operating point of the VSC so as to extend its dynamic range.

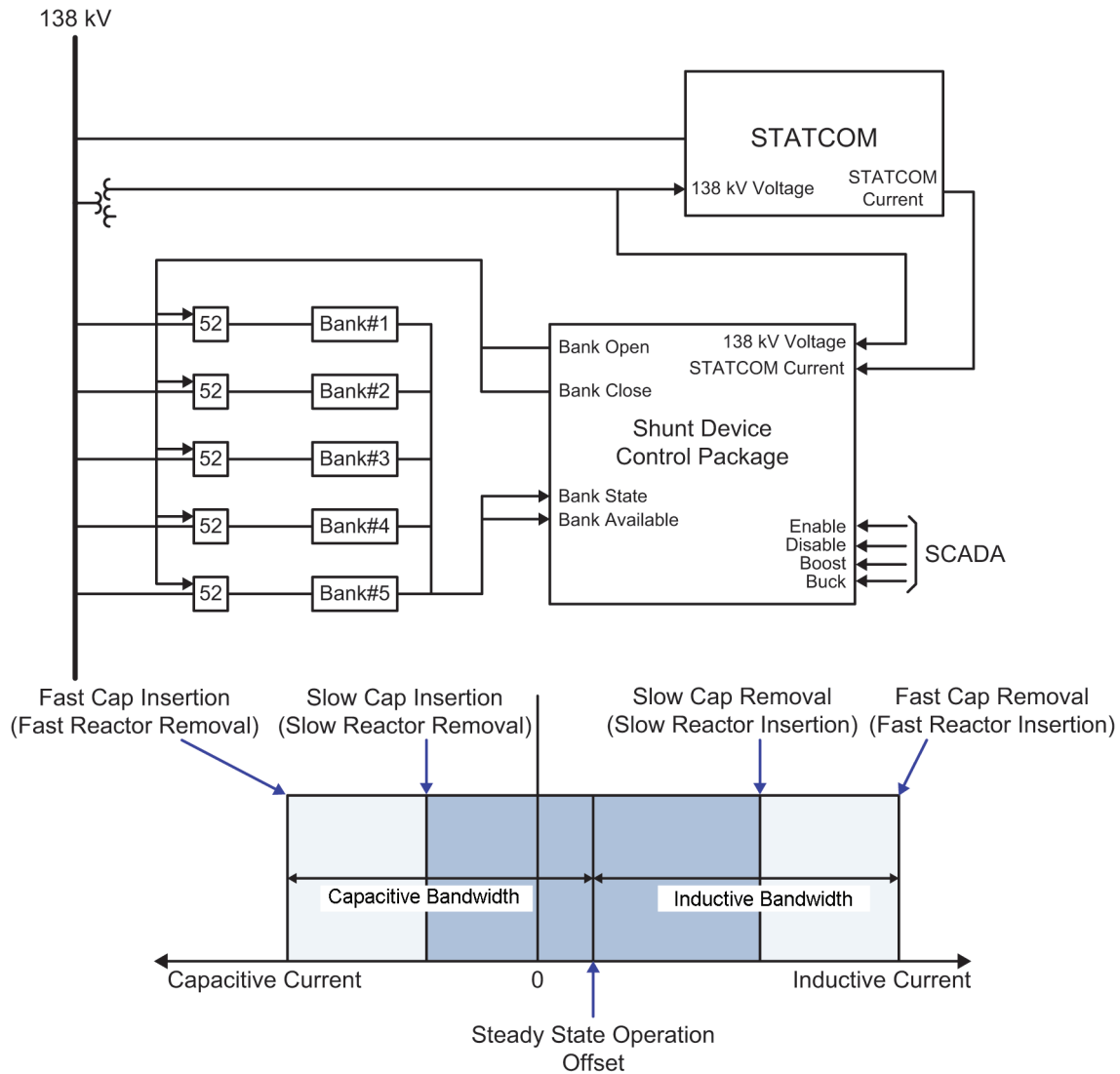


Figure 4—Local bank control scheme

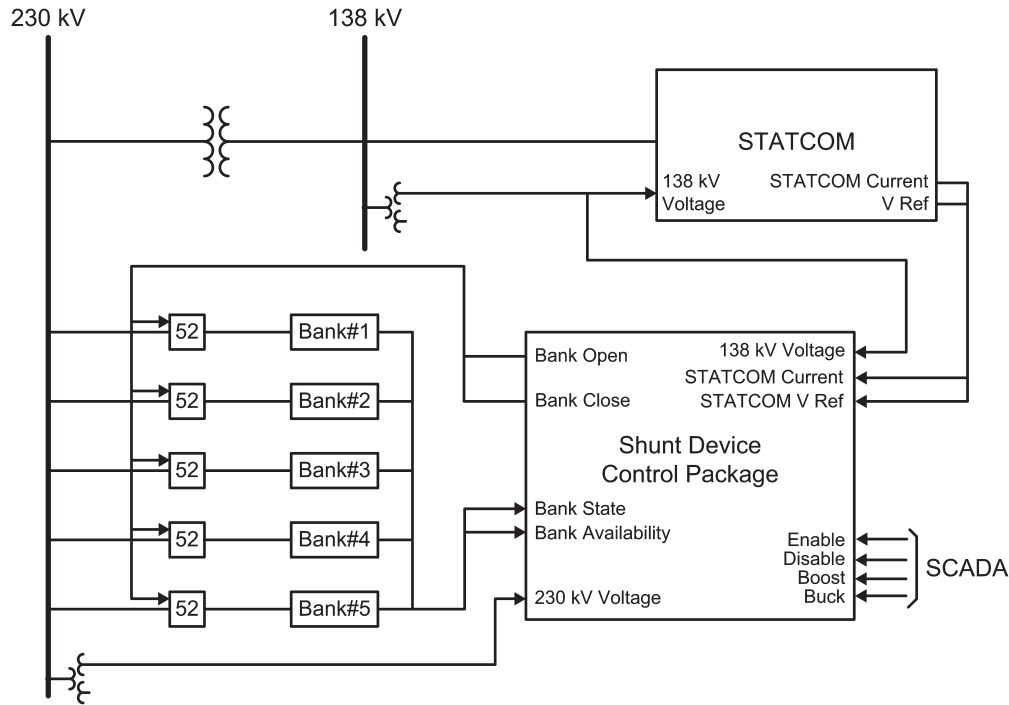


Figure 5—Remote bank control scheme

3) Supplementary VSC current controller (optional)

To optimize the use of dynamic vars versus steady state vars, a control function that slowly reduces or offsets the STATCOM point of operation can be implemented. By deliberately adjusting the voltage reference setting within a narrow window the STATCOM system output is pushed toward either a specific point or toward a window to preserve dynamic range. This slow operating function is meant to provide for slower controllers, such as transformer LTCs or externally connected shunt bank standalone AVR systems to operate and meet the slower long term voltage variations caused by daily or weekly load variations. Rapid changes in the system voltage that call for dynamic compensation will have priority over this type of controller. Figure 6 shows an example of implementation of a VSC current controller.

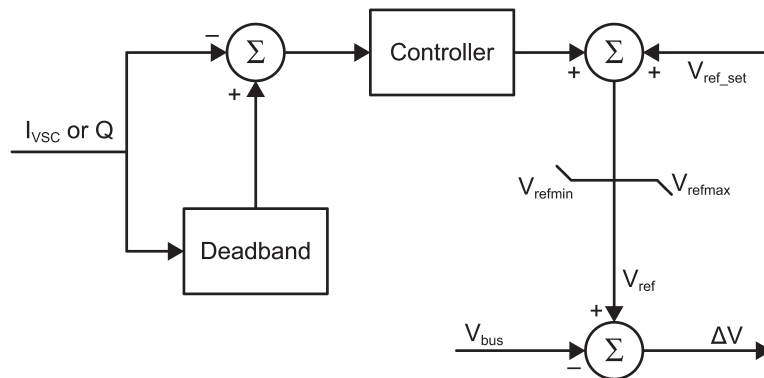


Figure 6—Supplementary VSC current controller

4) Power oscillation damping (optional)

To increase the damping of power system oscillations occurring in the power system close to the STATCOM installation, a power oscillation damping (POD) function can be implemented in the STATCOM control. Power or frequency are measured and used as input signals for a supplementary control function that supply a modulated output, with gain and phase shift optimized to the oscillation mode or modes of interest. These are usually in the range of 0.2 to 2.0 Hz. Figure 7 illustrates how POD function can be integrated in the STATCOM system controller.

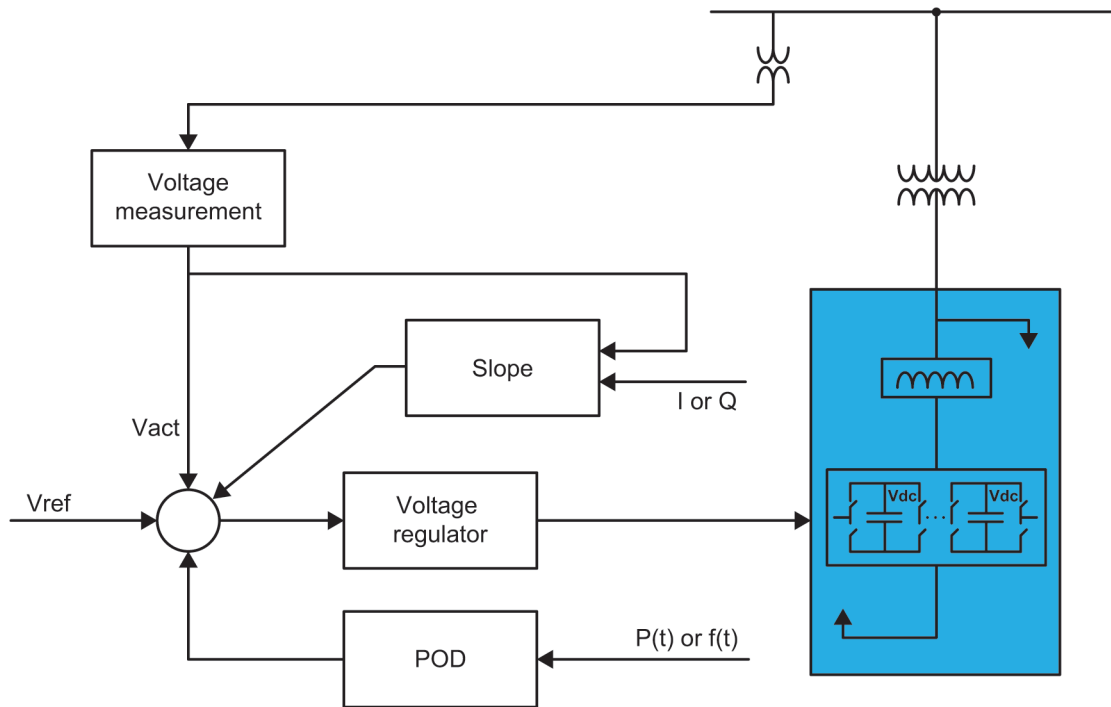


Figure 7—STATCOM controller with POD

5) Gain optimization (optional)

To provide operation at optimal regulator gain, a fully automatic optimizing function can be implemented. This function operates by inducing a small change in the STATCOM output. The gain is adjusted based on the network response signal.

8.2.2 Response

The response time of a STATCOM system is often defined by its step response and can be specified as follows:

The step response defined in Figure 8 has the aim to define the speed of the control system (controller, system, and measuring circuit). By specifying the response and settling time the performance of the control system will be defined. In the case where the step is not only performed by linear control devices [thyristor controlled reactor (TCR) or VSC] and a switched branch like a TSC is switched in during a step response, the result of overshoot and settling time cannot be used to evaluate the control system performance. For linear control devices the change of measured system voltage to small disturbance should reach 90% of the desired total change within ____ ms of the initiating a ____% step change of voltage reference. The maximum overshoot should not exceed ____% of the total change, and the settling time should not exceed ____ ms, after which the voltage should be within $\pm 5\%$ of the final value. This response characteristic within these limits must be

respected when the system three-phase fault MVA is between the minimum and the maximum value defined in [Clause 7](#). The response of the system voltage using the actual controller should be validated on a real time simulator during the factory acceptance test (FAT). A Thevenin network equivalent is sufficient for this purpose.

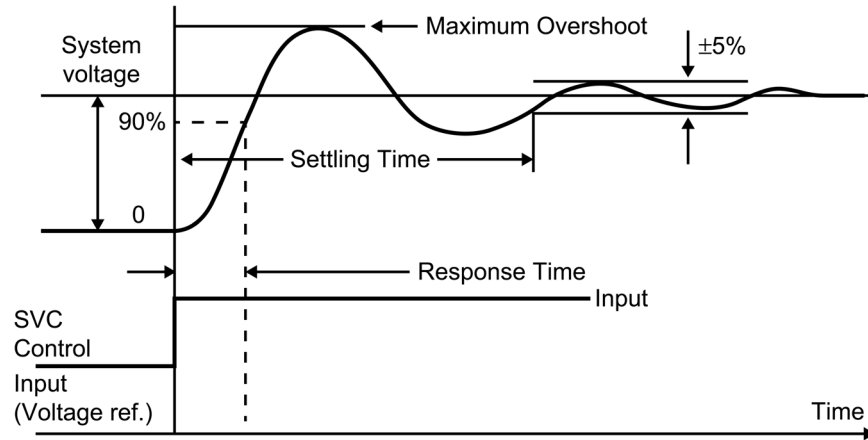


Figure 8—Definition of response and settling time

8.3 Harmonic performance

8.3.1 General information

The STATCOM system should be designed to reduce the effects of resonance between its shunt capacitor banks, filter branches, and the ac system, and, hence, to limit the harmonic distortion imposed on the connected transmission system.

The STATCOM system purchaser will also need to indicate whether the full planning level limit (taking into account the distortion already existing) is available for the distortion due to the VSC, or only a part of that planning level is available based on the size of the STATCOM system as a proportion of the total MVA capability of the substation (refer to Chapter 9 of IEC 61000-3-6).

Refer to [B.5.4](#) for additional information.

8.3.2 VSC filter design and performance

Filters may have to be used to meet harmonic distortion requirements.

Given the many available STATCOM system configurations, many harmonic filter designs can be used. The choice of design implementation is the responsibility of the STATCOM system supplier. More detailed description is available in [B.5.4](#).

8.3.3 Filter component rating

The harmonic filter system should be rated to carry continuously the harmonic currents produced by the VSC and, if relevant, the harmonics present in the form of background harmonic distortion of the system. Unless otherwise specified, harmonic currents from the power system and those of the STATCOM system of the same order should be added following the general summation law (refer to Chapter 7 of IEC 61000-3-6). All harmonic currents of different order should be added quadratically (root sum of squares) or following the guidance of IEC 62001-4 [\[B27\]](#).

NOTE—The open circuit system calculation described in Chapter 2.2.4.2 of IEC 62001-4 [B27] is not applicable to STATCOM systems.

More detailed description is also available in B.5.4.

8.4 Telephone and radio interference

8.4.1 Telephone interference (refer to IEEE Std 519™ for additional details)

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

- The $I \times T$ product should be less than _____. The $I \times T$ product is defined by IEEE Std 519™ as the inductive influence expressed in terms of the product of its root-mean-square (rms) magnitude (I), in amperes, multiplied by its telephone influence factor (TIF). The weighting factors from the “C-message” are established in IEEE Std 519.
- The $kV \times T$ product should be less than _____. The $kV \times T$ product is defined by IEEE Std 519 as the inductive influence expressed in terms of the product of rms voltage magnitude (V), in kilovolts, multiplied by its TIF. The weighting factors from the “C-message” are established in IEEE Std 519.

More information is available in B.5.5.1. The user should specify the impedance and the equivalent circuit or model, which is necessary for the calculation.

8.4.2 Broadband interference

If required, broadband interference limits should be included in the technical specification. The user should refer to local standards to determine the specific limits acceptable for their respective country.

More information is available in B.5.5.2.

8.5 Audible noise

The supplier should design and construct the STATCOM system to limit the audible noise interior and exterior to the facilities. The technical specification should contain the applicable limits and the measurement locations, as well as measurement procedures to be used if required. B.5.6 gives additional guidance.

8.6 Loss evaluation

8.6.1 General information

Power losses of electrical apparatus are becoming increasingly important due to the high cost of energy. The STATCOM system purchaser should clearly state how cost of losses is considered in the whole STATCOM system project. Some STATCOM system purchasers may consider STATCOM system losses only for information; others will consider cost evaluated losses in the overall STATCOM system costs. The purchaser should state whether the cost of losses is to be considered in the evaluation of the bid. The losses should be stated for the POC.

The bidder should supply the estimated or warranted total losses (kW) calculated in accordance with the equations summarized in B.5.7 and Annex C. It should be assumed that ambient temperature is _____ °C, the busbar voltage is _____ per unit, and the slope setting is _____ %. The STATCOM system 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 STATCOM system in operation or connected, whether conducting current or not. Parts can be defined to be any system’s subsystem or device that is required

to be operational or in service, which will allow the STATCOM system to fulfill the specified requirements, dynamic and transiently. When more than one combination of STATCOM system parts might operate at a given output (so called overlap range of at least two switching states) and almost continuous operation at the switching state with lower losses is possible, these lower losses should be taken into consideration. This, however, depends on the control strategy minimizing the losses in the overlap range and has to be described by the bidder and checked at the FAT. If such a control strategy is not used, 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). The losses are calculated including all redundant auxiliary supply systems (ac and dc), and control and protection systems, but exclude dual devices on the cooling systems such as redundant cooling pumps and redundant fans since they are not in operation. However, redundant valve levels are to be included. As a general rule, all devices that are required to fulfil the operational requirements of the STATCOM system, are to be included in the determination of the losses.

8.6.2 Switching devices losses

8.6.2.1 VSC losses

VSC converter losses are composed of losses in power electronic switches [insulated gate bipolar transistor (IGBT) or other], made up of conduction and switching losses, and the losses in dc capacitors, resistors, and inductors used within the converter system. See [B.5.7.2](#) and [Annex C](#) for details.

8.6.2.2 Thyristor valves losses

Refer to [B.5.7.3](#).

8.6.3 Transformer losses

The transformer losses are a function of the transformer resistance and the 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 STATCOM system operating point required in [8.6.8](#) should then be calculated using this resistance and the predicted transformer current for that STATCOM system output.

More details can be found about transformer losses measurement in IEEE Std C57.123™.

8.6.4 Reactor losses (if used)

The reactor losses are calculated from the rms fundamental phase current I . For formulas see [B.5.7.5](#).

The calculation in [B.5.7.5](#) applies to VSC phase reactors, thyristor switched reactors (TSR), MSRs, TSC tuning reactor (if used), and filter reactors (if used).

8.6.5 Capacitor bank losses [TSC, MSC(DN), and filters (if used)]

In the test report for each capacitor unit, as per IEEE Std 18™, the dissipation factor (tan delta) is given. An average value for all capacitor units is used to calculate the capacitor bank losses. For formulas see [B.5.7.6](#)

8.6.6 Resistor losses

Resistors are included in damped filter configurations [e.g., high pass (HP) filters, high frequency blocking filters, mechanically switched capacitive damping network (MSCDN)]. The resistor losses are calculated according to formulas shown in [B.5.7.7](#).

8.6.7 Auxiliary system power

The power used by the auxiliary systems for pumps, fans, and building cooling and heating systems is deduced for each specified condition of the ambient temperature and reactive power flow. Nominal auxiliary supply voltage is assumed. Values for auxiliary power can be assumed from previous projects and have to be measured after installation for comparison purposes.

8.6.8 Total loss evaluation

The losses for each equipment in operation that the end-user wants to include ([8.6.2](#) through [8.6.7](#)) are summed for each load level from full capacitive to full inductive output and shown in a loss curve over its steady-state operating range at a system voltage of 1.0 pu.

The losses in the different operating ranges should be averaged and evaluated by the operating time. Refer to [B.5.7](#).

The sum of the loss values should be added to the investment cost of the equipment to determine the total evaluated cost (see [Annex C](#)).

A similar calculation may be done after the equipment FAT to determine the final loss costs. Auxiliary losses can be measured and evaluated after commissioning. If the losses are higher than the losses stated in the enquiry document, the difference may be calculated as a penalty and can be subtracted from the final cost.

8.7 STATCOM system availability and reliability

8.7.1 Definitions

The following definitions apply:

- a) Forced outages are outages caused by faults in the STATCOM system equipment that result in loss of part or all of the essential functions of the STATCOM system.
- b) Scheduled outages are outages necessary for preventive maintenance to assure continued and reliable operation of the STATCOM system. They may result in the temporary loss of part or all of the STATCOM system.
- c) Outage duration is the elapsed time in hours from the instant the STATCOM system 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 STATCOM system 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 by Equation (1) with duration in hours:

$$\left[1 - \sum \frac{D}{8760}\right] \times 100 \quad (1)$$

where

D is the duration of the equivalent event (forced outages) in hours

8.7.2 Required availability and reliability

Reliability performance is required of the STATCOM system, as follows:

- The annual availability for forced outages for the STATCOM system should be at least _____%.
- There should be less than _____ (number) forced outages of the STATCOM system per year.
- The bidder should state the expected or guaranteed average number and duration of scheduled outages per year.

The bidder should guarantee the quoted availability performance for ____ years from commercial operation. The supplier will be notified of major outages. During the guarantee period, the user will 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 different from the values stated in item a) and item b) of 8.7.2, 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 the average over ____ consecutive years of operation within the guaranteed values have been achieved.

- 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

9.1 General requirement

All materials that will become a part of the completed work should comply with applicable standards listed in Clause 2.

9.2 Switching devices [VSC (STATCOM) and thyristor valves (TSC/TSR)]

9.2.1 Overall performance

The electronic switches should be designed with the aim to achieve operation according to the overall performance requirements of the STATCOM system.

9.2.2 Access to power switching device submodules

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

9.2.3 Design robustness

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

- a) The switching devices should withstand maximum overvoltage and overcurrent stresses due to system faults and switching.
- b) The switching device's design should include an appropriate allowance for unequal voltage distribution across individual devices in the valve due to stray capacitor and component tolerances.
- c) The switching devices 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 switching device should be able to operate within component ratings, generally with at least one failed submodule or level. The number of possible failed submodules or levels should be selected by the supplier, demonstrated to the user, and be consistent with the availability requirements of the STATCOM system.

9.2.4 Maintenance

Switching submodule monitoring and maintenance requirements are as follows:

- A monitoring means to identify any VSC submodules or thyristors that have failed should be provided.
- The switching devices should be designed to allow easy replacement of failed submodules' components or thyristors. Other system components or filter branches should be capable of continued service while a submodule component is being changed or during similar maintenance.

9.2.5 Switching devices protection

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

- VSC submodules should be protected against overvoltages with appropriate strategies. Description of the failure mode of the switching device and the strategies used following failure should be provided.
- TSR valves should be protected against overvoltages by a forced firing system (refer to IEEE Std 1031™).
- TSC valves should not be fired under overvoltage conditions.

9.2.6 Testing

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

9.2.7 Startup and energization

The STATCOM system should be designed to allow full and automated start-up with and without energization of the voltage source internal capacitors. The bidder should describe the details of the energization sequence, including the charging circuits for the VSC, auxiliary power requirements, and constraints for all switching devices. The bidders should provide details on the impact on the system voltage during all possible energization and charging conditions and, in particular, during the maximum and minimum system strengths (three-phase fault current conditions). The information should provide timing sequences for both the pre-charging and energization duration until the STATCOM is fully in service. The bidders should include an analysis of the ability or constraints to start the STATCOM with no auxiliary ac power available from the network.

9.2.8 Low-voltage and overvoltage ride through (LVRT and OVRT) of the STATCOM system

The STATCOM system should be designed to allow effective ride through of the STATCOM during short durations of LV or HV conditions. The bidder should describe the details of the dynamic performance and output of the STATCOM during different LV or HV conditions (both as a function of the voltage magnitude and the duration of the abnormal voltage condition).

9.3 VSC (STATCOM) and thyristor valves (TSC/TSR) cooling system

9.3.1 Liquid cooling (if applicable)

If liquid cooling can be provided by the manufacturer, the user should specify the minimum requirements for such a cooling system. The following requirements may be used:

- a) A closed-loop recirculating system should provide full heat rejection capacity with redundancy for pumps, heat exchangers, and fans, appropriate to the STATCOM system availability requirements. The cooling system should be able to maintain full capacity at maximum ambient temperature and maximum STATCOM 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 deionization material should be sufficient for a period longer than the specified maintenance interval operation without replacement. Deionization 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.

9.3.2 Air cooling (if applicable)

If an air cooling system can be provided by the manufacturer, the minimum requirements should be specified by the user. The following may be used:

- 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.

9.3.3 Cooling system protection

The cooling system should monitor its own operation and the condition of the cooling medium, as follows:

- a) For liquid-cooled systems, the protection system should include, at a minimum, the following warning alarms:
 - 1) Depleted demineralizer (deionizing) cell
 - 2) Low water resistivity