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COMPENSATION DEVICES TO SUPPORT GRID INTEGRATION OF VARIABLE RENEWABLE ENERGY

TECHNICAL GUIDE

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ABBREVIATIONS

AC	alternating current
AVR	automatic voltage regulation
CAES	compressed air energy storage
CAGR	compound annual growth rate
CLR	current limiting reactor
DBR	dynamic braking resistor
DC	direct current
DO	distribution operator
EV	electric vehicle
FACTS	flexible alternating-current transmission system
FC	fixed capacitor
FCL	fault current limiter
FES	flywheel energy storage
FCC	forced commutated converter
FCL	fault current limiter
FMEA	failure mode and effects analysis
FSC	fixed-series capacitor
GCT	gate commutated turn-off thyristor
GTO	gate turn-off thyristor
GW	gigawatt
HMI	human-machine interface
HTS	high-temperature superconductor
HVAC	high-voltage alternating current
HVDC	high-voltage direct-current
HVRT	high-voltage ride-through
IGBT	insulated-gate bipolar transistor
ITP	independent transmission project
kV	kilovolt
LCC	line commutated converter
LVRT	low-voltage ride-through
MMC	modular, multilevel converter
MOV	metal-oxide varistor
MSC	mechanically switched capacitor
MVA	megavolt-ampere
MVAr	megavolt-ampere (reactive)
MW	megawatt
NCC	natural commutated converter
ONAF	oil natural, air forced
ONAN	oil natural, air natural
POI	point of interconnection
PPC	power plant controller
PST	phase-shifting transformer

PV	photovoltaic
RFB	redox flow battery
rms	root mean square
RTU	remote terminal unit (for SCADA)
SIL	surge impedance loading
SR	shunt reactor
SCC	synchronous condenser controller
SCCC	static synchronous series compensator
SCR	short-circuit ratio
SDBR	series dynamic-braking resistor
SSR	subsynchronous resonance
SSSC	static synchronous series compensator
SSSC+ES	static synchronous series compensator with energy storage
STATCOM	static synchronous compensator
STATCOM+ES	static synchronous compensator with energy storage
STATCON	static synchronous condenser
std	standard
SVC	static VAR (volt-ampere reactive) compensator
TCPAR	thyristor-controlled phase angle regulator
TCSC	thyristor-controlled series capacitor
TPSC	thyristor-protected series capacitor
TCR	thyristor-controlled reactor
TRV	transient recovery voltage
TSC	thyristor-switched capacitor
TSSC	thyristor-switched series capacitor
TSO	transmission system operator
VAR	volt-ampere reactive
VRE	variable renewable energy
VSR	variable-shunt reactor
VSC	voltage-source convertor
UPFC	unified power flow controller
WT	wind turbine

TECHNICAL GUIDES ON VRE GRID INTEGRATION: PREFACE

Over the past ten years, the cost of technology for variable renewable energy (VRE) such as wind and solar energy, has declined considerably, providing a cost-effective and sustainable means of meeting electricity demand in developing and middle-income countries. Taking advantage of variable sources of energy requires significant expansion and modernization of electrical grids and implementation of VRE-specific technologies, processes and requirements to gradually transition power systems into “VRE-friendly” grids that will significantly reduce integration costs in the long term. The need for technical assistance on VRE integration is greatest in countries with limited capacity to tackle technical and regulatory challenges. To meet this growing demand, the Energy Sector Management Assistance Program (ESMAP) of the World Bank has prepared a set of technical guides that can help World Bank staff and clients understand some of the essential requirements and available technical and regulatory measures to integrate large shares of VRE into power grids without compromising the adequacy, reliability or affordability of electricity. The technical guides have been developed as a joint initiative between ESMAP’s Variable Renewable Energy (VRE) Grid Integration Support Program and the Global Sustainable Electricity Partnership (GSEP). The Global Sustainable Electricity Partnership is a not-for-profit international organization comprising the leading companies in the global electricity sector who promote sustainable energy development through electricity sector projects and human capacity-building activities in developing nations worldwide.

It is projected for the next five years that annual worldwide addition of solar and wind energy will continue to grow and is likely to at least double compared to their current share in power systems. Modern renewable energy generation technologies provide a strong alternative for grid electrification in locations where renewable resources are abundant and are starting to become the least-cost option in many of the client countries thanks to rapid decline in prices. For this, many emerging economies have started to adopt policies to encourage the development of the industry to realize the benefits that renewable power generation can have for their energy supply and on the local environment. Solar and wind installations can be built relatively quickly, which presents a major incentive in rapidly-growing, emerging markets with urgent need for power and also tackle the realization of climate change commitments.

The key challenging issue, however, is the intermittent nature of solar and wind power, which increases the complexity of overall grid operations. The grid operators have to manage variability of the energy resource, reliability of grid operations and least-cost optimal performance. The fast penetration of renewable energy, and especially, a high level of their penetration into the power grid requires an adapted power system planning, better forecasting methods, introduces challenges in grid management, imposes stringent requirements for VRE integration into the grid, and necessitates standardization and structured process for the conducting studies to ensure compliance with the grid code requirements. The basic grid support services are becoming now relevant to all generators, including VREs, which are connected to medium and lower voltage levels. The modern electricity industry is restructuring with two major trends: significant increase of renewable energy and deregulation providing consumers with energy purchasing options of highly reliable delivery. However, deregulation, open energy access, and cogeneration are creating scenarios of transmission congestion and forced outages. Restructuring envisions the transmission grid as flexible, reliable, and open to all exchanges no matter where the suppliers and consumers of energy are located. The modernization of the grid requires the increased power quality, system stability, and increased transfer capacity of the transmission. New approaches to Power System Operation and Control are gaining the development momentum for overload relief and efficient and reliable operation. High-voltage direct current (HVDC) and Flexible Alternating Current Transmissions Systems (FACTS) technologies appear especially effective for improvement of grid operations and management.

The proliferation of smarter infrastructure, enabling participation of increasing amounts of demand in activities also help mitigate the variability of renewable generation along with technological advances of renewable and complementary technologies like batteries allow renewable generators themselves to effectively contribute to maintaining reliability. A variety of emerging end-use technologies like electrical vehicles, heat pumps, and smart and efficient buildings enable greater flexibility in power systems and lead to higher demand for wind and solar. These technologies help to enable even greater usage of VRE resources, but at the same time, they bring additional challenges of overall grid operations, which require new approaches to system operation and planning to ensure that the new trends contribute to clean, reliable and affordable power systems. A shorter dispatch cycles in combination with more accurate shorter-term forecasts of renewable generation can be used to reduce forecast variations from renewable generators and result in reduced ancillary service requirement. A look-ahead unit commitment and stochastic unit commitment can effectively deal with uncertainty. Wind farm can be tasked to provide frequency response, inertial response, and regulation if they meet eligibility requirements. Storage technologies are beginning to be gradually deployed or included in provision of ancillary services. Frequency regulation market, which awards quick-start and fast responding resources including batteries, has been attracting an increasing amount of battery storage and new ways of using storage. There are also ongoing innovations combining variable renewable production with measures aiming to make demand more responsive. The benefits and effectiveness of new emerging trends are well recognized, but there are yet to reach full maturity and become standardized. The focus of the technical guides is primarily on the industry proven technologies and methodologies, which have already been established, widely adopted, and continue to proliferate in electrical utilities. However, the discussion of some new VRE related technologies that have already started influencing the utility landscape (e.g. dynamic energy storage, implementation of superconducting materials in fault current limiting devices, advanced forecasting methodologies, wind farm synthetic inertia and regulation response) are selectively included in the technical guide material where appropriate.

The information presented in the technical guides is compiled from various sources of information to serve as a high-level guidance and quick reference for the World Bank personnel on electrical power system projects involving implementation of VRE along with associated technologies and analysis. The technical guides are comprised of the following four sets of sub-documents, which are identified as the subjects of prime technical interest for VRE implementation:

- Grid Integration Requirements for Variable Renewable Energy
- Compensation Devices to Support Grid Integration of Variable Renewable Energy
- Studies for Grid Connection of Variable Renewable Energy Generation Plants
- Using Forecasting Systems to Reduce Cost and Improve the Dispatch of Variable Renewable Energy

“Grid Integration Requirements for Variable Renewable Energy” document presents a general overview of VRE technology along with some recommendations for VRE technical specifications, applicable standards, and essential testing. The main focus of the document presents a detailed outline of the essential requirements of VRE power plants integration into power grid. The different levels of VRE penetration in the grid determine different technical requirements for VRE integration. However, some of the requirements are fundamental and need to be respected for a VRE integration in any power system, e.g. regulation and automatic response to grid events, power quality, protection system, forecasting and analysis. The basic and advanced VRE integration requirements are discussed in detail in this document in order to provide a guiding reference for VRE projects regardless of the grid code’s maturity. All essential requirements in the grid are summarized in the checklist table and can be used in course of VRE’s project planning, implementation, and connection to the grid. The compliance with the technical requirements and grid code where applicable is validated through extensive series of interconnection studies such as steady state analysis, short-circuit and circuit breaker duty review, dynamic stability, and facility studies.

“Compensation Devices to Support Grid Integration of Variable Renewable Energy” document provides an overview of FACTS and other compensation devices along with the essential characteristics describing industry need, applicable standards, functionality, applications, and recommendations for minimal technical specification. The main objective of the document is to discuss all available FACTS technologies with the underlying concept of independent control of active and reactive power flows, the essential differences and benefits of FACTS devices, and industry applications. Classification and comparison of performance factors are analyzed in detail and summarized to orient the reader in the wide spectrum of FACTS devices, and their effects on the power system. The applications of FACTS devices are associated with the following essential technical enhancements: System Capacity, System Reliability, Power Quality, System Controllability. Environmental benefits of FACTS are obtained through the deferral of the construction of much more expensive transmission lines and better utilization of existing system assets.

“Studies for Grid Connection of Variable Renewable Energy Generation Plants” discusses the power system studies requirements for the stable grid integration of renewable energy plants. These requirements differ depending on the size of generation, the location of the connection, and whether it is transmission or distribution system. The main purpose of screening studies involved in the interconnection process is a successful integration of the VRE into the grid. Power system planning for interconnection of new variable generation resources ensures that there are sufficient energy resources and evacuation capacity to interconnect new supply, and that demand requirements are met in a reliable and efficient manner. Also, the studies verify that adequate reserves and necessary system resources exist to reliably serve demand under credible contingencies such as the loss of a generating unit, a transformer, or a transmission facility.

“Using Forecasting Systems to Reduce Cost and Improve the Dispatch of Variable Renewable Energy” document discusses the need and benefit of forecasting capabilities and how it is becoming more relevant to both system operators and large-scale VRE generators. Forecasting solar or wind generation over a timeframe of days, hours and minutes before real time power system operations can reduce balancing costs, minimize VRE curtailment levels, improve system reliability and ultimately increase the penetration of VRE sources in the energy mix. The main objective is to focus primarily on the types of forecasting methods and how physical and statistical models are used for developing short- to long-term forecasts. Good forecast helps to reduce the gap between contracted supply of power and actual provision of power, reducing imbalance costs for the generator. Essentially, an effective forecasting system helps move the entire power system closer to a fully merit-order dispatch system, with reduced uncertainty and costs around variable generation supply. Technological advances in weather forecasting, which, together with better data on historical performance of renewable energy, allow significantly improved forecasting accuracy of renewable generation, which results in a more efficient utilization of VRE.

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The Technical Guides on VRE grid integration is a joint initiative by the Energy Sector Management Assistance Program (ESMAP) of the World Bank and the Global Sustainable Electricity Partnership (GSEP). GSEP is a not-for-profit international organization made up of the leading companies in the global electricity sector that promotes sustainable energy development through electricity sector projects and capacity-building activities in developing countries.

This Technical Guide is part of ESMAP's variable renewable energy (VRE) grid integration support program. This global program helps World Bank client countries achieve the cost-effective and sustainable scale-up of VRE by providing technical assistance, capacity building, and knowledge products for the development and implementation of planning, regulatory, market, and operational best practices in VRE integration.

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EXECUTIVE SUMMARY

The modern electricity industry is undergoing a major restructuring featuring a significant increase in the market penetration of variable renewable energy (VRE) sources. The deregulation of electricity markets has given consumers highly reliable options both for purchasing energy options and for selling it on the open market in a deregulated power system.

Driving this shift is a vision of the transmission grid as flexible, reliable, and open to all exchanges, no matter where the suppliers and consumers of energy are located.

However, the same trends are also contributing to transmission congestion and forced outages. Grid modernization requires an increase in the power quality, system stability, and increased transfer capacity of the transmission. The employed technologies range from passive reinforcements to electrical industry innovations such as super-conducting equipment, energy storage, and large-scale devices for routing grid power flow. Passive reinforcement, which generally involves the addition of new transmission lines, is often a challenging solution due to environmental and other considerations. Therefore, new approaches to power system operation and control are gaining development momentum for overload relief and efficient and reliable operation. High-voltage direct-current (HVDC) and flexible alternating-current transmissions system (FACTS) technologies appear especially effective in improving grid operations and management.

This objective of this guidance note is to discuss available FACTS technologies with the underlying concept of independent control of active and reactive power flows, the essential differences and benefits of FACTS devices, and industry applications.

The applications of FACTS devices are associated with four essential technical enhancements:

1) *System capacity*, i.e., a significant improvement in the operational efficiency of existing transmission lines and other equipment, and the elimination of transmission bottlenecks;
2) *System reliability*, i.e., greater voltage stability and power flow control, which improves system reliability and performance while reducing loop flows and increasing transient grid stability;
3) *Power quality*, i.e., a decrease in harmonics and voltage flicker and a reduced risk of potential subsynchronous resonance problems, which is important for industries that are sensitive to power quality; and
4) *System controllability*, i.e., the ability to instantaneously respond to disturbances and redirect power flows through “intelligence” built into the grid.

The average installation time of FACTS devices is 12 to 18 months, and capital investments for each installation usually involve tens of millions of U.S. dollars. However, FACTS implementation usually implies environmental benefits by deferring the construction of expensive transmission lines and better utilizing existing system assets.

Structure

This document compiles information on FACTS from various sources to serve as high-level guidance for World Bank personnel working on electrical power system projects. A wide variety of FACTS devices and supporting technologies are presented in Sections 2 through 8, with each section describing relevant industry needs, functionality, applications, benefits, and recommendations for technical specifications. Section 9 then presents the conclusion and final remarks for the document. Finally, following the

Reference list,[1] Appendix A presents illustrations of some FACTS devices deployed at substations, while Appendix B outlines the FACTS procurement process and offers additional references to public-domain documents to do with procurement.

This guidance note frequently refers to vendor-specific offerings to help the reader comprehend the variety of FACTS technologies available on the market. However, these references are by no means comprehensive. Rather, they are intended only as a starting point for the reader to gain an appreciation of the general subject. The inclusion of references to particular products is not intended to reflect their importance. Also, any reference herein to any vendor, product or services by trade name, trademark, or manufacturer or otherwise does not constitute or imply the endorsement, recommendation or approval of the World Bank.

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[1] Works are shown (and numbered) in the Reference section in the order in which they are mentioned in the main text. Works are cited in the main text by corresponding number only – for example, (Donsión and others 2007).

1| INTRODUCTION

The flexible alternating-current transmissions system (FACTS) is a technology that, in combination with other static equipment, provides control of one or more alternating-current (AC) transmission system parameters to enhance controllability and increase power transfer capability. Based on power electronics,[2] FACTS technology increases the reliability of AC grids and reduces power delivery costs. It improves the transmission quality and efficiency of power transmission by supplying reactive power to the grid in a proper/suitable way. There are variety of FACTS devices, and the purpose of this guidance note is to describe their features, functionality, design, industry applications, and benefits.

FACTS TECHNOLOGY

The term *FACTS* encompasses a wide range of controllers, many of which incorporate large power-electronic converters that can increase the flexibility of power systems, making them more controllable. Some of these are already well established, whereas some are still in the research or development stage.

Originally, FACTS devices were conceived for use in stabilizing and regulating power flow in transmission lines, which allows for the dynamic control of voltage impedance and phase angle. High-voltage AC lines protected by these FACTS devices can support greater current because breaker-tripping anomalies – such as frequency excursions, voltage drop, phase mismatch, malformed wave shape, and power spikes – are greatly reduced by FACTS conditioning. A FACTS device also limits the amount of current flowing on a line by effectively increasing the line's impedance. This enables a much greater degree of flow control than that provided by a switch or breaker. In particular, when current applied to a FACTS-protected line is greater than the permissible threshold, the power merely flows elsewhere rather than tripping a breaker, and power continues to flow on the protected line.

High-voltage, high-power FACTS devices are fairly large electrical devices, and they are relatively expensive. However, their cost is less (per added unit of electric power) than the construction of new high-voltage AC transmission lines.

FACTS technologies have evolved over the past 20 years, following the advent of power electronics. They significantly increase transmission system efficiency, maintain power quality, and respond quickly to disruptions in the reliability of bulk power systems.[3] FACTS can be used to manage the conditions on transmission lines to keep AC power in balance by maintaining voltage stability, keeping current and voltage "in sync," and dampening distortions. Transmission operators have always had to perform these functions. In the past, the operators used devices that relied on mechanical switches, which performed slowly, less efficiently, and less reliably. By dynamically managing AC power and line conditions, not only can FACTS raise the carrying capacity of existing lines, but it can also route power more efficiently, and direct power flow along contractual paths. Additionally, in regions with high renewable power penetration, FACTS can provide frequency response that traditionally required inefficient spinning generators.

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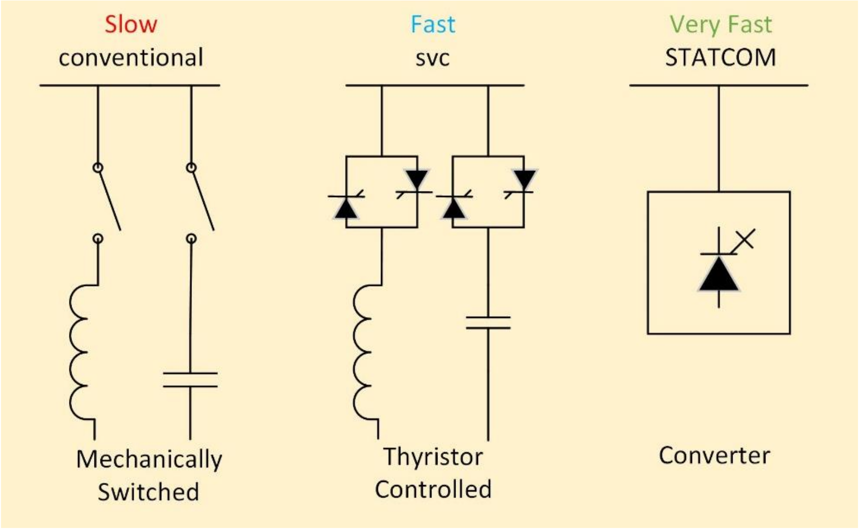
[2] *Power electronics* is the application of solid-state electronics to the control and conversion of electric power.

[3] A *bulk power system* is a large, interconnected electrical system made up of generation and transmission facilities and their control systems.

The conceptual illustration of controls using FACTS devices is presented in FIGURE 1.1, where the relative speed of controls is:

1) Slow, i.e., breaker delay
2) Fast, i.e., 2-3 cycles
3) Very fast, i.e., 1-2 cycles

FIGURE 1.1: Overview of FACTS Control



CLASSIFICATION OF FACTS

The power system industry commonly recognizes two classifications for FACTS devices (Donsión et al. 2007). First, they can be classified by type of connection:

a) Series controllers
b) Shunt controllers
c) Series-to-series controllers
d) Series-shunt controllers

Second, they can be divided into three "generations" according to their technological features (see FIGURE 1.1):

a) First generation: mechanically switched reactors and capacitors
b) Second generation: thyristors with ignition controlled by gate
c) Third generation: semiconductors with ignition and extinction controlled by gate.

These two classifications are independent, and there are devices in the first classification that can belong to various groups of the second classification.

Series controllers. This category comprises controllers connected in series with the line to inject voltage in series with the line. To meet grid requirements – i.e., to provide the compensation needed to address different system conditions and improve system stability – these devices can be variable-impedance (such as capacitors or reactors); variable-source (a power-electronics-based source of main, subsynchronous, or harmonic frequency); or a combination of the two. A typical controller is serial synchronous static compensator (SSSC).

Shunt controllers. This category comprises controllers connected in shunt with the line to inject current into the system at the point of connection. They can also be variable-impedance, variable-source, or a combination of the two. A typical controller is a synchronous static compensator (STATCOM).

Combined series-series controllers. This category comprises separate series controllers controlled in a coordinated manner in the case of a multiline transmission system. It can also be a unified controller in which the series controllers perform the reactive power compensation in each line independently, whereas they facilitate real-power exchange between the lines via the common direct current (DC) link. A typical controller is the interline power flow compensator (IPFC).

Combined series-shunt controllers. This category comprises a combination of separate series and shunt controllers that are operated in a coordinated manner. They are capable of injecting current into the line using the shunt part and injecting series voltage with the series part of the respective controller. If they are unified, the shunt and series controllers can exchange real power via the common DC power link, as in the case of unified power flow controllers (UPFCs).

The classification by generation is determined by the stage of technological advance. The first generation of mechanically switched reactors and capacitors is still widely employed in electrical systems but is giving way to modern technologies based on power electronics. The main difference between second- and third-generation devices is the capacity to generate reactive power and to interchange active power. The second-generation FACTS devices work like passive elements using impedance or tap-changer transformers controlled by thyristors. The third-generation FACTS devices work like angle and module-controlled voltage sources and without inertia, based in converters, employing electronic tension sources (three-phase inverters, auto-switched voltage sources, synchronous voltage sources, and voltage source control) fast proportioned and controllable and static synchronous voltage and current sources.

A large variety of FACTS devices have been proposed and are commercially available in the power system industry. This guidance note attempts to capture and discuss the most established FACTS and their essential characteristics. The FACTS devices discussed herein are summarized in TABLE 1.1 with performance factors. TABLE 1.1 also serves as a navigational aid with bookmarked links to relevant sections of the document and illustrations collected in Appendix A.

The assessment of each FACTS device's performance with respect to the factor listed in each row is relatively ranked as: D – dependent, L – low, M – medium, H – high.

TABLE 1.1: Performance Factors and Section Reference for FACTS

	React	Sh.Cap	FSC	TCSC	TPSC	SC	SVC	STATCOM	STATCOM+ES	DBR	TCR	TSC	SSSC	SSSC+ES	SDBR	TCPAR	UPFC
Document Section (Page)	7	17	20	20	20	29	39	48	48	43	42	42	52	52	43	44	53
Image in Appendix	0	0	A.3	A.4	–	0	0	-	–	–	-	-	–	–	–	–	–
Reactive power absorption	M	–	L	M	M	M	M	H	H	–	L	L	H	H	–	–	H
Reactive power generation	–	M	–	–	–	M	M	H	H	–	L	L	H	H	–	–	H
Active power generation/ absorption	–	–	–	–	–	–	–	–	H	L	–	–	–	H	L	–	–
Voltage control	M	M	L	L	L	M	M	H	H	–	–	–	L	L	–	L	H
Voltage stability improvement	M	M	L	M	M	M	M	H	H	–	–	–	H	H	–	–	H
Power flow control/support	D	D	L	L	L	L	L	L	L	–	–	–	H	H	–	H	H
Power oscillation damping	–	–	–	–	–	L	L	M	M	–	–	–	H	H	M	H	H
SSR mitigation	–	–	L	M	M	–	–	–	–	–	–	–	H	H	L	M	H
Phase jump reduction	–	–	L	M	M	–	–	–	–	–	–	–	–	–	M	H	H
Rotor angle stability improvement	–	–	D	D	D	L	L	L	M	–	–	–	H	H	M	H	H
Flicker mitigation	–	–	–	–	–	M	M	H	H	–	–	–	–	–	–	–	H
Harmonics reduction	–	–	–	–	–	–	–	M	M	–	–	–	M	M	–	–	H
Inertia emulation	–	–	–	–	–	–	–	–	D	–	–	–	–	D	–	–	–
Curtailment	–	–	–	–	–	–	–	–	D	–	–	–	–	D	–	–	–
Primary, secondary, tertiary reserve	–	–	–	–	–	–	–	–	D	–	–	–	–	D	–	–	–
Frequency stability improvement	–	–	–	–	–	–	–	–	D	–	–	–	–	D	–	–	–
Increases transfer capability of lines	L	L	M	M	M	M	M	M	M	L	L	L	M	M	L	L	H

Note: D – dependent, L – low, M – medium, H – high. SSR – subsynchronous resonance.

NEEDS ANALYSIS

The following factors need to be considered before installing FACTS devices:

1) Device type
2) Required capacity
3) Optimal location to optimize the device operation and effectiveness

This document covers an extensive variety of types, features, benefits, and specification requirements of FACTS devices. However, it is essential to select the optimal location for FACTS device installation, because the location determines the actual effectiveness of FACTS implementation and optimizes the device operational functionality.

At a minimum, the following analysis and studies are usually expected prior to proceeding with FACTS procurement and project implementation (Paserba 2009; Abed 1999):

1) A detailed network study to investigate the critical conditions of a grid and the connections (e.g., undesired power flows, voltage problems, risks of voltage collapse, potential for power swings or subsynchronous resonances [SSR]);
2) An analysis of the potential for increasing the energy transfer capability of the transmission line;
3) A determination of FACTS type, rating, and location, and rating to resolve the issues or perform desired grid improvements (e.g., through enhancement of transfer capability, increase in system stability); and
4) A short list of potential suppliers based on common procurement and technical value practices (e.g., vendor market share and experience, timely delivery, capability of local maintenance and support).

Evidently, the technical study should be supplemented with budget and economic analysis to justify the return on the significant investment into FACTS compared with conventional solutions. The calculation methodologies for analyzing power network reliability, location optimization, transfer capability, system stability, and other effects of FACTS devices on the grid is a large topic well beyond the scope of this document. However, engineering handbooks like (Donsión et al. 2007; Wang et al. 2008) can be helpful in understanding the true depth of the studies involved in the analysis of FACTS devices selection and justification for their implementation in the power systems.

The details of procurement processes and methodology are similarly beyond the scope of this document, as procurement, bid evaluation, and project implementation represent fairly large subjects that can each form a document of its own. However, an overview diagram of the procurement process is presented in Appendix B, in order to give a general perspective on FACTS procurement and to re-emphasize the importance of planning studies and needs analysis. Appendix B also contains several official documents and guidelines for procurement that are useful for understanding the breadth and depth of processes related to FACTS procurement.

DEVELOPMENT TREND

Although the concept of FACTS devices has existed for decades, the practical implementation and development of new analytical procedures are still evolving. The first FACTS technologies were deployed in the late 1970s, starting with static volt-ampere reactive (VAR) compensators, or SVCs. Since then, FACTS technologies have continued to grow in variety and complexity. This market is becoming essential due to the increase in VRE integration where an estimated annual spending on transmission system infrastructure for large-scale renewable energy integration is expected to grow from $36.7 billion in 2016 to $46.7 billion in 2025. The technology segments are primarily divided into the HVAC equipment subcategories such as substations, transmission lines and FACTS devices and the emerging technologies such as HVDCs and utility-scale energy storage systems (Funicello-Paul 2016). The rating of the FACTS controllers can reach up to 800 megavolt-amperes reactive (MVar), as well as most of the large FACTS installed for the high-voltage class transmission lines.

To some extent, the U.S. grid relies on FACTS to improve the operational efficiency of the power network. In Texas, installation of four SVCs allowed existing transmission lines to carry more wind power and compensate for changes in voltage and power flow resulting from the variable output of wind generation. In Alaska, one SVC and two mechanically switched capacitors were installed to provide dynamic voltage control to a remote area of the grid subject to reliability challenges. FACTS technology can also be deployed incrementally as required to monitor line current and augment line impedance. The Tennessee Valley Authority (TVA) and Southern Company are using FACTS devices to manage power flow, maintain reliability, and integrate higher levels of renewable generation.

In the course of deregulation in Great Britain, new power stations were installed in the north of the country, remote from the southern load centers, and some of the existing power stations in the south were shut down due to environmental constraints and for economic reasons. To strengthen the transmission system, a total of 27 SVCs were installed because there was no right of way for new lines or higher transmission (Beck et al. 2006). An increasing number of large SVCs are also being installed in South America, where the main objectives were to improve the stability of the extended transmission grid, reduce the number of outages, and improve voltage quality (e.g., the 250 MVar SVC at Bom Jesus da Lapa, Brazil).

Large (up to 600 MVar) fixed and thyristor-controlled (and protected) series capacitors (TCSC, TPSC) for enhancement of high voltage transmission corridors, oscillations damping, and stability improvement have been installed in Fengjie, China (500 kV); Poste Monagnais, Canada (735 kV); Vincent, Midway, and El Dorado, United States (500 kV); and Serra da Mesa, Furnas, Brazil (500 kV) (Beck et al. 2006).

A major 500 kV transmission system extension has increased power transfer opportunities between Arizona and California, encompassing two main series-compensated 500 kV line segments and two equally rated static VAR compensators supplied by Siemens at the Adelanto and Marketplace substations. The SVC enabled the integrated operation of the existing high-voltage AC and DC systems, with a substantial increase in power system stability and power transfer rate.

In future, power systems will continue on the path of deregulation and privatization as new markets open and independent transmission companies (ITCs) and regional transmission organizations (RTOs) assume more-important roles. Deregulation, combined with urban growth and rising power consumption, will drive the need to mitigate transmission bottlenecks and overloading while increasing transmission capacity, improving loop flow control, and increasing system stability. The rapid increase in green energy resource penetration into the modern power grid requires better integrated generation management in the electric power sector. The green resource portfolios are introducing new challenges, many of which lie within the power transmission delivery sector. The current state of the power network already sets forth compelling reasons for this adjustment – and for employing more power-electronics control technologies throughout transmission and distribution systems in order to strategically interconnect green energy resources. The investments in power systems, especially in renewable energy and new transmission technologies, will determine the future shape of the industry.

2 | REACTOR

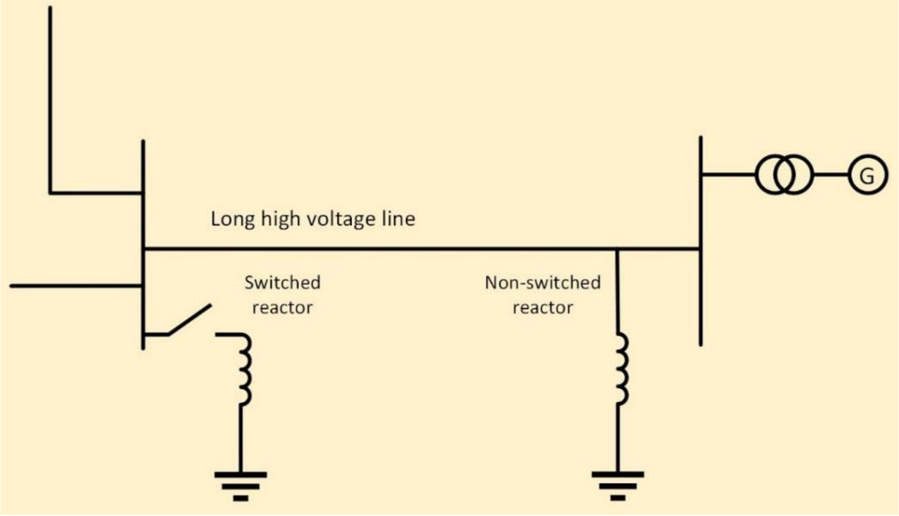
Key messages

- The expansion of voltage transmission systems often necessitates installation of shunt reactors to control excessive charging from high-voltage lines.
- Shunt reactors mitigate temporary overvoltages (or "voltage swell").
- Shunt reactors enhance voltage regulation (by lowering the voltage) if the variable renewable energy (VRE) is limited in its ability to absorb capacitive reactive power and can be required to help meet grid-connection requirements for voltage regulation.
- Shunt reactors compensate the capacitive reactance of the feeders connecting the VRE to the point of interconnection (POI) substation, where the feeders[4] are made of several long cables.
- Shunt reactors facilitate the grid-connection of large wind and solar power farms with long network connections.

DEFINITION

A shunt[5] reactor is a device with large inductance that absorbs reactive power and, therefore, can be used for reactive power compensation (FIGURE 2.1). A shunt reactor with mechanical switching – one of the simplest FACTS devices – can increase the energy efficiency of a system. Shunt reactors can be directly connected to a power line or to a tertiary winding of a three-winding transformer and is commonly switched via a circuit breaker. To improve the adjustment of the consumed reactive power, the reactor can also have a variable rating. If the load variation is slow, then a variable-shunt reactor (VSR) can be an economical solution for some customer applications.

FIGURE 2.1: Shunt Reactor – Simplified Connection Diagram



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[4] A *feeder* is the power line that connects the VRE plants to the main substation. The term *distribution feeder* is also used to describe distribution-system power lines that connect loads to distribution substations to which some small-scale VRE plants are connected.

[5] In electronics, a *shunt* is a device that is connected to the busbar and the earth. The shunt is generally configured to provide the reactive power compensation needed to improve voltage conditions at specific points in the system.

INDUSTRY NEED

The power systems of today are facing the increasing challenge of maintaining efficiency, reliability, and security of supply while connecting intermittent energy sources such as wind and solar power, which tend to generate more unpredictable and fluctuating active power than conventional power sources. This variation in active power from the VRE plants results in the need for various levels of reactive power (either capacitive or inductive) to control the voltage profile. The shunt reactors can offer an economical way to meet this need by compensating for excessive capacitive reactive power and thereby stabilizing the system conditions for overall active power transmission, or to mitigate switching or temporary overvoltages (Warne et al. 2003).

Transmission lines or cables, especially those used at high transmission-system voltage levels (over 300 kV), can produce a large amount of *capacitive reactive power* (coming from the capacitive reactance among phases and to the ground), thus increasing the voltage profile of the system beyond the acceptable or desired levels. At the same time, transmission lines consume *inductive reactive power* (in the longitudinal inductive reactance of the phases). The equilibrium point – called the surge impedance loading (SIL) – occurs when the amount of capacitive reactive power produced is exactly the amount consumed by the inductances within the line. For loading conditions below this point, the capacitive reactive power produced is greater than the inductive reactive power consumed within the transmission line, and it delivers capacitive reactive power to the system, forcing an increase in the power system’s voltage profile. By contrast, if the transmission line is carrying an amount of *active power* greater than the SIL, the *capacitive reactive power* produced by the line is lower than the *inductive reactive power* consumed by its inductances. In this case, the transmission line will absorb capacitive reactive power from the system and tends to reduce the power system’s voltage profile.

Shunt reactors can be used for this purpose, depending on the variable renewable energy’s (VRE) ability to absorb capacitive reactive power and the voltage regulation requirements at the point of interconnection (POI). Beyond this, the need to increase and expand the transmission system connected to the POI (to cope with higher amounts of power transfer from large VRE sources) can require the installation of more shunt reactors at the transmission level, in order to control excessive capacitive reactive power when the dispatch of VRE sources is low (e.g., due to weak wind conditions). This approach has the same reason as explained earlier: the transmission lines, when not carrying high amounts of active power, produce an excessive line-charging effect (due to the Ferranti effect), and voltage-control devices need to react in order to keep the voltage within the desired levels. Shunt reactors are installed to offset the capacitive effect of transmission lines, to improve the voltage profiles of transmission lines, and also to regulate the voltage and reactive power in the grid.

Some VRE sources, particularly wind farms, can be dispersed over wide areas. To connect every wind turbine to the POI substation, especially for large amounts of VRE, a considerable number of transmission lines – or more specifically, underground or undersea cables – can be used in some cases. The use of a multitude of long transmission lines or underground/undersea cables generates significant capacitive load (line charging due to Ferranti effect) that must be compensated by the VRE reactive power control (capacitive reactive power absorption capability) or by other means. Shunt reactor can also be installed at the POI at the medium-voltage level where large solar photovoltaic (PV) power plants are connected to the grid.

DESIGN AND FUNCTIONALITY

A shunt reactor can be either a three-phase unit or a set of single-phase units, depending on planning design criteria, the voltage of the system in which it will be installed, and its rated reactive power. The shunt reactor can be permanently connected (i.e., a fixed shunt reactor) or switched via a circuit breaker (i.e., a switched shunt reactor), and can be installed on a POI substation busbar to assist with voltage profile control (depending on the VRE dispatch context). A variable shunt reactor with tap changer is used for precise and slow voltage variation regulation. For coarse but flexible voltage regulation, more than one switched shunt reactor can be used.

In normal operation, a shunt reactor operates in a so-called *linear region*. The reactance does not change with voltage and the behavior of the shunt reactor is predictable. Once a physical limit is reached, the reactance changes (decreases) with voltage, and the shunt reactor no longer operates in the linear region; here the behavior of the shunt reactor becomes difficult to predict. Typically, there is a requirement for shunt reactors to remain linear up to, and slightly beyond, the maximum system voltage. For strong networks, users would typically specify linearity up to 110 percent of nominal voltage (CIGRE 2013).

Shunt reactor design have two basic classifications: (a) a *dry type*, with an air core and (b) an *oil-immersed* type. The oil-immersed designs have four variants:

- Coreless
- Core-form, gapped core
- Core-form, magnetically shielded
- Shell-form, magnetically shielded

At low voltage and small rated reactive power, the shunt reactors are the *dry type* (including alternatives with no iron core to reduce equipment costs).

For shunt reactors with high voltage and reactive-power ratings, the shunt reactor type is *oil-immersed*. Most oil-immersed shunt reactors manufactured are based on the “gapped core” concept. This employs an iron core with air gaps to minimize losses, sound, and vibration, and is similar in design to large power transformers. The benefit of the iron core with air gaps is a dampening effect which prevents the reactor from reaching the knee-point voltage[6], thus preventing extreme overcurrent conditions when the reactor is energized, i.e. connected to the power system. The core is made from radially laminated iron packages, while ceramic spacers ensure precise compliance with the specific air gap requirements.

Large shunt reactors normally have iron cores with integrated air gaps. Due to the air gaps, the iron cores cannot be significantly saturated, and the reactors therefore will have a reasonably linear behavior during energizing events. Three-phase shunt reactors may either consist of three separate single-phase cores or be a three-leg core type. The design depends on the voltage class. Shunt reactors rated between 60 and 230 kV are usually oil-filled and have three-legged gapped cores with layer, continuous-disc, or interleaved-disc windings. Between 300 and 500 kV, the reactors can be single-phase or three-phase units with three-legged, five-legged, or shell-type cores. For shunt reactors rated below 60 kV, the design is either an oil-filled, three-legged, iron-core type or a dry-coil type (ABB 2010; ABB 2013).

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[6] The *knee-point voltage* is defined as the voltage at which a small increase in voltage results in a considerable increase in current. The linear relation between the voltage and current changes significantly after this voltage due to saturation of the iron core.

Depending on the intended function, a shunt reactor can be designed to have linear or adjustable inductances. Linear shunt reactors have constant inductance within specified tolerances. A shunt reactor whose inductance can be adjusted (by changing the number of turns on the winding or by varying the air gap in the iron core) is called a variable shunt reactor. Variable shunt reactors (VSRs) can help fine-tune the voltage, thereby reducing the number of fixed shunt reactors required to be installed in one regulated reactor. The number of turns on a winding is changed by means of a tap changer.

Service conditions are vital to the design of a shunt reactor. For oil-immersed shunt reactors, the specified ambient temperatures usually range from -25°C to 40°C; exceeding these temperatures may reduce the reliability and the life of the shunt reactor. The shunt reactor is installed as either a three-phase shunt reactor or three single-phase shunt reactors. Single-phase shunt reactors are less expensive than three-phase shunt reactors and are smaller, which makes them easier to transport.

Fixed shunt reactors are usually available at voltages up to 800 kV and with ratings up to 1,500 MVar. Variable shunt reactors are usually available at voltages up to around 400 kV and three-phase ratings up to around 250 MVar. The maximum regulation range for some of the newer technologies is 80 percent, where the VSRs are equipped with 33 taps to cover a rating from 50 up to 250 MVar at 400kV – which can reduce the amount of expensive SVC equipment required for dynamic grid operations (Siemens 2016b).

Another limitation of variable shunt reactors is the electrical behavior of the regulating winding at transient voltage stresses. The regulating winding in a VSR is electrically much longer than a regulating winding used in transformer applications. The feasible regulation range depends on the voltage rating of the reactor.

A high harmonic content in the load current can cause increased loss due to additional eddy-current losses in the winding, oil tank, iron core and other metallic parts, as well as increased I^2R loss.[7] This could require measures to be taken either to reduce the harmonics in the current or to ensure that the design of the shunt reactor takes the increased losses (due to harmonic currents) into consideration.

APPLICATIONS

Large shunt reactors are typically used in systems where long transmission lines carry voltages over 200 kV. Additionally, shunt reactors are used in large urban networks to prevent excessive voltage rise when a high load suddenly falls due to a failure. Shunt reactors are applied to regulate the reactive power balance of a system by compensating for the surplus reactive power generation of transmission lines or cables. Reactors are normally switched off at times of heavy load and are switched on to lines during periods of low load.

Shunt reactors' other industry application is controlling excessive voltage rise. This voltage rise is caused by a Ferranti rise on the transmission lines and a capacitive rise when lines are lightly loaded. Reactors are usually placed on a section of the transmission line.

If the load on the line increases, consequently decreasing the voltage, then the reactor will be switched off because it is no longer needed. If the load lessens and the voltage starts to rise again, the reactor will be switched on to keep the voltages at a safe level. In some applications, the shunt reactor is on most of the time or off most of the time and is switched only for certain contingencies. Wind, solar thermal, and

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[7] The power loss is expressed as I^2R, where *I* is the current and *R* is the resistance.

photovoltaic generators have a large daily output swing, and most shunt reactors employed in connecting these to the power grid are switched at least daily.

Series reactors can be used to increase the impedance on a congested line as a way to reduce the power flow congestion. This allows the power to be distributed to adjacent lines in the system, where applicable. However, using this option generally requires performing power flow studies to get the maximum benefit out of the series reactors – which may not work in cases when not enough alternative routes exist to divert the power flow to the adjacent lines. Series reactors are generally designed and manufactured as single-phase units without an iron core (air core), and with only a magnetic-flux return circuit.

This section focuses on mechanically switched shunt capacitors and the advanced forms of thyristor-switched shunt capacitors. The combinations of shunt capacitors and reactors are described in Section 0.

TABLE 2.1 lists the essential applications of shunt reactors and provides a comparison of fixed and variable reactor types.

TABLE 2.1: Applications of Shunt Reactors

Applications	Fixed	Variable
Compensation of reactive power in overhead lines	High	High
Compensation of slow variation in reactive power	N/A	High
Compensation of fast variation of reactive power	N/A	N/A
Compensation of reactive power in underground cables	High	High
Complexity of applying to system operation	Low	Medium

BENEFITS

Shunt reactors provide voltage control and reactive power compensation in the presence of excessive capacitive reactive power, and can also be designed as variable-shunt reactors with tap changers. They serve to:

1) Compensate for the capacitive reactive power of transmission lines – particularly on grids operating under a low- or no-load condition, which can frequently occur when dispatching large VRE sources;
2) Reduce network switching or temporary overvoltages in the case of sudden load/generation variation, load/generation shedding, or changes in the topology (i.e. configuration) of the grid; and
3) Improve the stability and economic efficiency of power transmission.

Although shunt reactors provide a low-cost voltage-control solution in power systems, their control capabilities are somewhat limited compared to more sophisticated and expensive FACTS devices.

RECOMMENDATIONS FOR SPECIFICATION

The following topics should be covered for the specification of this equipment. They govern the choice of a shunt reactor and it is recommended they be addressed in the specification:

1) *Single-phase or three-phase*

  a) The shunt reactor used for VRE will be either single-phase or three-phase, depending on the technical and economic assessment and rated reactive power for each application.
  b) Three-phase units are less expensive, take up less space in the substation, and require less connecting equipment, whereas the single-phase configuration is used for larger-rated reactive power and/or for higher reliability designs.

2) ***Fixed or switched***

  a) A fixed shunt reactor does not require a circuit breaker with appropriate performance to maneuver the shunt reactor and is thus a simpler design.
  b) Multiple switched shunt reactors can be used to have more flexible, but still coarse, capacitive reactive power absorption capability.
  c) The use of a circuit breaker makes the substation more complex, needs more space in the substation, requires additional maintenance, and is more expensive.
  d) A study of the capacitive reactive power absorption capability of the VRE and transmission system usually determines which solution is more suitable to meet POI grid connection requirements.

3) ***Variable shunt reactor***

  a) Variable shunt reactor should be used for precise and slow (reacting within few seconds) capacitive reactive power absorption capability.
  b) The use of a tap changer increases the equipment's complexity, size, cost, and required maintenance.
  c) Additional engineering is required to supply power to the tap changer.

4) ***Type of core***

  a) At high voltage and for large rated reactive power, the shunt reactor should be of the gapped-core, oil-immersed type to minimize losses, sound and vibration.
  b) At low voltage and small rated reactive power, the shunt reactor will be of the dry type (including alternatives with no iron core for lowering equipment costs).

5) ***Cooling***

  a) Shunt reactors with high ratings for both voltage and reactive power require cooling (gapped-core oil-immersed type shunt reactor).
  b) The use of cooling makes the equipment more complex, bigger, and pricier, and environmental precautions must be taken.
  c) In addition, for ONAN (oil natural, air natural) and ONAF (oil natural, air forced) types of cooling, fans are used to cool the oil.
  d) Fans require power supply, additional maintenance, and engineering. These drawbacks often compensate for the additional size and price of an ONAN shunt reactor.

6) ***Insulation.*** The choice of appropriate insulation levels for the equipment must also take into consideration the electrical characteristics and performance of circuit breakers and surge arrestors, if such equipment is used. This is in addition to the usual aspects to be considered for insulation coordination, such as standardized values, personnel safety, altitude correction factors, and pollution.

7) *Losses.* The specification needs to state the capitalization factor which is the capitalized cost of losses in the shunt reactor. For a stepwise[8] variable-shunt reactor, the losses in the two extreme positions and the middle position must form the basis of calculation of the capitalization factor. For a continuously variable shunt reactor, the losses in the two extreme positions (maximum and minimum reactive power) and the middle position must form the basis of calculation of the capitalization factor. In the invitation to tender, the buyer must state how the losses in the three control positions are weighted in the calculation. If the losses deviate by more than +10 percent from the losses guaranteed in the tender, the buyer reserves the right to reject the shunt reactor. The capitalization factor must also be used when capitalizing the power requirements of the cooling equipment, and the power consumption of the cooling equipment must be considered as a loss.

The following related standards can be used to establish the specification requirements:

1) IEC std 60076-6, "Power transformers – Part 6: Reactors," Edition 1.0, 2007-12
2) IEC std 60076-1, "Power transformers – Part 1: General," Edition 3.0, 2011-04

Additionally, CIGRE working group A2.36 produced brochure 528, which discusses aspects of transformer specifications. It is mostly applicable to shunt reactors, with some exceptions (e.g. system technical requirements, and testing).

TABLE 2.2 presents a reference summary guideline for the equipment specifications. When developing the specification data sheets and requirements, the specific needs of the electrical utility must be taken into account.

TABLE 2.2: Shunt Reactors – Specification Sample

Specifications	Value
1. Operating Conditions	
➢ Power System Frequency	Usually 50 or 60 Hz
➢ Ambient Temperature Range	For example: -50°C to +40°C
➢ Occurrence of Switching in Overvoltage Conditions	For example: X switching per year at 1.05 per unit (p.u.) Y switching per year at 1.3 p.u. Etc.
2. Main Characteristics	
➢ Rated Voltage	Depends on the system voltage where the shunt reactor is to be installed.

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[8] *Stepwise* refers to the reactance being varied in a stepwise manner (for example, 33 tap changes) by the thyristor valve.

Specifications	Value
➢ Rated Power	Based on wind power plant performance studies and VRE reactive power absorption capability (from the assessment electrical studies for VRE integration).
➢ Knee Point and Xac (air core reactance)	Values defined according to system studies in order to reduce/mitigate transient overvoltages in the power system.
➢ Maximum Temperature Elevation	To limit material degradation at high temperature. For example, it is a good practice to keep the maximum temperature at 95°C for an oil-immersed shunt reactor, taking into account the maximum ambient temperature. For example, the maximum temperature elevation would be +55°C considering a maximum ambient temperature of +40°C.
➢ Type of Cooling	ONAN (oil natural, air natural) or ONAF (oil natural, air forced) for oil-immersed shunt reactors. No oil needed for the dry type of shunt reactors.
➢ Type of Connection	YN for wye-neutral grounded connection (could be a four-legged shunt reactor when using neutral impedance for limiting secondary arcs in single auto-reclosing schemes).
➢ On-load Tap Changer	Range of rated reactive power regulation, in % or MVar.
➢ Number of Taps	Depends on the range of rated reactive power regulation (in % or MVar) desired; characteristics of the on-load tap changer are available from the manufacturer.
➢ Losses Capitalization Factor	The largest percentage of reactor total losses originates from the conductor winding (I^2R). To decrease losses from this area, Trench (a German supplier – see next section) can increase the cross-sectional winding, with a resultant lower temperature rise and lower I^2R loss factor. On very large shunt reactors with inherent high field strength, stray losses can become significant. To overcome high stray loss areas, shunt reactors can be designed with non-magnetic stainless-steel

Specifications	Value
	spider arms while support insulator caps can be made of bronze or stainless steel. Another large source of loss is eddy currents in the winding conductor. By utilizing individually insulated, stranded wire, eddy-current losses can be reduced.
3. Insulation coordination requirements (Note 1)	
➢ Requirements to be established according to the following standards:	IEC *std 62271-1, "High-voltage switchgear and controlgear – Part 1: Common specifications," Edition 1.1, 2011-08* *IEC std 60071-1, "Insulation co-ordination - Part 1: Definitions, principles and rules," Edition 8.0, 2006-01* *IEC std 60137, "Insulated bushings for alternating voltages above 1 000 V," Edition 6.0, 2008*-07 10)
4. Radio Interference Requirements R.I.V. (if required and above 123 kV)	Value to be respected usually determined by national standards or regulation Proposed value 2,500 µV measured according to IEC STD 62271-1 at 0.5 MHz and 1.1 p.u. of the rated voltage IEC std 62271-1, *"High-voltage switchgear and controlgear – Part 1: Common specifications,"* Edition 1.1, 2011-08 IEC CISPR TR 18-2, *"Radio interference characteristics of overhead power lines and high-voltage equipment – Part 2: Methods of measurement and procedure for determining limits,"* 2010
5. Maximum Audible Noise	The maximum audible noise should be set between 50 to 100 db(A). Lower values in the range would be more suitable for areas sensitive to audible noise; higher values would be acceptable for areas not exposed to public.

VENDORS

The following is the list of some suppliers of high-voltage reactors in alphabetical order:

1) ABB (Sweden)
2) Fuji Electric (Japan)
3) General Electric (USA)
4) Mitsubishi Electric (Japan)
5) Reinhausen (Germany)
6) Siemens (Germany)
7) Trench (Germany)

3 | CAPACITOR

Key messages

- A capacitor charges into the grid capacitive reactive power that compensates for reactive power consumption.
- The need to expand the transmission system connected to POIs, and to cope with higher amounts of power transfer coming from large VRE sources, can necessitate installation of capacitor banks at the transmission level. This installation helps control the power system's voltage profile when the dispatch of VRE sources is high and mitigates temporary undervoltages (or "voltage sag").
- A capacitor can improve voltage regulation (by increasing the voltage) if the VRE is limited in its reactive power generation capability; to do so, it must meet grid-connection requirements for voltage regulation.
- Capacitors can be used as part of various harmonic filtering solutions to improve power quality.
- Capacitors can facilitate grid-connection of large wind and solar power farms.

DEFINITION

Single capacitors are electrical or electronic components that store electrical energy. They consist of two conductors separated by an insulating material called a *dielectric*. When an electrical current is passed through the conductor pair, a static electric field develops in the dielectric that represents the stored energy. Unlike batteries, this stored energy is not maintained indefinitely, as the dielectric allows for a certain amount of current leakage, which results in the gradual dissipation of the stored energy (Warne & Laughton 2003).

A *capacitor bank* is a grouping of several identical capacitors interconnected in parallel or in series with one another. These groups of capacitors are typically used to correct or counteract undesirable characteristics, such as power factor lag or phase shifts inherent in alternating current (AC) electrical power supplies. Capacitor banks may also be used in direct current (DC) power supplies to increase stored energy and improve the ripple current capacity of the power supply.

Capacitor banks produce reactive power that compensates for the inductive reactive power consumption of transformers, highly loaded lines (above the SIL), inductive loads, and so on. In shunt compensation (see FIGURE 3.1), the power system is connected in parallel with the capacitor and works as a controllable current source. Shunt capacitive compensation improves the power factor. Whenever an inductive load is connected to the transmission line, the power factor lags because of lagging load current. To compensate, a shunt capacitor is connected, which draws current leading the source voltage. In series compensation (see

FIGURE 3.2), the power system is connected in series with the capacitor (e.g. a switchable capacitor is inserted into a transmission line). Series compensation reduces voltage drops, increases transfer capability, and reduces transmission angle.

Mechanically switched capacitor banks are very economical reactive power compensation devices. They are simple and low-cost, and a low-speed solution for voltage control and network stabilization under heavy load conditions. Their utilization has almost no effect on the short-circuit power but it supports the voltage at the point of connection. An advanced form of mechanically switched capacitor is the mechanically switched capacitor with damping network (MSCDN) for avoidance of system resonances, which in some cases can also provide harmonic filtering.

FIGURE 3.1: Shunt Capacitor – Simplified Connection Diagram

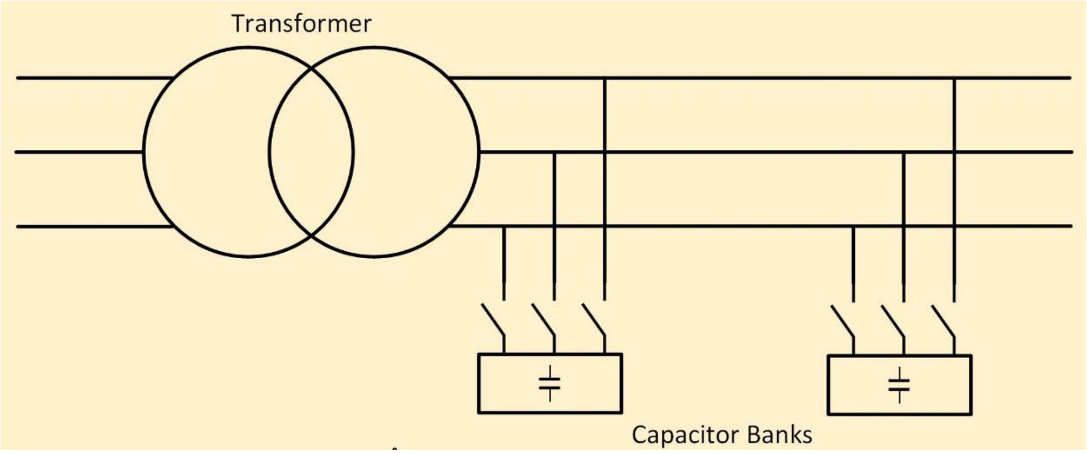
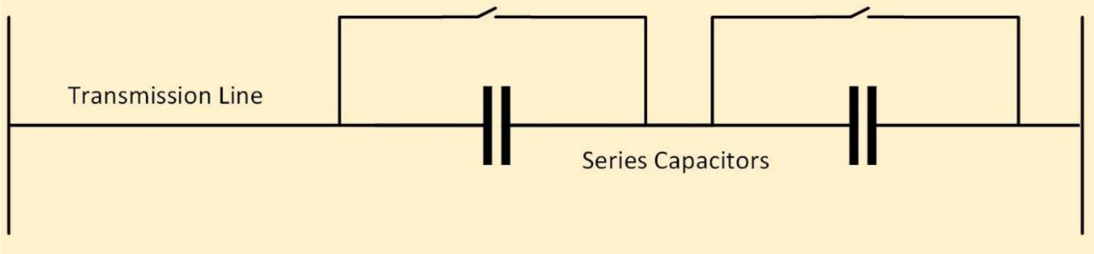


FIGURE 3.2: Series Capacitor – Simplified Connection Diagram



INDUSTRY NEED

Improving the transmission system to cope with higher amounts of power transfer coming from large VRE sources can necessitate installing more capacitor banks at the transmission level, in order to support the power system's voltage profile control when the dispatch of VRE sources is high. This approach is the same action explained in Section 2: transmission lines, when carrying high amounts of active power (higher than the SIL), consume more capacitive reactive power than the amount produced by line charging effect, and voltage control devices (including capacitor banks) should act to keep the voltage levels in the power system within desired levels.

The use of capacitor banks results in increased transmission capacity and reduced losses (due to higher power factors), which leads to higher voltage profiles. Capacitor banks may help voltage regulation (by increasing the voltage) if the VRE sources are limited in their own capacitive reactive power capability, and such capacitor banks can be helpful in meeting grid connection requirements for voltage regulation, power quality, and stability.

DESIGN AND FUNCTIONALITY

As discussed earlier, a capacitor consists of two conductors (or metal terminals) separated by an insulating material called a *dielectric*. When current passes through the capacitor terminals, a static electric field develops in the dielectric, which creates stored energy (in terms of electric field). The dielectric also allows for a certain amount of current leakage, which results in the gradual dissipation of the stored energy when de-energized. It is common to have dissipation/discharging circuits in parallel with capacitor cells in order to rapidly decrease the stored electric energy. The capacitor units usually have a low failure rate and a high degree of reliability.

The single-phase power capacitor is an all-film type, with low dielectric losses and long service life. The capacitors are impregnated with a hydrocarbon fluid that possesses high insulation strength. The edges of the electrode foils are folded, enabling higher electrical stress. The capacitor unit is usually available with internal or external fuses or fuseless designs. The capacitor unit is made up of a number of elements, each consisting of very thin layers of dielectric materials and thin foils of aluminum as electrodes. The elements are stacked inside the capacitor container and connected in series and parallel to accommodate the voltage and capacitance ratings specified for the entire capacitor unit. The dielectric is the most influential factor for the reliability of the entire capacitor or capacitor bank (ABB 2010; ABB 2013; GE 2016).

Capacitive banks are the most basic and cost-effective means of supplying reactive power to the system but are provided only in steps.[9] This may result in either steady-state overvoltages (due to the amount of capacitors inserted in the power system compared to its short-circuit power) or transient overvoltages (due to the transients resulting from the switching of such banks). This can of course be addressed in the equipment design phase by choosing the adequate features for each application in power systems; however, attention must be paid to designing the capacitive banks so that resonance or major overvoltage problems are avoided.

Maximum bank size is influenced by:

1) The change in system voltage upon capacitor bank switching
2) Switchgear continuous current limitation

Minimum bank size is influenced by:

1) The type of capacitor bank used (e.g. externally fused, internally fused, fuseless)
2) The available ratings of capacitor units
3) Capacitor bank unbalance considerations
4) Fuse performance and/or coordination
5) The cost of the required switchgear and protection

Capacitor Shunt Compensation

At buses where reactive power demand increases, bus voltage can be controlled by connecting capacitor banks in parallel to a lagging load. Capacitor banks supply part of a load's full reactive power, thus reducing the magnitude of the source current necessary to supply load. The voltage drop between the sending end and the load gets reduced, power factor is improved, and increased active power output is available from the source. Depending on load demand, capacitor banks may either be permanently connected to the system or varied by switching (on/off) the parallel connected capacitors manually or automatically.

The usage of shunt capacitor banks has the following weaknesses:

1) Shunt capacitors do not affect current or power factor beyond their point of application.

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[9] Capacitor banks are made up of a combination of capacitor "steps" (each comprising a capacitor and a contactor) connected in parallel.

2) The reactive power supplied by the shunt capacitor banks is directly proportional to the bus voltage.
3) When the required reactive power is less on light loads, capacitor bank output is high; however, it can be reduced by connecting a number of capacitors in parallel and varying the capacitance by switching on and off (depending on the load requirement).

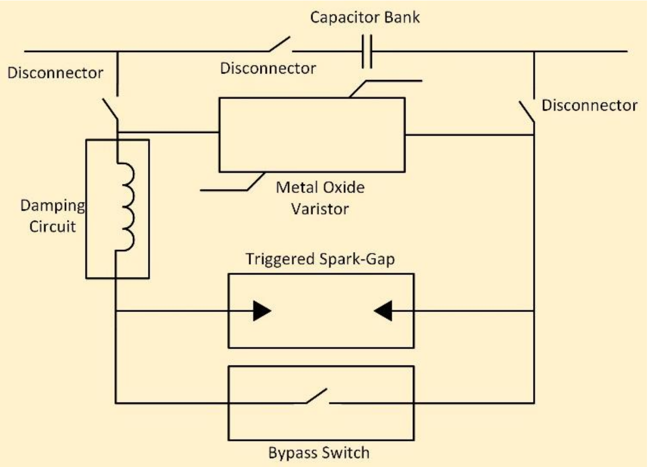
This section focused on *mechanically switched* shunt capacitors. The advanced forms of *thyristor switched* shunt capacitors and combinations of shunt capacitors and reactors are described in Section 0.

Capacitor Series Compensation

The simplest and most cost-effective type of series compensation for optimizing power transmission is provided by fixed-series capacitors (FSCs). Under short-circuit conditions, the high voltage produced may damage the capacitor, so it must be protected.

An FSC is made up of actual capacitor banks and parallel arresters (e.g. the metal-oxide varistor, or MOV), self/forced triggered spark gaps, and a bypass switch, as shown in FIGURE 3.3. The surge arresters, spark gaps, and bypass switch all have a protection function in an FSC bank installation. The bypass switch protects the spark gap, which defends the arrester from excessive energy absorption. The surge arresters in turn protect the capacitor from overvoltages during and after transmission system failures. Three high-voltage switches serve to integrate the FSC into, and isolate it from, the transmission line (e.g. for maintenance purposes). A damping circuit is connected in series with the triggered spark gap and is not always stressed by the AC-line current. The bypass-breaker is located in parallel to the spark gap to provide current commutation for times when the current capability of the spark gap or MOV is exceeded. During internal faults (i.e. faults occurring on the high-voltage line to which the capacitor bank is connected), the spark gap and the bypass-breaker are allowed to operate and protect the capacitor and MOV from overload.

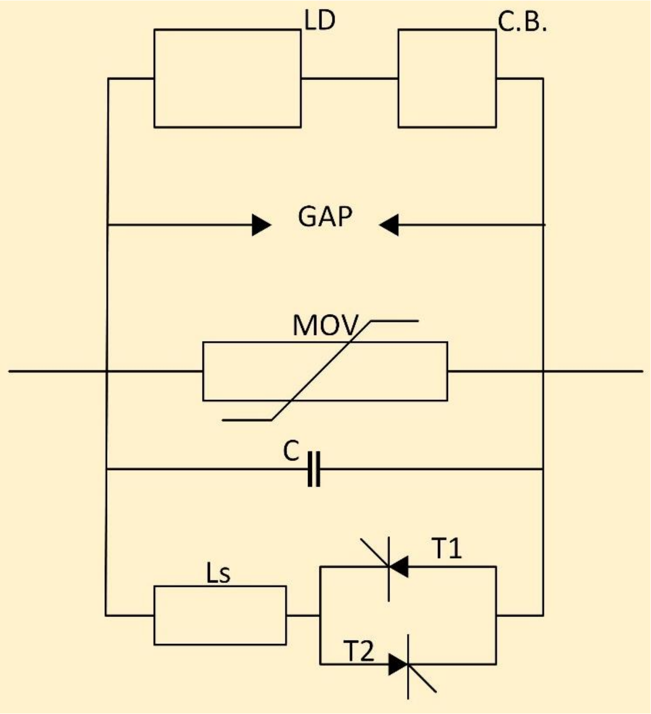
FIGURE 3.3: Fixed Series Capacitor



Advanced forms of series capacitors include the thyristor-controlled series capacitor (TCSC), thyristor-switched series capacitor (TSSC), and thyristor-protected series capacitor (TPSC).

Reactive power compensation by means of TCSC or TSSC can not only be adapted to brand-new installations but can also be implemented in a wide range of existing systems. In addition to the conveniences of a conventional FSC, the TCSC and TSSC are also capable of controlling the current, and subsequently the load flow in parallel transmission lines, which simultaneously improves system stability, as show in FIGURE 3.4. Other applications for TCSC and TSSC include voltage stability, power oscillation damping, and mitigation of subsynchronous resonance, which is a crucial issue in the case of large thermal generators.

FIGURE 3.4: Thyristor Controlled Series Capacitor



TPSCs are the first choice whenever transmission lines must be returned to maximum carrying capacity as quickly as possible after a failure. The thyristor used is the direct-light-triggered type, which eliminates the need for conventional spark gaps or surge arresters. Due to the very short cooling times of the light-triggered thyristor valves, TPSC can be quickly returned to service after a failure, allowing the transmission lines to be employed to their maximum capacity.

APPLICATIONS

The capacitor injects reactive power into the system, thus reducing the load in the entire transmission and distribution system. The advantage of reactive power compensation was realized early, and most power utilities and some large consumers of electrical power are installing capacitor banks in their systems. The key reasons for installing power capacitors are as follows (Warne & Laughton 2003; CIGRE 2013):

1) Reactive power compensation reduces active losses in transformers, cables, and transmission and distribution lines. The higher the power factor, the lower the losses in the grid.
2) Capacitors allow for better use of existing transmission and distribution systems – an increasingly desirable feature at a time when it is becoming challenging to obtain the rights of way necessary for the construction of new (and fairly expensive) transmission lines. Reactive power compensation reduces the amount of apparent power drawn from the network, which can provide the following benefits:

    a) Additional loads can connect to previously fully loaded transformers.
    b) Investments in new transformers, cables, and lines can be postponed.

3) Including capacitors at the planning stage of new plants can improve the designs of transmission and distribution systems.
4) Voltage drops in transmission and distribution systems result mainly from the reactive power consumption of the system itself (transmission lines and other transmission power system equipment) and at the load-end of the system. Capacitor banks can be used to compensate the voltage drop and thus stabilize the voltage.
5) The starting current for induction motors is almost purely inductive and causes a significant voltage drop, consequently disturbing other loads connected to the same busbar and sometimes making it impossible to start the motors. To eliminate this problem, specially designed capacitors are switched in during startup.

Capacitor banks can be either fixed or switched. At a voltage rating of 72.5 kV and above, each individual bank is typically switched with its own switching device and may incorporate active (controlled switching, pre-insertion impedance) and/or passive (series reactors) means to limit the effects of inrush and/or outrush currents. Some capacitor-bank installations are fitted with series reactors ("damping reactors") to limit the inrush/outrush current; for this last configuration type, harmonic current flow could be of concern due to possible resonances.

A common criterion for determining the maximum size of a capacitor bank is that it should not result in a steady-state voltage variation of more than 3 percent of the rated system voltage. That is, the size of the capacitor bank (expressed in MVar) should be limited to allow the ratio of MVar to short-circuit power (expressed in MVA) to be less than 3 percent. Some grid codes (which may be regional, national, or promulgated by the local TSO) allow a variation limit of up to 5 percent.

Capacitor bank transient voltages and currents are:

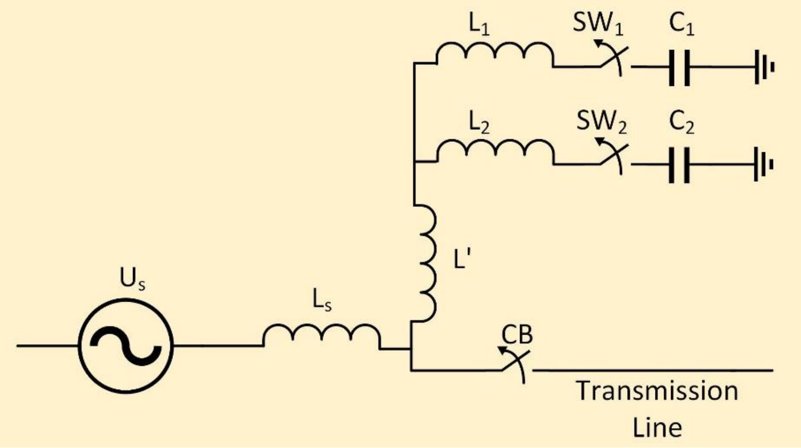
1) Inrush currents, and
2) Overvoltages caused by the system response to the voltage dip when energizing capacitor banks.

It is common for more than one capacitor bank to be connected to the same bus. This has no influence on the conditions at interruption of the capacitive current. However, the current at closing is highly affected. Two situations may occur:

1) The capacitor bank is energized from a bus that does not have other capacitor banks in operation. This is called single-capacitor bank switching.
2) The capacitor bank is energized from a bus that has other capacitor banks already in operation. This is called back-to-back capacitor bank switching. Even energized capacitor banks in nearby substations may contribute to the inrush current such that a back-to-back situation occurs. Back-to-back capacitor bank switching may give rise to inrush currents of very high amplitude and frequency, and they sometimes have to be limited in order not to be harmful to the switching device, the capacitor banks and/or the network. This can be done by inserting additional series inductance in the circuit, using pre-insertion resistors or controlled switching. Typical amplitudes of the inrush currents for back-to-back energization of capacitor banks are given in Table 9 of IEC 62271-100 and Tables 4, 8 and 14 of IEEE C37.06.

FIGURE 3.5 shows a single-phase equivalent circuit where two capacitor banks are connected to a busbar. Inductance L' represents the busbar inductance and L1 and L2 represent the additional damping inductance (if used). The inductance Ls of the supply network will be several orders of magnitude higher than L', L1 or L2.

FIGURE 3.5: Parallel Capacitor Banks



The replacement of overhead lines with underground/undersea cables, or the addition of new circuits to the latter at the same substation where there are capacitor banks, require taking into consideration the capacitor bank switching in back-to-back configuration with the underground/undersea cables. If the inrush current amplitude and frequency need to be limited, additional series inductance can be inserted into the circuit, or pre-insertion resistors can be used. Another possibility is to use controlled switching.

BENEFITS

By producing reactive power, capacitors compensate for the reactive power consumption of other electrical devices in the power grid. The results of compensation translate into more stable power grids with increased transmission capacity and reduced losses due to higher power factors.

Capacitors also constitute a key component in the various filter solutions that reduce harmonic content. A non-distorted sinusoidal voltage without harmonics reduces the risk of problems in the form of production equipment issues, metering errors, and malfunctions in relay protection. It also extends the service life of connected equipment.

Improving the power quality results in the following electrical utilities benefits:

1) Enhanced asset use in electrical utilities
2) Lower network losses and CO_2 emissions
3) Expansion of network capacity
4) Improved voltage stability

Series compensation through the insertion of reactive power elements into transmission lines:

1) Increases transfer capability of transmission lines;
2) Reduces network switching or temporary undervoltages in case of sudden load/generation variation, load/generation shedding, or sudden changes in the grid topology;

3) Compensates for reactive power consumption of power transformers, highly loaded lines (above the SIL), and large inductive loads;
4) Reduces line voltage drops;
5) Limits load-dependent voltage drops;
6) Influences load flow in parallel transmission lines;
7) Reduces transmission angle;
8) Reduces SSR; and
9) Improves the stability and economic efficiency of power transmission

Series compensation using fast-switching thyristors (e.g. via TCSCs or TPSCs) is very effective for improving stability. Damping of electromechanical (0.5-2 Hz) power oscillations often arises between areas in a large interconnected power network. These oscillations are due to the dynamics of inter-area power transfer and often exhibit poor damping when the aggregate power transfer over a corridor is high relative to the transmission strength. Also, local mitigation of SSR permits higher levels of compensation in networks where interactions with turbine-generator torsional vibrations or with other control or measuring systems are of concern.

Integrating VRE into transmission systems tends to generate more unpredictable and fluctuating active power than integrating conventional power sources does. To maintain appropriate power quality, new VRE integrations must sometimes cope with unpredictable variations of active power and may need to improve control of the voltage profile. Capacitor banks can offer an economical solution for such challenges by compensating the system's capacitive reactive power consumption and thereby stabilizing the system conditions for overall active power transmission. They also contribute to the mitigation of switching and removing of temporary undervoltages (or voltage sag).

RECOMMENDATIONS FOR SPECIFICATION

The following topics should be incorporated into the equipment specifications:

1) ***Ratings.*** Capacitor banks are designed to experience abnormal system conditions during their life spans. To withstand these abnormalities at optimum manufacturing cost, the capacitor banks are rated using parameters that exceed normal system peak voltage (e.g., 110 percent), normal root mean square (rms) voltage for the system (e.g., 120 percent), normal rated MVar (e.g., 135 percent), and normal rated rms current (e.g., 180 percent). A capacitor bank should continue its service within the rated limits.
2) ***Temperature rating of a capacitor bank.*** Outdoor type capacitor bank is generally installed at open space where sunlight strikes on the capacitor unit directly. Production of heat in the capacitor unit is also initiated from the VAr delivering by the unit. Hence, allowances for heat radiation should be accounted for and mitigated. It is also necessary to specify the maximum allowable ambient temperatures and humidity for capacitor bank operations with consideration of the climate zone. For better ventilation, ensure there is enough spacing between capacitor units. Sometime forced air flow can be used to dissipate the heat from the bank.
3) ***Phase.*** Capacitor bank units are manufactured in single-phase or three-phase configuration. Single-phase capacitor units are designed as double bushing or single bushing. A three-phase capacitor unit has three bushings to terminate the three-phase respectively. There is no neutral terminal in a three-phase capacitor unit.
4) ***Basic insulation level (BIL) of the capacitor unit.*** A capacitor bank has to withstand various voltage conditions, such as power frequency overvoltages and lightening and switching overvoltages. Basic insulation level must be specified on every capacitor unit rating plate.

5) ***Internal discharge device*.** Capacitor units are normally provided with internal discharge device that ensures the quick discharge of residual voltage to a predefined level within the specific time period; a capacitor unit is also rated with its discharge period.
6) ***Transient overcurrent rating*.** Power capacitor may undergo an overcurrent situation during switching operation. The capacitor unit must be rated for allowable short-circuit current for a specified time period.
7) ***Essential capacity parameters*.** Essential parameters are as follows:

    a) Nominal system voltage (in kV)
    b) System power frequency (in Hz)
    c) Temperature class with allowable maximum and minimum temperature (in ℃)
    d) Rated voltage per unit (in kV)
    e) Rated output (in MVar)
    f) Rated capacitance (in µF)
    g) Rated current (in amps, or A)
    h) Rated insulation level (nominal voltage / impulse voltage)
    i) Discharge time/voltage (in seconds/voltage)
    j) Fusing arrangement (internally fused / externally fused / fuseless)
    k) Number of bushings (single/double/triple)
    l) Number of phases (single-phase or three-phase)

The following related standards can be used to help establish the specification requirements:

1) IEC std 60871-1, “Shunt capacitors for a.c. power systems having a rated voltage above 1 000 V – Part 1: General,” Edition 4.0, 2014-05
2) ANSI/IEEE 18-2002, “IEEE Standard for Shunt Power Capacitors”
3) IEEE 1036-2010, “IEEE Guide for the application of Shunt Power Capacitors”
4) C37.99 -2012, “IEEE Guide for the Protection of Shunt Capacitor Banks”

TABLE 3.1 presents a reference summary guideline for the equipment specifications. When developing the specification data sheets and the requirements, the specific needs of the electrical utility must be taken into account.

TABLE 3.1: Shunt Capacitors – Specification Sample

Specifications	Value
1. Operating Conditions	
➢ **Power System Frequency**	Usually 50 or 60 Hz
➢ **Ambient Temperature Range**	For example: -50°C to +40°C
2. Capacitor Bank Main Characteristics	
➢ Rated Voltage	Depends on the system voltage where the capacitor bank is to be installed
➢ **Rated Power**	Based on wind power plant performance studies and VRE capacitive reactive power capability
➢ **Number of Units**	The number of capacitor units in the capacitor bank (may vary according to the design of the equipment to be installed at the POI)
➢ **Type of Connection**	Delta, Wye, Wye-grounded, Wye-grounded through an impedance (to reduce transient inrush/outrush currents; harmonic current flow could be of concern)
➢ **Arrangement of Capacitor Units**	Number of series and parallel capacitor units in the capacitor bank (may vary according to the design of the equipment to be installed at the POI)
3. Capacitor Units Main Characteristics	
➢ **Number of Terminals**	Capacitor units will usually be made of two terminals
➢ **Type of Capacitor Units**	Internally fused, externally fused, fuseless
➢ **Rated Voltage of the Capacitor Units**	Usually few kV (voltage available from manufacturer)
➢ **Rated Power of the Capacitor Units**	Usually few kV (rated voltage available from manufacturer)
➢ **Permanent Voltage in Capacitor Unit Including Harmonics (may be required for capacitor bank installed in**	Higher than the rated voltage of the capacitor units

Specifications	Value
environment with high harmonic content)	
➢ **Permanent Current in Capacitor Unit Including Harmonics (may be required for capacitor bank installed in environment with high harmonic content)**	Higher than the rated current of the capacitor units
4. Insulation Coordination Requirements (Note 1)	
➢ **Requirements to be established according to the following standards:**	IEC std 62271-1, *“High-voltage switchgear and controlgear – Part 1: Common specifications,”* Edition 1.1, 2011-08 IEC std 60071-1, *“Insulation co-ordination - Part 1: Definitions, principles and rules,”* Edition 8.0, 2006-01 IEC std 60137, *“Insulated bushings for alternating voltages above 1 000 V,”* Edition 6.0, 2008-07 IEC TR 62271-306, *“High-voltage switchgear and controlgear - Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating current circuit-breakers,”* 2012 IEEE C37.06, *“IEEE Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis--Preferred Ratings and Related Required Capabilities for Voltages Above 1000 V,”* 2009 IEEE C37.012, *“IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers,”* 2005 CIGRE Technical Brochure 624, *“Influence of shunt capacitor banks on circuit breaker fault interruption duties,”* 2015
5. Radio Interference Voltage (RIV) Requirements (if required and above 123 kV)	Value to be respected usually determined by national standards or regulation Proposed value 2,500 µV, measured according to IEC STD 62271-1 at 0.5 MHz and 1.1 p.u. of the rated voltage IEC std 62271-1, “*High-voltage switchgear and controlgear – Part 1: Common specifications*,” Edition 1.1, 2011-08

Specifications	Value
	IEC CISPR TR 18-2, "*Radio interference characteristics of overhead power lines and high-voltage equipment - Part 2: Methods of measurement and procedure for determining limits*," 2010

Note: In addition to the electrical characteristics, the choice of appropriate insulation levels for the equipment must take into consideration (a) the performance of circuit breakers and surge arrestors, if such equipment is used; and (b) the usual aspects considered for insulation coordination, such as standardized values, personnel safety, altitude correction factors, and pollution.

VENDORS

The following list shows a few suppliers of high-voltage capacitors, listed in alphabetical order:

5) ABB (Switzerland)
6) Eaton (Ireland)
7) General Electric (USA)
8) Siemens (Germany)
9) Shizuki Electric (Japan)

4 | SYNCHRONOUS CONDENSER

Key messages

- Synchronous condensers ensure efficient and reliable operation of power grids through reactive power compensation and additional short-circuit power capacity.
- Synchronous condensers are a proven, robust, reliable solution; can operate for extensive periods between inspections and services; and are suitable for installation in remote areas.
- The applications for wind and solar plants include increasing the short-circuit ratio (SCR), supporting dynamic voltage, improving wind plant capacity ratings, and improving frequency regulation by increasing inertia.

DEFINITION

A synchronous condenser (SC; also called synchronous compensator) is a synchronous machine whose shaft is not connected to anything and spins freely with no load. However, unlike a motor or generator (which converts electric power to mechanical power or vice versa), the purpose of a synchronous condenser is to adjust conditions on the electric power transmission grid. Its field is controlled by a voltage regulator to generate or absorb reactive power as needed to adjust the grid's voltage or to improve the power factor. The condenser's installation and operation are identical to that of large electric motors and generators. The SC connection to the grid is also the same as for any synchronous machine.

INDUSTRY NEED

The grid changes have an operational impact on the electrical infrastructure, in particular creating an overall deficiency in:

1) Reactive compensation support
2) Voltage support
3) System inertia
4) Short-circuit strength

The principal advantage of the synchronous condenser is the simplicity and continuous effectiveness of its reactive power correction, which can be performed through field excitation. The kinetic energy stored in the rotor of the machine can help stabilize a power system during rapid fluctuations of loads such as those created by short circuits or electric arc furnaces. Large installations of synchronous condensers are sometimes used in association with high-voltage, direct-current converter stations to supply reactive power to the alternating current grid.

Unlike a capacitor bank or reactor, the amount of reactive power from a synchronous condenser can be continuously adjusted, while the reactive power from capacitor bank or reactor can be adjusted only in discrete steps. The smooth continuous control allows for high flexibility and accuracy of reactive support in the power grid. The installation of synchronous condensers provides a simple, reliable, and well-proven solution for meeting reactive-compensation and voltage-support requirements in weak grid applications, especially in support of renewable generation and high-voltage direct-current (HVDC) systems. A synchronous condenser supports network voltage by providing reactive power compensation and additional short-circuit power capacity.

The efficiency of long power transmission lines may be increased by placing synchronous condensers along the line to compensate lagging currents caused by line inductance. More real power may be transmitted through a fixed-size line if the power factor is brought closer to unity by synchronous condensers absorbing reactive power.

Synchronous machines have higher energy losses than static capacitors and reactors, and their construction and installation are more expensive as well. Moreover, synchronous condenser operation usually requires burning fuel for its operations, similar to a synchronous generator.

DESIGN AND FUNCTIONALITY

A synchronous condenser has all the design and functional attributes of a synchronous machine. Indeed, under steady-state conditions, all synchronous machines operate at a speed determined by the power system frequency, which is why they are called “synchronous machines”. In a power plant, the shaft of the steam, hydro, or wind turbine is mounted in series to the shaft of the synchronous generator (Siemens 2016b). It is in this generator that the conversion from mechanical energy into electrical energy takes place.

The two basic parts of the synchronous machine are the *rotor* and the *armature* (or *stator*). The rotor is powered by either (a) the mechanical energy provided to its shaft or (b) the electric rotating magnetic field created by the system voltage applied to the stator windings, depending on if the machine is working as a generator or a motor. The armature is a group of windings in a static position that will be submitted to the DC magnetic field of the rotor coils. Thus, the iron rotor is equipped with a DC-excited winding that acts as an electromagnet. In a synchronous generator, when the rotor rotates, and the rotor winding is excited by the DC source, a rotating DC magnetic field is present in the air gap between the rotor and the armature. The armature has a three-phase winding in which a time-varying electromotive force (EMF) is generated by the rotating magnetic field of the rotor piece (the EMF varies at each point of the armature due to the rotor’s rotation).

If the machine is working as a motor, the stator will be submitted to a rotating magnetic field caused by the three-phase voltages applied to the windings terminals. The rotor’s DC magnetic field will follow the rotating magnetic field produced by the stator windings in a synchronous way (having the same angular speed). If the synchronous motor has its rotor used with no load applied to the axis (i.e. it spins freely), it is called a *synchronous condenser* (or sometimes a *synchronous capacitor* or *synchronous compensator*).

The energy-efficiency of synchronous machines or synchronous condensers is very high, reaching levels of 99 percent or greater. This means that 1 percent or less of the rated output power is transformed into heat – and thus that the machine must be cooled to keep the temperature of the windings and insulation under the maximum limits. Large synchronous condensers are cooled with hydrogen or water flowing through the hollow stator windings. Cooling equalizes the temperature distribution in the generator parts, which is important because occasional temperature hot spots may greatly diminish the lifespan of the electrical insulation. The synchronous condenser’s installation and operation are similar to that of large electric motors and generators.

The synchronous condenser consists of the following components (GE 2016):

1) Brushless, two-bearing synchronous motor with brushless exciter
2) Reduced current motor starter
3) Motor controls
4) Motor input circuit interrupter

5) Brushless, direct-connected, AC exciter with rotating rectifiers
6) Welded steel base with spring-type vibration isolators

The synchronous condenser is controlled by a synchronous condenser controller (SCC), which manages the condenser's regulation capability and mode (voltage, frequency, power factor, etc.) according to its settings. A digital voltage regulator adjusts the DC field current of the synchronous generator to control the terminal voltage. When operating in parallel with the electric grid, the adjustment of the DC field current controls reactive power on the lines, maximizing the amount of work that can be done with the power delivered. The SCC can be controlled remotely by a supervisory controller or locally with a touch screen interface. The touch screen operation may be limited to specific actions for quality control and safety reasons. The SCC actively monitors for fault conditions and will automatically shut down the synchronous generator if necessary. The SCC provides improved voltage and frequency regulation that counteracts the destabilizing influence of the wind turbines – which can be significant in gusty winds, when wind power fluctuations can be rapid and large. Even where there is a battery/inverter or flywheel/inverter system that regulates grid voltage, a synchronous condenser is often necessary to ensure an adequate supply of fault-clearing current, which inverters often cannot provide unassisted.

Fundamentally, a synchronous condenser is a synchronous generator operating without a prime mover. Generation/consumption of reactive power is achieved by regulating the excitation current. As mentioned earlier, the purpose of a synchronous condenser is not to convert electric power to mechanical power or vice versa, but to adjust conditions on the electric power transmission grid. The kinetic energy stored in the machine's rotor can help stabilize a power system during rapid fluctuations of loads such as those created by short-circuits. Its field is controlled by a voltage regulator to either generate or absorb reactive power as needed to adjust the grid's voltage, or to improve the power factor. Increasing the device's field excitation increases its reactive power (MVar) output. The synchronous condenser is thus a continuous variable source/sink of reactive power.

APPLICATIONS

The synchronous condenser provides a wide range of continuous capacitive or inductive power control while strengthening weak grids (i.e. those with low short-circuit capability) by providing inertia to the system. In some cases, it can also provide frequency regulation. The reactive power from a capacitor decreases when grid voltage decreases, while a synchronous condenser can increase reactive current as voltage decreases. The synchronous condenser's ability to absorb or produce reactive power on a transient basis stabilizes the power grid against short-circuits and other transient fault conditions. Transient sags and dips of milliseconds duration are stabilized. This increases longer response times of quick-acting voltage regulation and excitation of generating equipment. The synchronous condenser aids voltage regulation by drawing leading current when the line voltage sags; this increases generator excitation, thereby restoring line voltage.

To offer utilities greater reliability, ease of maintenance, and operational flexibility, the synchronous condensers can be configured in a modular way (i.e. combined in two- or three-unit systems) and rated for any range up to hundreds of MVar per machine, where steady-state and dynamic support to the power system is provided for efficiently by this modular configuration (Marken et al. 2010).

An important contribution of a synchronous condenser to grid operations is the improvement of overall short-circuit capacity in the network node where it is installed. This, in turn, improves the chances that equipment connected to the network will be able to "ride through" network fault conditions. A synchronous condenser is also well suited to operating during overload duty for shorter or longer periods of time.

Synchronous condensers can support the power system voltage during prolonged voltage sags by increasing the network inertia. They can therefore be used as VAr compensating devices in situations where voltage instability must be prevented at all cost.

Synchronous condensers can support and improve power transmission quality in a wide range of applications, including the following:

1) Stabilization of grids
2) High-voltage DC transmission links based on line-commutated converter technology
3) Transmission grids with a high amount of power infeed from renewable sources
4) Retirement/shutdown of conventional power plants

Unlike a capacitor bank, the amount of reactive power from a synchronous condenser can be constantly adjusted. In the case of the capacitor bank, the reactive power decreases when the grid voltage decreases (including the case of the SVC), while a synchronous condenser can increase reactive current as voltage decreases. However, synchronous condensers are costly devices, demanding higher and more complex maintenance (and suffering higher energy losses) than static capacitor banks. Most synchronous condensers connected to electrical grids are rated between 20 and 250 MVar, and many large condensers are hydrogen cooled. The risk of explosion hazard is reduced by maintaining hydrogen concentrations at above 70 percent; the level is typically kept above 91 percent.

The synchronous condensers market is expected to reach $572.9 million by 2021, having expanded at a compound annual growth rate (CAGR) of 2.1 percent from 2017 to 2021 (Markets and Markets 2017). The fastest-growing market segments in the synchronous condenser market are expected to be:

1) Synchronous condensers rated above 200 MVar, which held the largest market share in 2016. This growth is evident from the rising number of installations of synchronous condensers rated above 200 MVar, especially in North America and Europe.
2) Hydrogen-cooled synchronous condensers, as evidenced by the increasing adoption and efficiency of large-sized synchronous condensers.

For the past several years, synchronous condenser solutions have gained some new momentum as electrical utilities have used them to support transmission systems with short-circuit power, reactive power, and inertia. As more renewable power generation is added to the overall energy mix, and because converter-based renewable power generation does not contribute short-circuit power to the transmission network, the installation of standalone synchronous condenser applications is becoming more viable. Denmark is one of the few countries to include such a large share of wind energy in its energy mix, which is why synchronous condenser solutions are widely used in that country for stabilizing the transmission system. At present, wind turbines generate about 40 percent of Denmark's electricity; by 2020 this share is expected to rise to approximately 50 percent.

In 2015, Siemens manufactured and installed in Denmark a 250 MVar synchronous condenser, which provides the transmission system with more than 800 MVA of short-circuit power in addition to reactive power control. The installation of this standalone synchronous condenser solution enables operation of the transmission network without the need for a large thermal power plant. This makes the installation an economically and environmentally advantageous investment that will allow the influx of large amounts of renewable energy into the transmission network.

BENEFITS

The following list of benefits is adapted from a brochure by Grid Solutions, a General Electric and Alstom joint venture (GE 2016).

1) *Additional short-circuit power.* Synchronous generators enhance grid strength at connection points.
2) Capability to ride through network disturbances. Synchronous condensers can provide voltage support to the power grid during prolonged voltage sags.
3) *Short-term overload capability*. Synchronous condensers have a large current-overload capability, which can provide beneficial system support during emergencies or short-term contingencies.
4) *Low-voltage ride-through (LVRT).* The synchronous condenser system has the ability to remain connected and provide the necessary system benefits even under extreme low-voltage contingencies. Mechanical inertia combined with state-of-the-art excitation provides smooth, reliable support that is naturally compatible with generation. Because solutions based on power electronics lack mechanical inertia, and they cannot deliver comparable ride-through performance.
5) *System inertia*. Inertia is an inherent feature of a synchronous condenser because it is a rotating machine. The benefit of this inertia is improved frequency regulation where renewable generation is added or where existing generation is retired.
6) *Fast response time.* Synchronous condensers are fast enough to meet dynamic-response requirements by using excitation and control systems.
7) *Short-circuit contribution*. Synchronous condensers provide real short-circuit strength to the grid. The increased strength improves the stability of systems with weak interconnections, facilitates system protection, and can improve the operation of power electronics installations.
8) *Minimal harmonic generation*. The synchronous condenser is not a source of harmonics and can even absorb harmonic currents. The lack of harmonics helps make the synchronous condenser friendly to the surrounding grid and other devices, facilitating integration into existing networks.
9) *Minimal network interactions.* The synchronous condenser mitigates system control interaction concern by utilizing traditional and robust electrical components combined with a state-of-the-art control architecture that does not cause undesirable interactions with existing FACTS devices.

RECOMMENDATIONS FOR SPECIFICATION

The basic components of the synchronous condenser system should include a synchronous motor, a power factor controller, a system status and control panel, and an optional remote annunciator panel. The complete system should be pre-assembled and fully tested as a system prior to shipment.

The operation of the synchronous condenser is based on automatic control of the motor field. The synchronous condenser remains connected to the electrical system during normal operation and will not require any switching or produce any voltage transients that may affect other electrical systems.

The system comprises power and control section(s), which include all necessary interfaces for connecting it to the electrical system to be power-factor corrected. The controls consist of a power factor controller, voltage regulator, metering, starting logic, and protective systems required for normal operation.

The synchronous condenser can be a single system (or modular system) rated to supply the full load as specified by the system requirements.

During normal operation, the power-factor controller will monitor the phase difference between the voltage and current on the bus to be power-factor corrected. The power-factor controller will then convert the phase difference to a proportional voltage to be used by the voltage regulator. The voltage regulator will provide motor field control sufficient to smoothly produce the reactive power (in VAr) needed to correct the phase difference between the voltage and current monitored by the power-factor controller.

After a power interruption, the power factor controller should automatically restart one minute after power is restored.

The following list of related standards can be used to help establish the specification requirements:

1) IEC std 60034-1, "Rotating electrical machines – Part 1: Rating and performance," Edition 12.0, 2010-02
2) IEC std 60034, "Rotating electrical machines," relevant parts
3) IEC 60072 (all parts), "Dimensions and output series for rotating electrical machines"

TABLE 4.1 presents a reference summary guideline for the equipment specifications. When developing the specification data sheets and requirements, the specific needs of the electrical utility must be taken into account.

TABLE 4.1: Synchronous Condenser – Specification Sample

Specifications	Value
1. Operating conditions	
➢ **Power system frequency**	Usually 50 or 60 Hz
➢ **Ambient temperature range**	For example: -40°C to +40°C for outdoor installation or -5°C to +40°C for indoor installation
➢ **Nominal Voltage**	Depends on the system voltage where the shunt reactor is to be installed
➢ **System Voltage Variation for Normal Operating Conditions**	Typically between ± 5.0% and ± 10.0% of the nominal system voltage
➢ **Percentage of Negative Sequence Voltage Unbalance**	Typically between 1 and 2%
➢ **Grounding**	Ungrounded or effectively grounded (X0/X1 ≤ 3)
➢ **Overvoltage Ride Through**	Transmission system dynamic overvoltage profile for system perturbation to be provided according to transmission system operator (TSO) grid code

Specifications	Value
➢ **Low Voltage Ride Through**	Transmission system undervoltage profile for system perturbation to be provided according to TSO grid code
➢ **Frequency Variation**	Transmission system frequency variation and associated duration for system perturbation to be provided according to TSO grid code
➢ **Short-circuit at Connecting Point**	Short-circuit power at connecting point for: - Normal operating conditions - Degraded operating conditions - Maximum long-term SC level according to possible transmission system evolution
➢ **Harmonic Distortion**	The harmonic rates table is susceptible to being present on the system for harmonics; generally, up to the 50th order
2. Synchronous Condenser Characteristics	
➢ **Reactive Power**	Rated reactive power established by study of grid connection requirements Generally, up to ± 200 MVar
➢ **Overload Capabilities**	Temporary reactive power overload requirement For example, 10% overload capability for 30 min.
➢ **Voltage**	Voltage level at SC connecting point
➢ **Short-circuit Contribution**	Maximum value of the transient reactance on the polar axis (X'dv saturated) or short-circuit power contribution requirement
➢ **Inertia**	Constant of inertia of rotating parts established by planning study
➢ **Type of Cooling**	Hydrogen, air or water
➢ **Excitation System**	Static, rotating diode, brushless or other Voltage and reactive power regulator requirements Over and under excitation limiter requirements The requirements above are established depending on the SC response speed required and integration studies

Specifications	Value
➢ **Starter**	Type of auxiliary equipment (if any) to start the SC (full voltage, reduced voltage, reactor start, capacitor start, auto-transformer, pony motor, etc.)
➢ **Synchronization**	Any special and general requirements that the TSO may have concerning the circuit breaker that will have to put on or off the SC load (standards, opening time, minimum out-of-phase operating requirements, maximum fault clearing time, etc.)
➢ **Insulation**	This follows industry-standard practices. Specify any constraints related to pollution, humidity, altitude, etc.
➢ **Operating Performance**	1. Performance when starting the SC Specify the details of the automated SC starting procedure (admissible voltage variation at start for various system configurations, start duration, automatic and rapid re-synchronization, etc.) 2. Performance in steady state Specify normal operating conditions for the SC (voltage variation, frequency variation, negative sequence voltage unbalance, etc.) 3. Performance under perturbed operating conditions Specify the perturbed operating conditions for the SC (voltage variation, frequency variation, negative sequence voltage unbalance, etc.)
➢ **Maximum Audible Noise**	The maximum audible noise should be set between 50 to 100 db(A). Lower values in the range would be more suitable for areas sensitive to audible noise; higher values would be acceptable for foreign areas not exposed to public.
3. Controls	
➢ **Control Functions Requirements**	Specify the control functions required (starting sequence, synchronization, shut-down sequence, voltage reference set point, reactive power reference set point, manual or automatic regulation, etc.) Specify whether control functions are local, remote, or both.

Specifications	Value
4. Protections	
➢ **Excitation System Protections**	Specify the type of protection required for the excitation system (rotor overvoltage, voltage regulator, and excitation system failure), action to be taken (circuit-breaker opening or other) and time of operation
➢ **SC Protection**	Specify the type of protection required for the synchronous condenser (differential, overvoltage, negative sequence currents, mass protection of the stator and rotor, field or synchronism loss), action to be taken (circuit-breaker opening or other), and time of operation
➢ **Monitoring**	The manufacturer must provide (a) all sensors and the data acquisition system and (b) a list of electrical, mechanical and thermal parameters to monitor so that preventive maintenance can be performed before degradation occurs. It should specify whether monitored parameters have to be displayed locally, remotely, or both
5. Plant Availability	Specify the life expectancy of the installation, service factor, and the annual planned maintenance constraint.

VENDORS

Suppliers can tailor synchronous condenser modules to match each project's specific system performance requirements and site conditions, and to deliver optimum cost-efficiency. This allows for a flexible product as well as a quick turnaround time for commissioning. Further advantages are as follows:

1) *Complete modular package:* Uniform and fully compatible excitation and protection control equipment simplifies control interaction.
2) *Customizable modular design:* The modular solution ensures the smallest possible footprint as well as fast installation and minimum assembly on site.
3) *Cutting-edge technology:* Synchronous condensers are carefully designed for minimum losses, noise levels, vibrations, and weights.

The following list shows some suppliers of synchronous condensers in alphabetical order:

1) ABB (Switzerland)
2) Eaton (Ireland)
3) General Electric (USA)

4) Hyundai (South Korea)
5) Mitsubishi Electric (Japan)
6) Siemens (Germany)
7) Voith (Germany)

5 | STATIC VAR COMPENSATOR

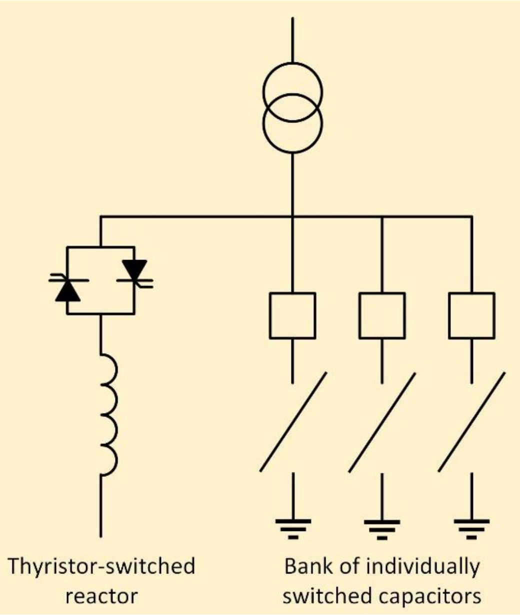
Key messages

- A static VAR compensator (SVC) is one of the essential solutions that can help VRE power plants meet interconnection requirements.
- An SVC provides quick and reliable voltage regulation as well as compensation and enables high-speed and smooth control of reactive power.
- The investment cost is lower compared to the STATCOM approach.

DEFINITION

A static volt-ampere reactive (VAR) compensator, or SVC, is a shunt-connected static VAR generator or absorber whose output is adjusted to exchange capacitive or inductive current so as to maintain or control specific parameters of the electrical power system (typically bus voltage). Typically, an SVC comprises several banks of capacitors and reactors switched by thyristors. To optimize both costs and the overall control of the reactive power in a network, thyristor-controlled reactors and thyristor-switched capacitors are often combined with mechanically switched shunt reactors and/or capacitors controlled by the SVC (FIGURE 5.1). By means of phase angle modulation, the reactor and capacitor may be variably switched by thyristor into the circuit and provide a continuously variable reactive power injection into, or absorption from, the power system. The thyristor-controlled switching provides smooth control and flexibility of reactive power and voltage regulation. When the system voltage is low, SVC generates the reactive power; when the voltage is high, it absorbs the reactive power. The reactive power is varied by switching the three-phase inductor and capacitor banks.

FIGURE 5.1: SVC – Simplified Connection Diagram 1



INDUSTRY NEED

SVCs are applied by utilities in transmission system applications for several purposes. The primary purpose is usually for rapid control of voltage at weak points in the network. An SVC can improve the transmission and distribution performance in several ways; installing an SVC at one or more suitable points in the network can increase the transfer capability, reduce losses while maintaining a smooth voltage profile under different network conditions, and improve the transient stability of the grid. The increase in the penetration of variable renewable energy (VRE) flow in the grid has introduced some potential stability problems (depending on the context of VRE integration), and grid operators are introducing more stringent grid codes to ensure the best integration of new VRE sources.

According to the grid code, the VRE plant must provide:

1) Low-voltage ride-through (LVRT) capability
2) High-voltage ride-through (HVRT) capability
3) Dynamic reactive current injection
4) Reactive power capability
5) Voltage control
6) Power factor control
7) Reactive power control
8) Power quality

The VRE plants must maintain their connection to the grid even during voltage drops (in fault conditions, for instance), and they must provide the dynamic reactive power source to address the fault requirements at the speed required by the transmission system operator (TSO).

Experience has shown that this equipment can fulfill the requirements of most grids. If the grid code has hard requirements for HVRT capability and for the harmonics level, it is preferable to use the STATCOM approach and capacitor banks/shunt reactors, which will require a higher investment cost.

DESIGN AND FUNCTIONALITY

The SVC provides flexible support to the system in the form of different configurations described in this sub-section. FIGURE 5.2 shows a simplified connection diagram of the SVC. The compensator normally can include a thyristor-controlled reactor (TCR), thyristor-switched capacitors (TSCs), and harmonic filters. The compensator might also include mechanically switched shunt capacitors (MSCs), in which case the term *static VAR system* would be used to describe it. The harmonic filters (for the TCR-produced harmonics) produce capacitive reactive power at the fundamental frequency. The TCR is typically larger than the TSC blocks so that continuous control is realized.

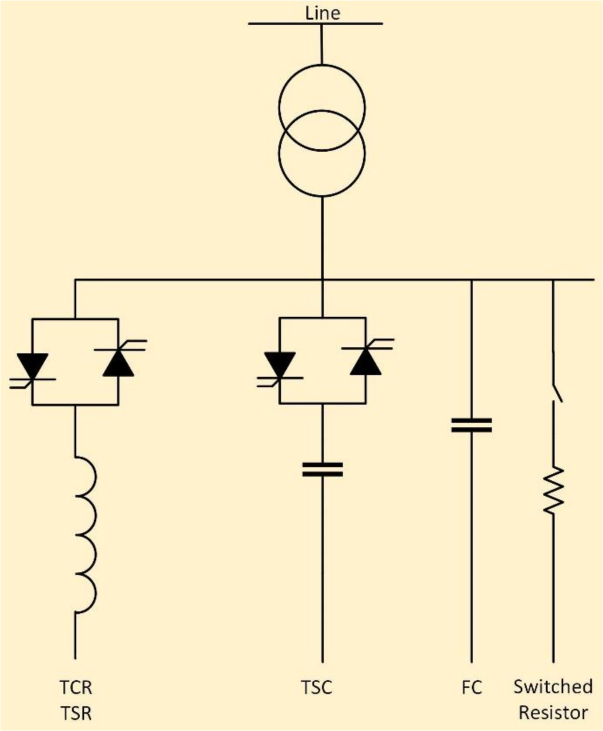
Another possibility is to combine fixed capacitors (FCs) with thyristor-switched reactors (TSRs) for an SVC solution with a lower investment cost. Usually a dedicated transformer is used, having a tailor-made reactance for the SVC project, with the VAR compensator equipment set at medium voltage to reduce costs. The transmission-side voltage is controlled while the MVar ratings are referred to the transmission side, whose range depends on the requirements of each solution.

The rating of an SVC can be optimized to meet the required demand for reactive power supply and voltage control. The rating can be symmetric or asymmetric with respect to inductive and capacitive reactive power limits. As an example, the rating can be 200 MVar inductive and 200 MVar capacitive, or 100 MVar inductive and 200 MVar capacitive.

Two particular characteristics of the SVC are as follows:

1) The SVC is an impedance controlling device whose reactive power *Q* is dependent on the square of the voltage *V* such that $Q = V^2/X$[10].
2) The output of the reactive power supply will be limited by low-voltage conditions.

FIGURE 5.2: SVC – Simplified Connection Diagram 2



Normally the SVC comprises the components mentioned above, and its design is defined according to the system requirements for dynamic reactive power supply at the POI.

Combined Thyristor-Controlled Reactor and Fixed Capacitor

The conceptual diagram of thyristor-controlled reactor (TCR) in a combination with fixed capacitor (FC) is shown in FIGURE 5.3. A reactor and thyristor valve are incorporated in each single-phase branch. Power is changed by controlling the current through the reactor via the thyristor valve. The on-state interval is controlled by delaying the triggering of the thyristor valve relative to the natural zero-current crossing.

The TCR is used in combination with the FC, where the TCR has a higher reactive-power rating (in MVAr) than the fixed capacitor to provide net reactive power generation or absorption, depending on the system conditions and requirements. The control objective of the TCR/FC combination is to maintain the desired voltage at the pre-defined level and adjusting the TCR to control the injection of reactive power into the network to control the system voltage. (To determine the appropriate injection and absorption levels of the reactive power, an analysis of the system must be performed by the system operator, taking into account voltage requirements.) This TCR/FC combination is often the optimum solution for

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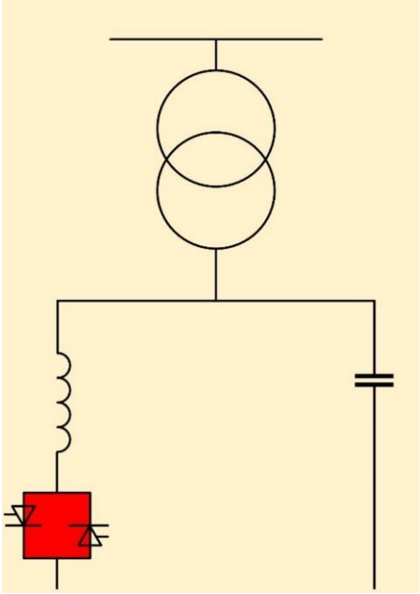
[10] Q is reactive power, V is system voltage and X is the system reactance.

sub-transmission and distribution, its main advantage over a switched capacitor being the provision of continuous control.

The main characteristics of the TCR are as follows:

1) Continuous control
2) No transients
3) Elimination of harmonics by tuning the FCs as filters
4) Compact design

FIGURE 5.3: Thyristor controlled Reactor and Fixed Capacitor – Conceptual Diagram



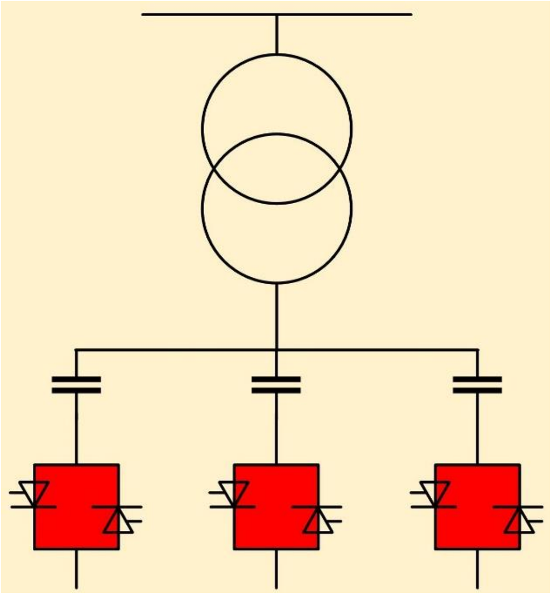
Thyristor Switched Capacitor

The thyristor-switched capacitor (TSC) is the only type of SVC (apart from a STATCOM) that can provide variable capacitance (although it is provided in steps). A conceptual diagram of a TSC is shown in FIGURE 5.4. A shunt capacitor bank is divided into the appropriate number of branches. Each branch is individually switched via thyristor valves. Switching takes place when the voltage across the thyristor valve is zero, making it virtually transient-free. Disconnection is affected by suppressing the firing pulses to the thyristors, which will be blocked when the current reaches zero. The TSC type, unlike the TCR, doesn't generate any harmonics and so doesn't require any filtering. This can lead to a relatively cost-effective solution in cases where the SVC requires only capacitive reactive power. However, with TSCs, there are occasions where transients may occur. For instance, very high inrush currents can occur when the capacitors are energized, making it necessary to accurately turn on the thyristors.

The TSC's main characteristics are as follows:

1) Stepped control
2) No transients
3) No harmonics
4) Low losses
5) Redundancy and flexibility

FIGURE 5.4: Thyristor switched Capacitor Conceptual Diagram



Combined Thyristor-controlled Reactor and Thyristor-switched Capacitor

In a combined TCR and TSC compensator, continuously variable reactive power is obtained across the entire control range plus full control of both the inductive and the capacitive parts of the compensator. The principal benefit is optimum performance in terms of reactive-power dynamic control during major disturbances in the power system, such as line faults and load rejections.

The main characteristics of the combined TCR and TSC compensator are as follows:

1) Continuous control
2) No transients
3) Elimination of harmonics via filters or TSR control
4) Low losses
5) Redundancy
6) Flexible control and operation

Dynamic Braking Resistor

The thyristor-controlled braking resistor, known as dynamic braking resistor (DBR), is also a shunt FACTS device; however, its purpose is different from that of an SVC. A DBR is mainly used for consuming active power available from the generator that cannot be sent to the grid due to voltage depression in the post-fault period. In this way, the DBR improves the rotor angle stability of central power plants (CPPs).

Another series-based FACTS device is the series DBR, or SDBR, which offers similar functions as a shunt DBR but performs better because it depends on current rather than voltage.

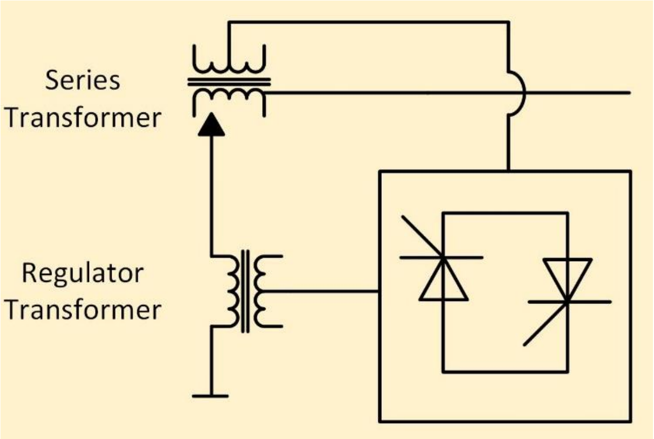
DBRs were developed to contribute directly to the balance of active power between the mechanical and electrical side of a wind turbine (WT) system during a fault, which potentially reduces or eliminates the need for pitch angle control or reactive power compensation devices. This is done by dynamically installing a resistor in series between the WT and the grid to boost the voltage at the generator's terminals, thereby alleviating instability concerns regarding electrical torque and power during the fault period. Some manufacturers provide an additional feature for SDBRs where the resistors are independently controlled in each of the three phases, enhancing performance during unbalanced fault conditions.

The SDBR can be considered a very simple and cost-effective means of enhancing the LVRT capability of a wind generator system because it uses a high-power resistor and fewer switches than other auxiliary methods. The SDBR can effectively dissipate active power but it cannot control reactive power; therefore, it is unable to minimize the voltage and power fluctuations of a wind generator. At present, the implementation of DBRs and SDBRs in electrical utilities is fairly rare compared to other FACTS devices, but there is good potential for implementing them in the future.

Thyristor-controlled Phase Angle Regulator

The thyristor-controlled phase angle regulator (TCPAR) is adjusted using thyristor switches to provide a rapidly variable phase angle, which is obtained by adding a perpendicular voltage vector in series with a phase (FIGURE 5.5).

FIGURE 5.5: Thyristor switched Capacitor for TCPAR



A TCPAR consists of a phase-shifting transformer adjusted by thyristor switches. In this system, voltage is injected in quadrature to the line voltage using the phase-shifting transformer such that the resultant voltage remains the same, with only the phase angle varying.

Low-frequency oscillations, which arise between areas in large interconnected power networks, are a problem of current interest in the power industry. These oscillations are related to the small-signal stability of the power system and are detrimental to the goal of maximum power transfer and power system stability. Adding a TCPAR provides an effective dampening of power oscillations in the grid; the number of inter-area oscillations can be reduced by increasing the voltage injection of the TCPAR. Thus, the system stability is improved, and the power transfer capabilities can be enhanced over a wide range of operating conditions. (Similar effects can be achieved with the addition of a TCSC as described in Section 0).

APPLICATIONS

Generally, SVC compensation is not done at the high voltage side as a bank of transformers steps the high transmission voltage down to a much lower level. This reduces the size and number of components needed in the SVC, although the conductors must be very large to handle the high currents associated with the lower voltage. For industrial applications such as electric arc furnaces, where there may be an existing medium-voltage busbar present, the SVC may be directly connected to eliminate the cost of the transformer.

According to *Research and Markets*, the SVC market was valued at $643.6 million in 2014 and is estimated to reach $807.7 million by 2020, at a CAGR of 3.8 percent between 2015 and 2020 (Research and Markets 2016).

The main consideration when choosing the SVC configuration is its intended application – for instance, reactive power support, VRE plant grid-code compliance, grid voltage stability, and industrial power quality. For VRE, the configuration should be determined only after a thorough analysis of the local grid code with respect to the plant power output of the VRE source. It is important to note that each country's grid code requirements can vary significantly and familiarity with these codes is key (Boström & Mehraban 2014; Halonen & de Oliveira 2016).

The SVC must be designed to operate safely and reliably in the transmission or distribution system to which it is connected. This can be quantified in a number of specific requirements in terms of dynamic range, system operating voltage conditions, contingency scenarios, and so on (Boström & Mehraban, 2014). The SVC sizing and topology should be such that undesired resonant conditions – both internal to the SVC and between the SVC and the AC system – are avoided or significantly minimized.

As an example, when SVC systems were installed in 2013 in the Texas Competitive Renewable Energy Zone (CREZ) operated by American Electric Power (AEP), the solution chosen comprised (a) two SVC units operating in parallel rated between -66 and +150 MVar installed at 345-kV substations close to the wind farms and (b) two SVC units operating in parallel rated between -25 and +100MVar at 138-kV substations close to the load. This was because the wind farms were located at remote areas where, because conventional synchronous generation was lacking, reactive power support was essential to facilitate high active-power transfers from the wind farms to the load centers (Boström & Mehraban 2014).

The primary purpose of the SVCs is to provide reactive support during system contingencies and improve voltage regulation. The SVC unit connected to the 345-kV substation is composed of one TSC branch rated at 94 MVar, one TCR branch rated at 122 MVar, and 56 MVar of fixed filters, distributed over two banks tuned to the third and fifth harmonics, respectively, to eliminated undesired resonant conditions. The vendor guarantees 99.1 percent availability for the installed SVC units, including one scheduled 37-hour-long outage for yearly maintenance. For details of the design and application of the SVCs in this particular, please refer to Reference (Boström & Mehraban 2014).

BENEFITS

The SVC helps to extend the life of inverters, wind turbine gearboxes, switches and other components by eliminating or greatly reducing stress in the form of transient voltage events, and by soft-switching capacitors and reactor banks using proprietary and patented technology.

The general benefits of SVC installation are as follows:

1) Fast and smooth dynamic control of the network voltage at its coupling point (i.e., keeping the network voltage constantly at a set reference value)
2) Reactive power control
3) Damping of power oscillations
4) Unbalance control

The following SVC advantages are specifically important for VRE:

1) Steady-state and dynamic voltage control/stabilization
2) Continuous power-factor control
3) Enabling/increasing the wind farm's fault ride-through capability
4) Enhancing power quality control by mitigating flicker

RECOMMENDATIONS FOR SPECIFICATION

The following IEEE guide contains comprehensive recommendations for SVC specification:

1) IEEE *Guide for the Functional Specification of Transmission Static Var Compensators.* 10.1109 IEEESTD.2011.5936078.

The guide includes an informative annex provided to allow users to modify or develop specific clauses to meet a particular application. The document includes the following topics:

1) Scope of supply and schedule
2) Site and environmental data
3) Power system characteristics
4) Main SVC characteristics
5) Main components – required functions and features
6) Spares
7) Engineering studies
8) Documentation
9) Training
10) Balance of plant (e.g. buildings, structures, fire protections)

The following related standard can be used to help establish the specification requirements:

1) IEEE Std 1303-2011, "IEEE Guide for Static Var Compensator Field Tests"

TABLE 5.1 presents a reference summary guideline for the equipment specifications. When developing the specification data sheets and requirements, the specific needs of the electrical utility must be taken into account.

TABLE 5.1: Static VAR Compensator – Specification Sample

Specifications	Value
Rating Power	40 – 800 MVar
Rated Voltage	33-800 kV
Voltage Tolerance	± 10%
Nominal Frequency	50 Hz or 60 Hz
Frequency Tolerance	± 10%
Power System	3-phase center-ground referenced (TN-S)

Specifications	Value
Efficiency	>98%
Quality	ISO 9001
Safety	IEC 62103
Electromagnetic Compatibility	Emissions CISPR 11 Class A, Group 1 Immunity IEC 61000-6-2
Performance	IEEE 519 IEEE 1031-2000
Operating Temperature Range	-40°C to 50°C
Operating Altitude	< 1000 m without derating
Humidity	< 95%, non-condensing
Pollution Degree Rating	2
Noise	< 85 dBA @ 2 m

VENDORS

The following is the list of some suppliers of SVC in alphabetical order:

1) ABB (Switzerland)
2) American Electric Power (USA)
3) American Superconductor (USA)
4) Eaton (Ireland)
5) General Electric (USA)
6) Hyosung (South Korea)
7) Mitsubishi Electric (Japan)
8) NR Electric (China)
9) Rongxin Power Electronic (China)
10) Siemens (Germany)

6 | STATIC SYNCHRONOUS COMPENSATOR

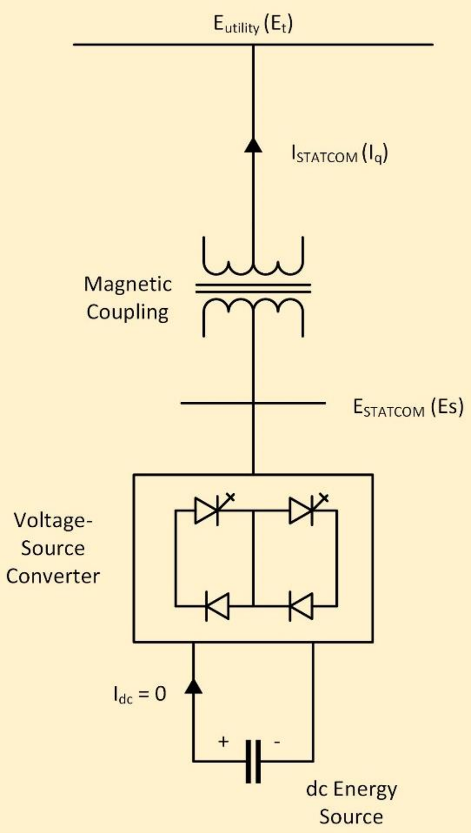
Key messages

- A static synchronous compensator provides voltage regulation and VAR compensation and enables high-speed control of reactive power.
- Its main advantages are a fast-dynamic response and a short overload capability.
- It is an effective solution for enabling VRE power plants to meet stringent interconnection requirements.

DEFINITION

A static synchronous compensator (STATCOM), also known as a static synchronous condenser (STATCON), is a converter that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in alternating-current (AC) electricity transmission networks (FIGURE 6.1). An inherently modular device, the STATCOM is based on a power-electronics voltage-source converter. It can act as either a source of, or a sink for, reactive AC power in an electricity network. If connected to a source of power, it can also provide active AC power. A STATCOM equipped with energy storage, or STATCOM+ES (also called E-STATCOM for transmission systems and D-STATCOM for distribution systems), can be used for active power exchange with the grid.

FIGURE 6.1: STATCOM – Simplified Connection Diagram



INDUSTRY NEED

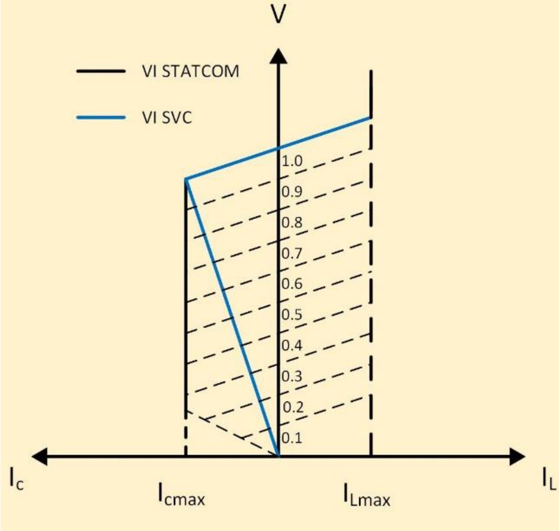
It is essential to balance the supply and demand of active and reactive power in an electric power system. If the balance is lost, severe system-frequency and voltage problems may occur in the power system. A very fast voltage and reactive-power control is essential for ensuring stable operations of the grid. The STATCOM is a highly advanced power-electronics technology that provides fast and continuous capacitive and inductive power supply to the power system.

The STATCOM is a dynamic reactive power source that can meet most stringent TSO requirements. Its fast response is made possible because it is based on power-electronics controls and can even be used to address resonance or power-quality issues. Like SVCs, STATCOMs also provide variable reactive power in response to voltage variations, thereby supporting the grid. The difference between SVCs and STATCOMs is that SVCs are directly connected to the AC system, which makes the output of the device depend on the voltage. The STATCOM is connected through a voltage-source convertor (VSC), which makes the reactive power output independent of any changes in the voltage in the AC system, and results in superior performance for low-voltage events. STATCOMs require practically no harmonic filters, which contributes to a small physical footprint. Their highly integrated and modular design means they are considerably more expensive than SVCs.

As was stressed in “Needs Analysis” of Chapter 1 (Page 5), the need for a FACTS device in a particular system depends on current system conditions (a grid interconnection study is required for the appropriate installation of the compensation devices). In cases where fast responses in voltage support are not needed, switched capacitors/reactors are cost effective. However, in cases where part of the power network is prone to various disturbances and outages, compensation devices such as SVCs, and especially STATCOM devices, would be a more appropriate choice to make the system less vulnerable to these events, and to improve the fault-ride-through capabilities of renewable generators that might be susceptible.

The difference between an SVC and a STATCOM stems from their respective connections. An SVC is directly connected through an AC connection and has a reactive power capability curve (see Figure 6.2) where the reactive current (which is the reactive power generated or consumed) provided by the SVC decreases as the system voltage decreases. A STATCOM, however, is connected through a voltage-source convertor (VSC), so the amount of reactive power is not affected by the system voltage level, which results in a quicker response to voltage drops in the system. A STATCOM is more expensive than an SVC because of the additional equipment required to convert DC to AC. Moreover, if needed, a limited-time active-power support can be provided by incorporating energy storage via a STATCOM+ES device.

FIGURE 6.2: Capability Curve Comparison for STATCOM and SVC



The rise of VRE flow in the grid has introduced potential stability challenges (depending on the context of VRE integration), with grid operators introducing more-stringent grid codes to ensure the best integration of those VRE sources. As mentioned in the previous sections, there are various compensation devices capable of providing system voltage support so that system conditions comply with the grid codes. Of these devices, the STATCOM is one of the most effective in terms of response time and performance and maintaining the voltage within the predefined system limits for normal and transient conditions.

According to standard grid codes, the VRE plant must provide:

1) Low-voltage ride-through capability
2) High-voltage ride-through capability
3) Dynamic reactive current injection
4) Reactive power capability
5) Voltage control
6) Power factor control
7) Reactive power control
8) Power quality

The VRE plants must be able to stay connected to the grid during voltage drops (e.g., in fault conditions), and they must provide a dynamic reactive power source capable of managing the fault requirements at the speed required by the TSO.

DESIGN AND FUNCTIONALITY

A STATCOM is a power-electronic device composed of power inverters that inject reactive current into a power system for smooth and fast control of the system’s voltage or power factor. The STATCOM is essentially a voltage-sourced, inverter-based device that converts the DC voltage into a three-phase set of AC output voltages to compensate the active and reactive needs of the system. STATCOM normally provides reactive power support, but it can also provide active power support when there is an additional storage device connected to it.

There are two main methods to design a voltage-sourced converter for a power utility application: pulse-width modulation (PWM) and multi-level converters, the latter being a newer type of technology. Inherently, the STATCOM has a symmetrical rating with respect to inductive and capacitive reactive-power limits; for example, the rating can be 100 MVar inductive and 100 MVar capacitive. For an asymmetric rating, the STATCOM needs a complementary reactive power source. This can be realized by using mechanically switched capacitors (MSCs).

Some manufacturers use a VSC concept based on a chain-link modular, multilevel converter (MMC) (Markets and Markets 2017) specially adapted for power system applications. Physically, this kind of STATCOM is a voltage source behind a reactance, which generates and absorbs reactive power by electronically processing voltage and current waveforms in the VSC, rendering it unnecessary to include physical capacitor and reactor branches for generating/absorbing reactive power. The technology is capable of injecting a large amount of reactive power into the grid more or less unimpeded by any grid voltage drops that may occur, and with a high dynamic response. This can support weak grids and improve the performance of large wind farms under varying grid conditions, as well as grids loaded by a large percentage of air conditioners in hot and humid climates. Various sizes of converter rating up to ±360 MVar are available for system voltages up to 69 kV. For higher voltages, a step-down transformer is used to connect the STATCOM to the grid. The described solution provides a symmetrical operating range. For asymmetrical operations and in order to optimize performance, thyristor-switched reactors and capacitors operate in parallel to create hybrid solutions.

Insulated-gate bipolar transistors (IGBTs) are key components of the system previously described. The multilevel chain-link solution is built up by linking H-bridge modules in series with one another to form the phase legs of the VSC. The amplitude and phase angle of the injected STATCOM current with respect to the voltage will determine the amount of the capacitive or inductive reactive power that flows from the inverters into the grid.

Some common characteristics of STATCOM are as follows:

9) A six-IGBT bridge can create three-phase current.
10) The DC source is common to all three phases.
11) IGBTs control current phases with respect to voltage (e.g., controlled MW and MVar flow).
12) STATCOMs are built in a modular configuration where the power of each module is generally a few MVar (e.g. 1-5 Mvar). The capacity of the STATCOM is increased by stacking these modules in series/parallel configurations.

STATCOM provides very fast response for dynamic performance. Its high level of system availability stems from the redundancy of power modules, minimized maintenance and service requirements, standardized control, and protection hardware and software. MMC technology provides low harmonic generation and low noise emissions. High-frequency noise is absorbed by small, standardized, high-frequency blocking filters, resulting in a design that is practically independent from individual network impedances. MMC with low switching frequencies results in reduced losses.

As with SVCs, the main factors affecting the choice of a STATCOM are the application, VRE plant grid code compliance, grid voltage stability, and industrial power quality (if used for industrial application).

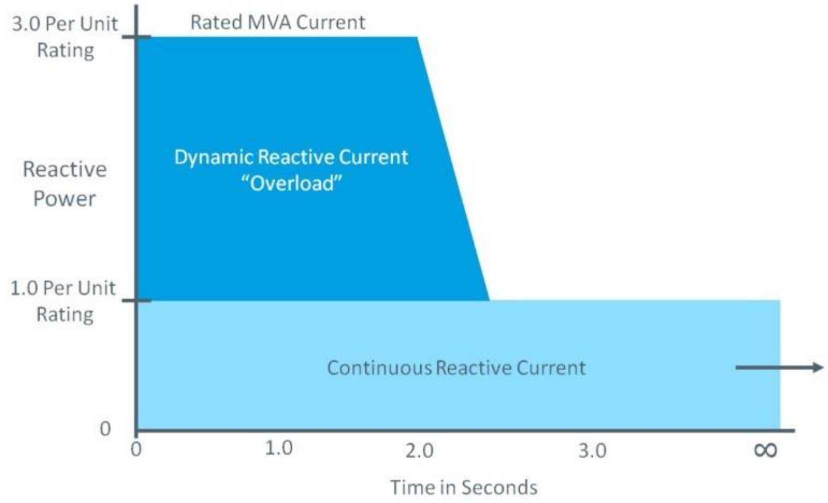
Grid code requirements for VRE grid connections can vary significantly from country to country, and the best solution can be selected only analyzing the code and conducting integration studies. The grid code requirements for VRE at the point of interconnection (POI) are as follows:

1) Voltage ride-through capability (low, high)
2) Dynamic stability
3) Power factor capability

Although a variety of reactive resources are required to fully meet most grid code requirements, STATCOMs are valuable for their fast-dynamic response, short overload capability, and ability to provide maximum reactive output current during sharp voltage drops.

The compensation the STATCOM provides allows the system to maintain a constant current; as a result, the maximum reactive-power output is not affected by the voltage magnitude, resulting in high device performance even at low voltages. Furthermore, the STATCOM's dynamic reactive-current capability (i.e. short-term overload capability) provides maximum reactive output current during sharp voltage drops, increasing the low-voltage ride-through capabilities of VRE power plants. FIGURE 6.3 shows an example of the short-term overload capabilities of STATCOM devices.

FIGURE 6.3: STATCOM Dynamic Capability



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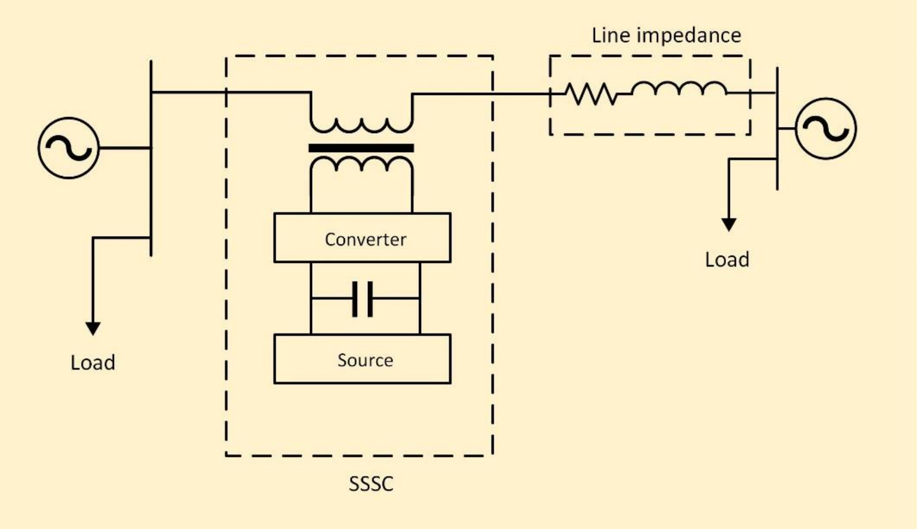
Static Synchronous Series Compensator

The static synchronous series compensator (SCCC) is based on the voltage source converter. It is connected in the series in the transmission line via a transformer, as shown in FIGURE 6.4. The SSSC injects a balanced set of voltages at the fundamental frequency that lags or leads the line current by 90 degrees. An SCCC with energy storage (ES) provides voltage across the DC capacitor and compensates the device losses.

FIGURE 6.4: SCCC with Energy Storage – Simplified Connection Diagram



The SSSC can be controlled to provide either series capacitive or inductive compensation. Moreover, the SSSC has no prohibited region[11], so the series compensation can be changed from inductive to capacitive and vice versa. If the SSSC is provided with a storage source, then it can exchange real power with the power system.

As the reactive compensator, the SSSC has two magnitude nodes:

1) Constant reactance mode, where the SSSC voltage is a function of line current; and
2) Constant quadrature voltage mode, where the SSSC voltage is independent of line current.

Unified Power Flow Controller

The unified power flow controller (UPFC) is a combination of a STATCOM and a static synchronous series compensator (SSSC). The UPFC merits a separate mention in this section due to the importance of its functionality and the attention it has recently gained in the industry. Normally, controlling power flow through the transmission network is very difficult because mechanical devices are too slow to switch alternating current cycle by cycle. As a result, power flows in the direction in which it "wants" to flow: along parallel paths of least resistance. Additionally, capacitors, reactors, or synchronous condensers can offer only so much voltage support and cannot provide rapid, smooth control. The UPFC can provide very rapid and smooth control and, most importantly, it can redirect power flow on existing lines so as to utilize more of the overall system. A UPFC can react almost instantaneously to counteract disturbances on a transmission line, thus improving system stability.

The UPFC can be envisaged as a device comprising two back-to-back VSCs sharing a common capacitor (on their DC sides) and a unified control system. FIGURE 6.5 illustrates how one VSC is connected to the AC network using a shunt transformer while the second is connected to the AC network using a series transformer. The UPFC operates both inverters at the same time, and the exchanged power at the terminals of each inverter can be reactive as well as active.

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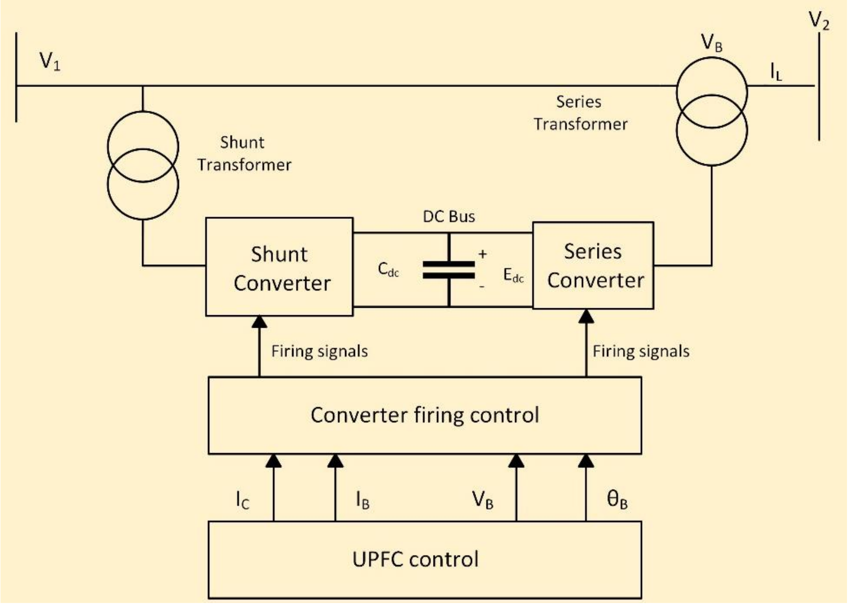
[11] No prohibited region means that the series compensation can be changed from inductive to capacitive and vice versa where continuous operation is guaranteed.

FIGURE 6.5: UPFC – Simplified Connection Diagram



In addition to providing a supporting role in the active power exchange that takes place between the series converter and the AC system, the shunt converter may also generate or absorb reactive power to provide independent voltage magnitude regulation at its point of connection with the AC system.

The active power demanded by the series converter is drawn by the shunt converter from the AC network and supplied through the DC link. The output voltage of the series converter is added to the nodal voltage, and the voltage magnitude of the output voltage provides voltage regulation (where the phase angle determines the mode of power flow control).

The UPFC's main advantage lies in its control of the active and reactive power flows in the transmission line; its controllable parameters are reactance in the line, phase angle, and voltage. It also provides the secondary, but still important, function of stability control – to suppress power-system oscillations and improve the transient stability of the power system.

Because the UPFC combines a STATCOM and an SSSC – both solid-state devices – coupled via a common DC voltage link, it has a functional flexibility generally not attainable by conventional thyristor-controlled systems.

It should be noted that the *phase-shifting transformer* (PST) is another device that, while strictly speaking not part of FACTS device family, can control the power flow through specific lines in a complex power transmission network. PSTs are used mainly in high-voltage systems (up to 500 kV) with large throughput power ratings (up to 1600 MVA), for the following purposes:

1) To control the power flow between two large, independent power systems;
2) To change the effective phase displacement between the input and output voltages of a transmission line, thus controlling the amount of active power that can flow in the line;
3) To balance the loading when power systems are connected together at more than one point (i.e. when loops exist and the impedances in parallel paths result in undesired distribution of power flow in the paths); and
4) To prevent thermal overload and improve transmission system stability.

APPLICATIONS

One of the first UFPCs was developed by American Electric Power (AEP), the Electric Power Research Institute (EPRI), and Westinghouse Electric, went into test operation in 1998 at Inez Station in eastern Kentucky. The main objectives of that installation were to improve the reliability and quality of bulk power transfers while also allowing utilities to control the flow of electricity through a transmission network. The UPFC was constructed in two phases: Phase I consisted of a +160 MVar shunt inverter (for voltage support) connected to AEP's existing 138 kV station. Phase II saw a +160 MVar series inverter (for power flow control) connected to a new, and at that time a very high capacity, 138 kV transmission line.

In 2002, the challenges associated with power system deregulation, combined with increased demand for system reliability and profitability, prompted San Diego Gas & Electric (SDG&E) to initiate a major transmission system enhancement project involving a key 230/138 kV substation and the installation of a STATCOM-based dynamic reactive compensation system (Reed et al. 2002; Boström & Mehraban 2014). SDG&E thoroughly studied various alternatives and decided the best solution would be to install a STATCOM system at the Talega substation. The fast-reactive power support enables the utility with more efficient utilization and control of the existing transmission system infrastructure.

As described in (Boström & Mehraban 2014), the STATCOM system at the Talega 138 kV substation has a rated dynamic capacity of 100 MVA and consists of two groups of voltage-sourced converters (50 MVA each). Each converter group in turn comprises four sets of 12.5-MVA modules plus 5-MVar harmonic filters (plus one spare filter switchable to either group) with a nominal phase-to-phase AC voltage of 3.2 kV and a DC link voltage of 6 kV. The two 50-MVA STATCOM groups are connected to the 138-kV system via two three-phase step-up transformers (each rated at 55 MVA, 3.2 kV/138 kV). Either 50-MVA STATCOM group, or both groups, can be connected to each of the 138 kV buses via the various automatically controlled, motor-operated disconnects. The main power semiconductor devices incorporated into the converter design are 6-inch gate-commutated turn-off thyristors (GCTs), each rated at 6 kV and 6 kA. These devices are arranged in each module to form a three-level inverter circuit, which reduces the harmonic current as compared to a two-level design. The control of the inverter is achieved with a five-pulse PWM (pulse-width modulation), which further decreases the harmonics as compared to three-pulse or one-pulse PWM control.

As part of the overall reactive-compensation scheme at the Talega substation, three 69-MVar shunt capacitors (or capacitor banks) are also connected directly to the 230 kV system. The STATCOM system is able to control the operation of both the STATCOM inverters and the three capacitor banks – which can be either remotely operated (via SDG&E's supervisory, control and data acquisition system, or SCADA) or manually operated from the control building.

The following are some of the essential benefits realized at the Talega substation with the STATCOM implementation:

1) Rapid response to system disturbances
2) Smooth voltage control over a wide range of operating conditions
3) Significant amount of built-in redundancy in the modular design of groups
4) Automatically reconfiguration to handle transformer failures without shutting down the STATCOM

SDG&E conducted a study to determine (a) which FACTS device would best meet SDG&E's planning requirements and (b) how much a FACTS device would be able to increase the usable capacity of the South-of-San-Onofre Nuclear Generating Station (SONGS) transmission system. (The South-of-SONGS path offered the largest potential increase in imports because it connected SDG&E to the rest of the Western System Coordinating Council (WSCC) to the north. The General Electric Power Flow Program was used to model FACTS devices in the study. Additional studies of real and reactive load flow were conducted to determine how installing FACTS devices could help increase SDG&E's import capability.

The studies determined the following:

1) The most beneficial FACTS technology for increasing import capacity into SDG&E's service area was the UPFC unit.
2) A UPFC installed anywhere on the South-of-SONGS path would be able to redistribute the power flow and increase SDG&E's import capability.
3) Of the five locations examined in the South-of-SONGS area, the installation of a UPFC on the San Onofre–Talega 230-kV lines at the Talega substation was the most suitable.
4) Installing a FACTS device could potentially increase the utility's import capacity by an estimated 300 MW (i.e., by 12 percent) and delay the construction of additional transmission lines or generating capacity.

In addition, SDG&E carried out a discounted cash flow analysis of five options for reactive power support. To compare costs, the utility assumed the cost of an SVC unit and the series or shunt element of the UPFC to be $40,000 per megavolt-ampere (MVA), based on information from EPRI and AEP. After comparing the net present value for each alternative, it was determined that (a) an 85-MVA UPFC on the San Onofre–Talega 230-kV lines would be the most economical alternative for a demonstration project to test the UPFC's effect on SDG&E's import capability and (b) the proposed installation would have a payback period of 13 years.

The overall study concluded that while FACTS devices could be useful to the SDG&E system, there was no indication that this technology alone could replace future transmission and generation projects needed to meet load growth. The technical and economic benefits of FACTS technology must be compared with those of conventional facilities on a case-by-case basis to determine if FACTS technology is a viable alternative. The research analysis demonstrated the potential benefits of FACTS technology to enhance power system operation and increase power import capability over existing systems, but the results are still preliminary, and subsequent studies are required.

BENEFITS

A STATCOM helps reduce stress on, and extend the life of, inverter, wind turbine gearboxes, switches, and other components by mitigating (by eliminating or greatly reducing) transient voltage events, and by soft-switching capacitors and reactor banks using proprietary and patented technology.

The following essential benefits of STATCOM implementation are applicable to the whole power system:

1) Reactive power compensation
2) Three-phase voltage balancing
3) Voltage regulation
4) Flicker suppression
5) Line loss minimization
6) Power transfer capacity increase
7) Power oscillation damping
8) Steady-state stability improvement
9) Transient stability improvement

The following advantages are identified for VRE applications in particular:

1) Steady-state and dynamic voltage control/stabilization
2) Continuous power factor control
3) Enabling/increasing the fault ride-through capability of the wind farm
4) Enhancing power quality control by mitigating flicker

The following are the STATCOM's distinct advantages over other technologies in the FACTS devices group:

1) Modular
2) Easy to expand and relocate
3) Relatively small footprint
4) Negligible harmonic injection
5) Does not require an external filter
6) No potential to cause harmonic resonances
7) Robust during low-voltage conditions
8) Has overload capability
9) Air-cooled

RECOMMENDATIONS FOR SPECIFICATION

IEEE is currently preparing its "Guide for the Functional Specifications for Transmission Static Synchronous Compensator Systems" (IEEE SA-SP1052). At the time of writing, the guide had not been finalized, but the expectation is that it will cover applications, main component characteristics, system functions and features, factory testing, engineering studies, commissioning, and operations of the STATCOM systems.

There is a limited number of published STATCOM-related standards and the industry definitely requires more work in this area. For now, the following standard can be used to help establish the specification requirements:

1) IEC 62927 Ed. 1.0., "Voltage Sourced Converter (VSC) Valves for Static Synchronous Compensator (STATCOM) - Electrical Testing"

TABLE 6.1 presents a reference summary guideline for the equipment specifications. When developing the specification data sheets and requirements, the specific needs of the electrical utility must be taken into account.

TABLE 6.1: STATCOM – Specification Sample

Specifications	Value
Rating Power	100 – 5000 kVAr
Rated Voltage	400-500 V
Voltage tolerance	± 10%
Nominal frequency	50 Hz or 60 Hz
Frequency tolerance	± 10%

Specifications	Value
Power system	Three-phase center ground referenced (TN-S)
Overvoltage category	III
Fault capacity	65 kA
Overload capability*	200% overload for 2 seconds* 150% overload for 30 seconds
Efficiency	>98%
Quality	ISO 9001
Safety	IEC 62103
Electromagnetic compatibility	Emissions CISPR 11 Class A, Group 1 Immunity IEC 61000-6-2
Performance	IEEE 519 IEEE 1031-2000
Operating temperature range	-40°C to 50°C, typical worldwide temperature range
Temperature derating	Above 40° C, derate at 2% load per degree °C to a maximum of 50°C
Operating altitude	< 1000 m without derating
Capacity derating with altitude	1% every 100 m above 1000 m; 2000 m maximum
Inverter Cooling	Forced ventilation
Humidity	< 95%, non-condensing
Pollution degree rating	2
Noise	< 85dBA @ 2 m

VENDORS

The following list shows some suppliers of high-voltage capacitors in alphabetical order:

1) ABB (Switzerland)
2) American Superconductor (USA)
3) Eaton (Ireland)
4) General Electric (USA)
5) Mitsubishi (Japan)
6) Siemens (Germany)

7 | POWER PLANT CONTROLLER

Key messages

- Additional control equipment is needed at power plants due to the increased share of VRE and fluctuation of load profiles.
- Power plant controllers (PPCs) help the grid operator (a) predict the VRE plant performance on active and reactive power control at the plant's POI and (b) guarantee the quality and stability of the electricity supply.
- Plant controllers include the SCADA (for the plant monitoring system) and a communications network.

DEFINITION

A power plant controller (PPC) is a new device of modular design that provides an intelligent and flexible control solution for power plants, and especially VRE plants. The PPC allows large-scale power plants to meet all the requirements of modern competitive power systems, provides plant operators with maximum yields, and contributes to the grid's stability. It provides the ability to regulate voltage, reactive power, active power, and the power factor at the grid feed-in point quickly and precisely. Parameterization, configuration, and plant diagnostics can usually be carried out directly on the controller's touch screen or conveniently via network connection.

INDUSTRY NEED

Today's electricity grid is characterized by increasing shares of VRE, fluctuating load profiles (day, night) with energy injection by VRE, and limited energy transport capacities of transmission and distribution grids. Grid codes are evolving to include the following stringent requirements for grid stability and security:

1) New regulation functions need to be implemented; for example, regulation of cosϕ(P), cosϕ(U), and Q(P).
2) More accurate and faster response times are required.
3) Existing installations need to be upgraded to comply with grid codes.
4) Generation outputs need to be forecasted.
5) Power quality levels need to be reported.

Also, VRE plants have a significant impact on the power quality and stability of the grid for reactive and active power control in the following ways:

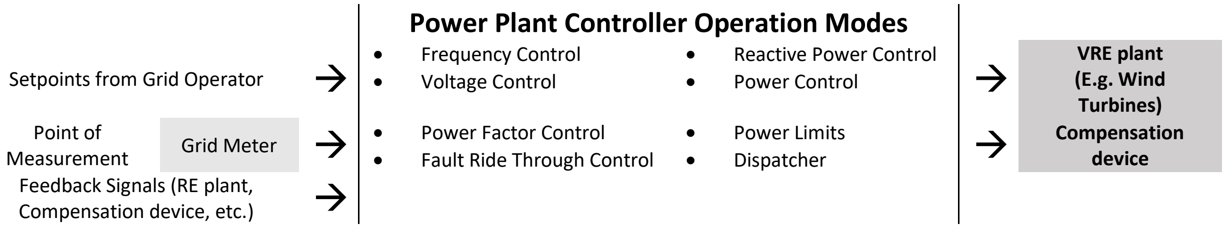
1) PV inverters and wind generators are key contributors to reactive power, but they have limitations and regulate only at the generator terminals, not the plant level.
2) Active power generation can be limited (curtailment, ramp-up control, and over-frequency response).
3) Active power generation boost is inherently not possible to support low-frequency events and ramp-down control.

The PPC is a new development that can help predict, to some extent, a VRE plant's performance and improve its controls. It features an advanced algorithm combined with a fast and efficient communications system, and response times of less than one second, allowing for precise control of the active and reactive power delivered to the grid. The PPC will manage the plant in accordance with the following:

1) An analysis of grid code requirements
2) Load flow studies to evaluate reactive power capabilities
3) Additional equipment characteristics (e.g. discrete, dynamic or hybrid compensation [static compensator, shunt reactor, capacitor bank]) and electrical energy storage

The PPC monitors system-level measurements; determines the desired operating conditions of various plant devices to meet specified targets using different operational modes (see FIGURE 7.1); and manages capacitor banks and/or reactor banks, if present. The PPC also manages all inverters in the plant, ensuring they are producing the real and reactive power required to meet the desired settings at the point of interconnection (POI) or point of common coupling.

FIGURE 7.1: Power Plant Controller Operation Modes



The simulation tools provide valuable predictions of PPC behavior, which can make the plant regulation much more effective and require less tuning and testing during the VRE commissioning. The PPC manages all parameters necessary for grid stability, and the parametrization and configuration of the PPPC can be performed both locally and remotely. With the expandability of new communication protocols, standards for individual connections, and a modular design, the PPC is well suited to meet the future requirements of VRE power plants.

DESIGN AND FUNCTIONALITY

The plant controller combines plant-level logic and closed-loop control schemes with real-time commands to the inverters to achieve fast and reliable regulation. Typically, there is one controller per plant that is regulating the output at a single high-voltage bus (referred to as the POI). The commands to the plant controller can be sent through the SCADA human-machine interface (HMI) or even through other interface equipment, such as a substation remote terminal unit (RTU).

A key component is the plant-level controller, which is designed to regulate real and reactive power output from a VRE plant in such a manner that it behaves as a single large generator. Because a VRE plant is typically composed of individual small generators (or more specifically inverters), the function of the plant controller is to coordinate the power output to provide features typical of large power plants, such as active power control and voltage regulation (through reactive-power regulation).

When the plant operator sends an active-power curtailment command, the controller calculates and distributes active-power curtailment to individual inverters. In general, the inverters can be throttled back only to a certain specified level of active power without causing the DC voltage to rise beyond its operating range. Therefore, the plant controller dynamically stops and starts inverters as needed to manage the specified active power output limit. It also uses the active power management function to ensure that plant output does not exceed the desired ramp rates (to the extent possible). It cannot, however, always accommodate rapid reduction in irradiance due to cloud cover.

Through the SCADA HMI, the plant control system can be set to operate in one of the three modes of automatic voltage regulation (AVR): voltage regulation, power-factor regulation, or reactive-power control. In voltage-regulation mode, the controller maintains the specified voltage set point at the POI by regulating the reactive power produced by the inverters as well as other devices such as capacitor banks. In power-factor regulation mode, the controller maintains the specified power factor.

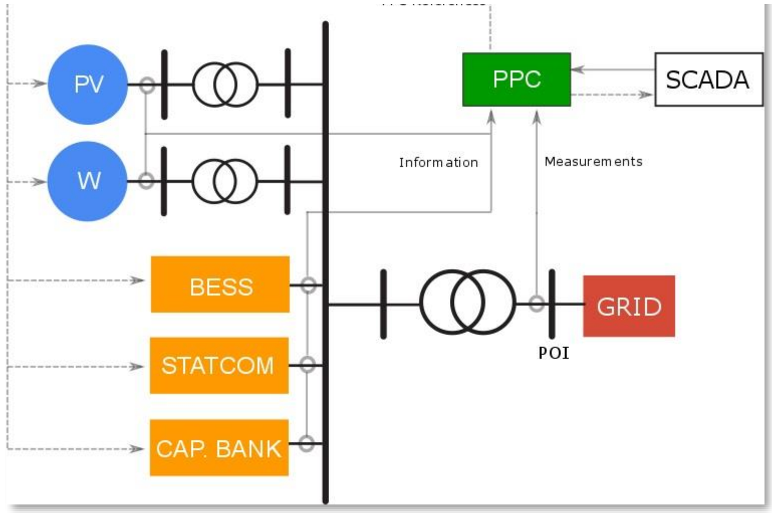
Also through the SCADA HMI, the controller can be set to control the active power output of the plant. When the control system detects that active power at the POI exceeds the specified set point, it calculates (using a closed-loop control mechanism) and sends the commands for each inverter individually to lower its output to achieve the desired set point. In some cases, the plant controller will turn off certain inverters to achieve this desired set point, since the output of each inverter cannot be lowered below a certain threshold without causing a high-DC-voltage operating condition.

The control system also provides frequency-drop control to handle unusual grid situations. For example, in case of above-normal frequency, the controller will reduce the active power of the plant. If the plant is under curtailment, the power can also be increased if a below-normal frequency is detected.

A VRE plant with a PCC typically consists of the following (FIGURE 7.2):

1) For measurement and control systems, the PCC can incorporate a communication network with the grid operator to receive the operating set points.
2) SCADA for the plant monitoring system
3) Communications network

FIGURE 7.2: Power Plant Controller, SCADA, and Communication Network



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A multifunctional plant controller can provide the following plant-level control functions:

1) Dynamic voltage and/or power factor regulation of the solar plant at the POI;

2) When required, curtailing the real-power output of the solar plant so it does not exceed an operator-specified limit;
3) Ramp-rate controls to ensure the plant output does not ramp up or down faster than a specified ramp-rate limit, to the extent possible;
4) Frequency control to lower plant output in case of an over-frequency situation or increase plant output (if possible) in case of under-frequency; and
5) Start-up and shutdown control.

The PPC system receives real-time data from the plant's SCADA system and analyzes the performance of each inverter. The PPC checks the grid requirements and set points (via command from the grid operator or remote operations center), sends individual instructions to each inverter within the plant, and collects historical data to ensure the plant adheres to its voltage, frequency, and power-output requirements.

In order to determine the operating set points for each inverter and transmit the set points through the communication network, the PPC measures the active power, frequency, reactive power, and voltage at the connection point. It also measures the instantaneous active and reactive power values from the various inverters, then uses the grid operator's requirements to establish parameters such as power ramps, active power reserve, and voltage at the point of connection. As a result,

1) Active and reactive power are controlled at the plant's POI;
2) Remote set points of active power and reactive power can be periodically updated; and
3) Voltage at the POI can be controlled by the VRE plant acting on reactive power exchanged with the grid.

The PPC guarantees the maintenance of set points that meet the requirements for the VRE power plant and the utility grid as determined by the plant and grid operators. The PPC controls the VRE power plants in accordance with the requirements of the grid operator and, by adjusting active and reactive power, helps stabilize the utility grid. Finally, thanks to its fast implementation of control commands, the PPC ensures the highest possible system availability at all times.

APPLICATIONS

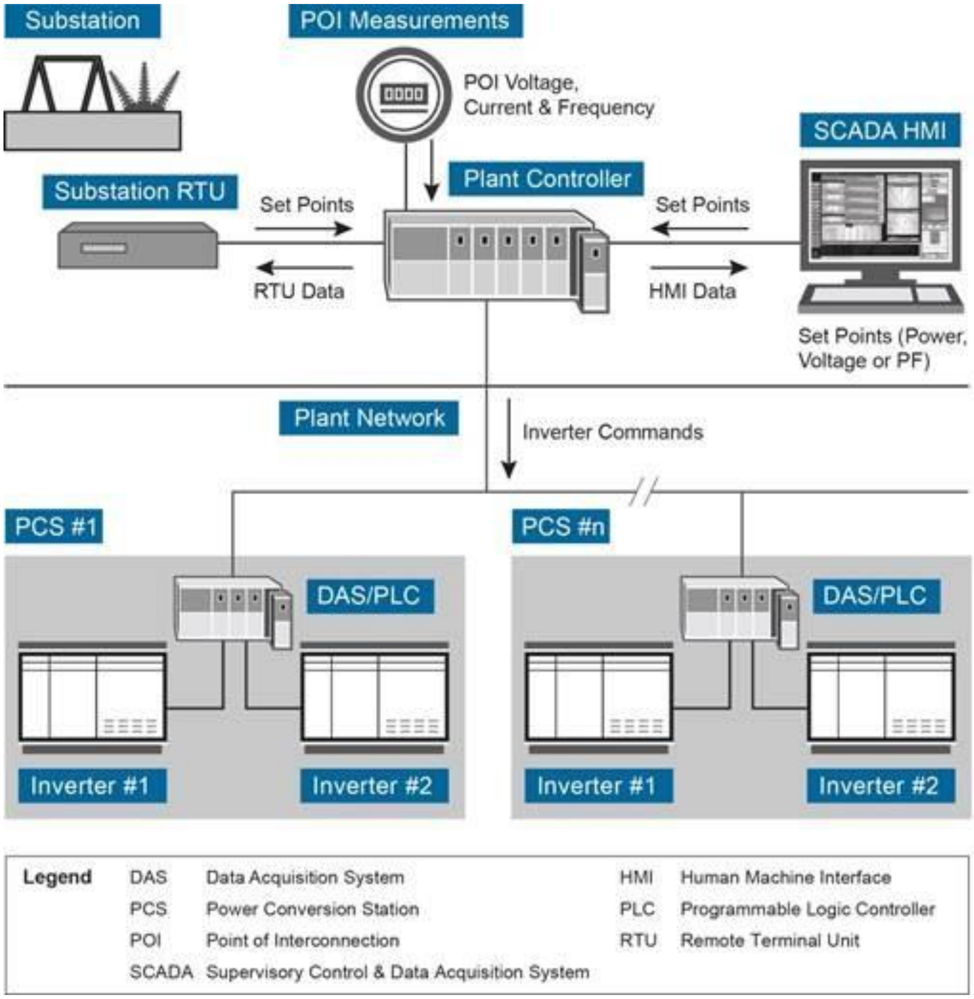
The PPC system's features are as follows:

1) Dynamic voltage and/or power factor regulation of the VRE plant at the point of interconnection, with the following control objectives:
    a) **New target:** Values for reactive power or the power factor are implemented in a matter of seconds.
    b) **Scheduled:** Predefined values for reactive power or the power factor are received and then implemented on time.
    c) **Constant:** Reactive power or power factor is made available on a permanent basis or by request.
    d) **Variable:** Dynamically specified values for reactive power or power factor are managed at the grid connection point.
2) Real-power output curtailment of the VRE plant, when required, so that it does not exceed an operator-specified limit;
3) Ramp-rate controls to ensure the plant output does not ramp up or down faster than a specified ramp-rate limit;

4) Frequency control to (a) lower plant output in case of an over-frequency situation or (b) increase plant output (if possible) in case of under-frequency;
5) Start-up and shutdown control; and
6) Curtailment mitigation in cases where plant output is constrained but the plant has additional generation capability.

Figure 7.3 illustrates PPC implementation for a solar PV system with full SCADA functionality and integration with solar monitoring software. This PPC enables a large range of control variables including power curtailment, ramp rate, and power factor. The control system can be accessed from an on-site workstation or remotely.

FIGURE 7.3: Power Plant Controller for Solar Plant



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BENEFITS

Most national grid codes require that VRE plant electrical interface variables be controlled by the distribution operator at the POI. This ensures better control by the transmission system operator (TSO) and distribution operators (DOs) over the entire VRE plant. The PPC offers intelligent and flexible solutions for the control of all PV and wind power plants in the megawatt range, with the following specific attributes:

1) Flexible
    a) For all plant topologies
    b) Modular system concept for individual requirements
    c) Simple to expand with new protocols and standards
2) Precise
    a) Exact grid voltage control
    b) Regulation of active and reactive power and power factor
    c) Individual activation of single inverters on the farm
3) Easy to Use
    a) Configuration and parameterization via remote access
    b) Compact design makes installation easy
4) Profitable
    a) Reliable plant operation with minimal downtime
    b) Fulfillment of global requirements for grid integration and international plant certification (PV or wind plant)

PPCs can also enhance financial returns for plant operators as follows:

1) Confidence in proven technology for the guarantee of smooth operation:
    a) Maximum system availability
    b) Optimum plant operation according to precise and quick management:
        i. Plant operation always "in view"
        ii. Reduced downtimes
        iii. Availability tracing
        iv. Enhanced efficiency and yield
        v. Secured return on investment (ROI) through optimum plant operation
2) Grid operators profit from:
    a) Stable grids due to predictable VRE plant behavior
    b) VRE power plants that can easily be connected to transmission lines
    c) Stability through highly flexible control functions
3) Developers can successfully plan their projects with:
    a) Easy commissioning and parametrization
    b) Flexible options for all VRE plant topologies
    c) Quick authorization and existing certifications for grid connection

RECOMMENDATIONS FOR SPECIFICATION

The PPC specification usually needs to cover the following functional scope:

1) Active Power Control
    a) Independent proportional-integral-derivative (PID) algorithm controller
    b) Static and dynamic set points and set-point curves
    c) Set-point ramping and permanent power-tracking
    d) Own-consumption mode
2) Reactive Power Control
    a) Independent PID Controller
    b) Static and dynamic set points and set point curves
    c) Reactive power and voltage control modes
    d) Night mode
    e) Passive and active compensation control
3) Additional Functions
    a) Power limitation monitoring
    b) Flexible network analyzer support
    c) Multiple interfacing options
    d) Cascading

The specification needs to address the details of measurement acquisition with embedded control algorithms and remote control of equipment. The following topics must be defined:

1) Multiple communication protocols: IEC 61850,101,104, DNP3, Modbus TCP/IP, etc.
2) Availability and redundancy
3) Industry-proven hardware and software
4) High performance to run power-control algorithms
5) Compliance with international standards
6) Resilient network architecture for future expansion
7) Cyber security, especially for remotely accessed controls

The specifications must include the following design characteristics:

1) Cabinet solution with integrated digital power meter, controller, HMI and power supply
2) Customizations to complement interfaces specified by power supply company, mounting space available, layout and configuration of VRE power plant and required functional scope
3) Based on standard hardware with proven reliability and widespread spare parts availability
4) Small overall dimensions suitable for easy installation in the Plant Control Room or in the Plant Connection Switchgear Room
5) Easy set-up by means of automatic computation of regulator parameters based on plant data
6) Intuitive and easy-to-use, password-protected, touchscreen HMI for commissioning
7) Working data inspection and data trend analysis
8) Fully integrated remote monitoring solutions
9) Power supply
10) Interfaces (e.g. energy storage systems, power meters, third party systems)
11) Protections

VENDORS

The following list shows some suppliers of PPCs, in alphabetical order:

1) ABB (Sweden)
2) AlsoEnergy (USA)
3) GE (USA)
4) Ingeteam (Spain)
5) Power Electronics (Spain)
6) Schneider Electric (USA)
7) Siemens (Germany)
8) Skytron (Germany)
9) SMA (USA)

8 | FACTS-SUPPORTING TECHNOLOGIES

Sections 2 | through 7 | discussed FACTS devices commonly employed in the industry. This section will focus on technologies closely related to FACTS in terms of their grid implementation objectives. These supporting technologies are implemented in transmission and distribution power systems. The following related FACTS topics are discussed:

- High-voltage DC (HVDC) lines
- Dynamic energy storage
- Harmonic filtering
- Fault current limiting devices

Each of these technologies represents a separate, larger topic fully deserving of dedicated analysis and discussion. However, that is beyond the scope of this high-level overview of FACTS-supporting devices. It should be noted that many other FACTS-related technologies are emerging in the electrical industry, and their variety is expected to increase in the next decade.

HARMONIC FILTERING

Harmonics have existed in power systems for many years. However, the recent increase in the use of capacitor banks and solid-state electronics has emphasized the need to reduce harmonics in the power grid. The flow of harmonic currents in power systems creates a distortion of the sinusoidal wave of the power current and voltage; this can cause equipment to overheat and interferes with communications, control and protection systems. Electrical utilities are committed to supplying consumers with reliable and "clean" fundamental-frequency sinusoidal electric power that does not have an adverse impact on electrical equipment.

Industry Need

The twin objectives of reducing harmonics and improving power quality require (a) monitoring of harmonic injection levels from the new VRE plants to the system and (b) verifying that the harmonic injection does not distort the voltage beyond the accepted levels in the external system. Most of the time, the VRE plant harmonic injection is generated by the power-electronic devices used to integrate the new power generation. In some cases, the collector system of the VRE plant can amplify or provide insufficient damping of background harmonics. Harmonic filtering can then be used to mitigate any harmonic distortion present in the transmission system prior to the VRE plant integration. The use of harmonic filtering can also help regulate voltage if the VREs are limited in their reactive-power generation capability; this can help the VRE plants meet grid-connection requirements for voltage regulation.

To connect to the distribution network, VRE plants often use rectifiers or inverters ranging in capacity from a few kilowatts up to thousands of kilowatts. Overall network power quality may experience significant disturbances resulting from the sum of the individual harmonic distortions caused by the inverters. Therefore, medium- and low-voltage distribution networks are expected to cope with voltage unbalances and harmonic distortion at lower and higher frequencies. This is caused by the time variability of the currents injected from a large amount of wind turbines and solar plants due to the random nature of solar radiation and wind.

Moreover, current imbalances resulting from single-phase connection of solar sources can cause unbalanced voltages; these can in turn produce harmonic currents, possibly leading to increased losses and overheating in numerous power system devices such as transformers and asynchronous and synchronous machines. In asynchronous machines (e.g., induction motors), the operating torque is influenced by the inversely rotating magnetic field caused by negative-sequence components, which affects the startup and introduces additional rotor heating. For capacitors used as reactive-power compensators, resonant conditions can occur, which may result in high levels of harmonic voltage and current distortion if the resonant condition happens at a specific harmonic frequency. Furthermore, under unbalanced conditions, the presence of negative-sequence, low-frequency harmonics can produce conflicts in the protection system of distribution networks in the presence of distributed generation.

Harmonic filters may be active, passive, or a hybrid of the two. Usually a passive filtering solution is used, but active or hybrid solutions are also possible. (An active filter is a power electronic amplifier that generates harmonic current or voltage signals which is then injected into the transmission system to cancel the harmonics to be mitigated.) However, active and hybrid filters are still mostly uneconomical compared to passive filters.

Passive filters are composed of a capacitor, reactor, and resistor (if required) connected together, giving a known impedance established by calculation over a given frequency range. These filters can be tuned or detuned as required. Tuned filters have a tuning frequency close to the power frequency to be filtered; detuned filters have a greater tuning difference.

Shunt filters are designed as single tuned filters, multiple (usually double) tuned filters, and damped filters of first, third, c-type order. The tuned filters are used to filter specific frequencies while damped filters are used to filter a wide range of frequencies. Passive and active power filters are used as solutions for harmonic filtering and reactive power compensation. In a passive filter, its components are passive elements such as capacitor, inductor and resistor to mitigate harmonics. Active filtering technology can have one or more of the functions as harmonic filtering, isolation, voltage regulation, voltage-flicker reduction, load balancing and reactive-power control for power factor correction, and damping.

Functionality

Because harmonic flow in power systems is a growing concern for transmission owners, harmonic filters play an increasingly key role in ensuring a high level of (a) power quality for grid customers and (b) protection for grid-connected devices such as step-up transformers and surge arrestors, helping to extend the operating lifetime of these devices. In addition, harmonic filters can contribute to VRE and transmission reactive-power control to meet POI grid-connection requirements.

The choice of which passive filter to use is governed by the following criteria:

1) Tuned or detuned
    a) Usually tuned filters are used.
    b) Detuned filters are used to filter out multiple harmonics that are in a similar frequency range.
2) Single-, double-, or triple- tuned
    a) The more tuning frequencies a filter has, the more complex, big, and expensive it will be.
    b) Multiple tuned filters can be used if each filter has to be switched; this can eliminate the need to use additional circuit breakers.

    c) Multiple tuned filters may not be suitable in all cases, depending on the conditions needed for the harmonic injections to occur.

3) Band-pass, high-pass, C-type
    a) In many cases, the filters associated with VRE plants will be of the high-pass or C-type variety, used to filter out high-order frequency injection caused by the switching of power electronics.
    b) Band-pass filters are generally used to solve harmonic injection at a specific harmonic order.
4) Damped or undamped
    a) Damped filters have higher losses than undamped filters.
    b) Damped filters provide attenuation of resonance over a range of frequencies.
    c) Damped filters are less sensitive to detuning effects (ambient temperature, elements fabrication tolerance, etc.).
5) Fixed or switched
    a) A fixed harmonic filter is simpler and does not require a circuit breaker for proper performance.
    b) Multiple switched harmonic filters may be required if the harmonic injection varies, depending on VRE plant production, system topology, etc.
    c) The use of a circuit breaker makes the substation more complex, requires more space in the substation, adds maintenance, and is more expensive.
    d) Switched harmonic filters may be a more flexible solution if they contribute to the VRE and transmission reactive-power control required to meet POI grid-connection requirements.

The following harmonics-related issues frequently occur in VRE plants (sometimes caused by inadequately specified requirements or the design of power electronics):

1) Harmonics from the renewable generation are amplified until the harmonic overvoltages cause the surge arresters to fail, damaging the step-up transformers connecting the VRE plant to the power network. The main reason for this is usually resonance caused by the total capacitance of the extensive system, and sometimes a combination of the cables and shunt capacitor banks used for power factor correction.
2) High levels of harmonics can occur when inverters for energy storage inject a low level of DC current into the transformer, resulting in transformer saturation.

The chief reason for these negative impacts relates to the rectifiers and inverters used with VRE as well as the resonance issue resulting from the interconnection of the VRE sources. A common mitigation of this problem is installing harmonic filters when the allowed voltage distortion limits are exceeded.

In the case of a VRE integrated into power grids that (as verified through assessments) can cause harmonic distortion above allowable limits, filters should be installed at the POI, next to the VRE plant.

Harmonic filter specifications should focus on the capacity to reduce voltage distortions to acceptable values while also considering the operational stress experienced by filter components and extending their lifespans.

Maximum-current requirements in passive filters for VRE plants should have conservative criteria, and these criteria must be used when defining the nominal capacities of filter elements so as to avoid overloads/overstressing conditions during their lifetime. Both the harmonic currents of the VRE plants and the harmonics coming from the overall network entering the filters need to be taken into consideration.

When choosing the appropriate insulation levels for the equipment, the electrical characteristics and performance of circuit breakers and surge arrestors (if such equipment is used) must be taken into account, in addition to the usual requirements for insulation coordination (e.g. standardized values, personnel safety, altitude correction factors, and pollution, etc.)

The following related standards can be used to help establish the specification requirements:

1) IEC std 61642, "Industrial a.c. networks affected by harmonics – Application of filters and shunt capacitors," Edition 1.0, 1997-09
2) IEC TR 62001, "High-voltage direct current (HVDC) systems – Guidebook to the specification and design evaluation of A.C. filters," Edition 1.0, 2009-10
3) IEEE Std 519, "Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," 1992 – Revision 2014
4) IEEE Std 1459, "IEEE standard definitions for the measurement of electric power quantities under sinusoidal, non-sinusoidal, balanced, or unbalanced conditions," 2010

ENERGY STORAGE

As long as there has been an electrical grid, companies have sought ways to safely and efficiently store energy so that it can be consumed on demand, output can be meticulously controlled, and the exact frequency of the energy distributed can be tightly regulated. Today, a wide array of technologies has been developed and deployed to ensure the grid can meet our everyday energy needs – from saleable banks of advanced chemistry batteries and magnetic flywheels, to pumped-hydroelectric power and compressed air storage. Energy storage is resource neutral (it is neither a net generator nor a net load) and helps to optimize the electricity usage from different power sources. Since the discovery of electricity, effective methods have been sought to store that energy for use on demand. Over the last century, the energy storage industry has continued to evolve and adapt to changing energy requirements and advances in technology.

Industry Need

Renewable resources largely depend on factors such as sunlight and wind speed to produce electricity. Therefore, if wind speed drops at a wind farm or clouds move over a solar farm, the power generated by these sources can change significantly and at very fast ramp rates. In some cases, a grid operator can see a significant portion of its total generation capacity drop off in just a few seconds. In other words, the intermittent nature of electricity supply from renewable resources often does not align well with factors governing the demand for this intermittent resource.

Energy storage technology has the potential to contribute to the stable and efficient operation of the electricity grid, especially with the increasing proportion of intermittent renewable generation. By allowing electricity from intermittent renewable sources to be stored for later use, it matches generation to demand in all circumstances. The technology also has a wide range of other potential applications, such as providing load balancing capabilities (frequency regulation, load following, ramp-up and down), managing peak demand and power quality at various levels throughout the electricity network, providing backup power and black-start capabilities, and shaping customer usage in response to tariffs to name a few.

Time-shifting

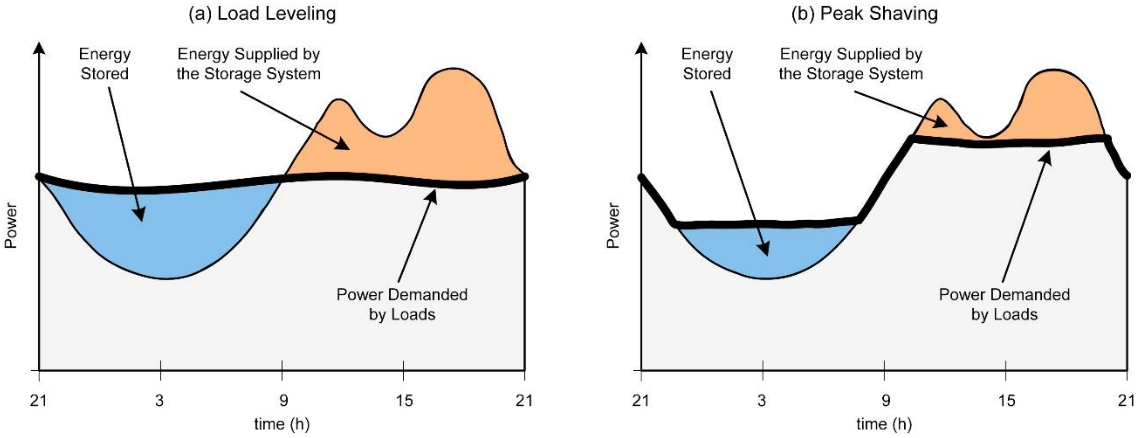
Time-shifting enables energy produced at peak generation times to be stored and released at peak load times – which is especially important for the integration of solar and wind energy. Up to 111 gigawatts (GW) of renewable energy could be installed in the U.S. by 2020; assuming each generation site stores six hours of production for later resale, time-shifting would require 666 GWh of storage. The potential revenue is estimated to be $13 billion per year. This would however be inefficient and capital intensive to store most or all the electricity produced by VRE generation and discharge during peak hours. The optimal amount of storage required by each power system would need a separate system dispatch study to optimize the generation fleet.

Various storage technologies have been associated with time-shifting (see Functionality, Page 72). There are currently 240 pumped-hydro facilities around the world providing approximately 100 GW of stored power, compressed air energy storage (CAES) is emerging as a potentially well-suited technology, and smaller battery technologies have been deployed on a pilot scale.

Time-shifting will be crucial to the displacement of conventional fuels in meeting renewable portfolio standards. It is also necessary for solar and wind power, which may be unable to provide sufficient generation at peak load times (FIGURE 8.1):

1) Peak renewable power (i.e. wind or solar) rarely coincides with peak system load.
2) Time-shifting involves storing power output during periods when it is not required and providing it to the grid when it is required, generally during times when demand is highest.

FIGURE 8.1: Load Shifting with Energy Storage Device



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Deferral of Investments

Utilities have recently indicated they may be willing to spend up to 50 percent of the cost of a readily available solution on energy storage. Additional factors to be considered are labor cost reductions, lower costs due to simplified permitting, and minimizing environmental impact. Energy storage solutions mainly involve investing in infrastructure upgrades for the better utilization of the existing system assets such as transmission lines and substations (sodium sulfur batteries are one of the more advanced technologies in this area). Two technologies that may compete with substation storage in the future are:

1) Smart-grid and demand-side management
2) Distributed generation and distributed storage

Storage mobility will continue to be an important factor, as will the ability to use assets for multiple revenue streams (e.g. ancillary services), something that is currently difficult due to policy constraints. Some of the industry needs in energy storage associated with better utilizing existing utility assets are as follows:

1) The load experienced by transformers at certain substations exceeds their rated capabilities, leading to lower operating efficiencies, increased wear and tear, and ultimately failure.
2) Because of high capital and labor costs, utilities typically upgrade substations by 25–33 percent increments, far more than is warranted by the incremental usage triggering the upgrade.
3) Energy storage can provide a more precise solution than an upgrade, thereby deferring capital investments by one or more years.

Functionality

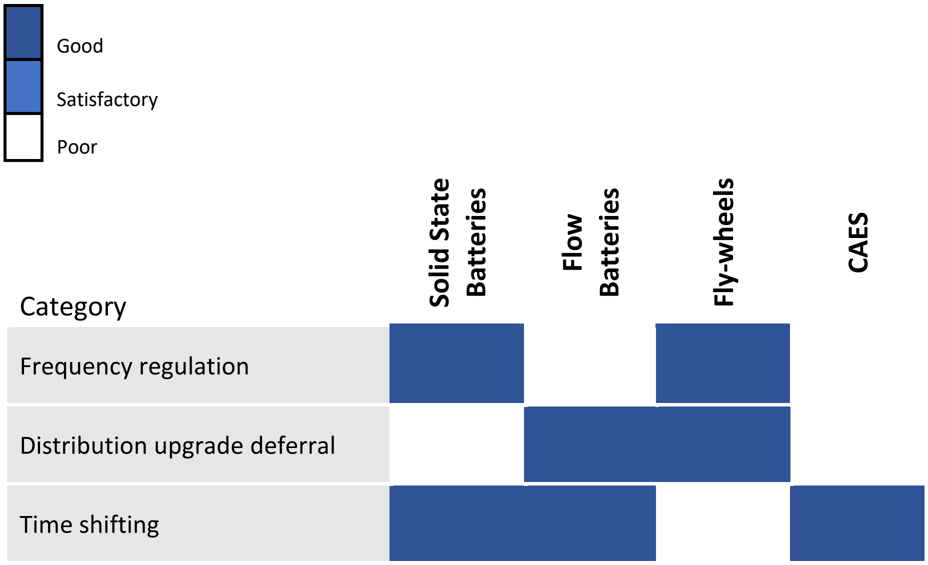
Energy storage systems provide a wide array of technological approaches to managing overpower supply by creating a more resilient energy infrastructure and reducing costs for utilities and consumers. To help understand the diverse approaches currently being deployed around the world, they are here divided into four categories:

1) *Solid state batteries* – a range of electrochemical storage solutions, including advanced chemistry batteries and capacitors (Lithium-ion, Sodium sulfur (NaS), etc.;
2) *Flow batteries* – batteries in which the energy is stored directly in an electrolyte solution for longer cycle life and quick response times;
3) *Flywheels* – mechanical devices that harness rotational energy to deliver instantaneous electricity; and
4) *Compressed air energy storage* – which uses compressed air to create a potent energy reserve.

It should be noted that there is another type of storage well known in the industry: *pumped-storage hydro* with large-scale reservoirs of energy. The water at one of these hydro plants can be used to either to produce electric power (“generation mode”) or to pump the water back into the reservoir for future use (“motor mode”). Globally, there are 270 pumped hydroelectric storage (PHS) stations either operating or under construction with a combined capacity of 120 GW. Of these total installations, 36 units consist of variable-speed machines, 17 of which are currently in operation (about 3.5 GW). There are various reasons for this including additional equipment costs for variable speed as well as the lack of recognition for the additional services provided by the equipment upgrades (ie. ancillary service market development) (Energy Storage Association 2017). However, although PHS is an essential technology for VRE grid integration, it is outside the scope of this guidance note.

FIGURE 8.2 illustrates the main applications for these four technologies, including their relative performance (good, satisfactory or poor) in each application.

FIGURE 8.2: Main Applications for Different Energy Storage Technologies



■ Good

▨ Satisfactory

□ Poor

Category	Solid State Batteries	Flow Batteries	Fly-wheels	CAES
Frequency regulation	■	□	■	□
Distribution upgrade deferral	□	■	■	□
Time shifting	■	■	□	■

Lithium-ion Batteries

Lithium-ion (Li-ion) batteries are commonly used in electric appliances such as laptops and mobile phones. Currently, they are also the technology of choice for electric-vehicle (EV) batteries (with major research efforts under way to advance the technology). Li-ion batteries comprise different classes of cathodes, anodes and electrolytes. When selecting a battery, there are four important criteria: cost, life, abuse tolerance, and performance.

Advantages:

1) High energy density
2) Advanced technological development due to mass production for electric appliances
3) Easy to obtain high energy capacities for discharging

Disadvantages:

1) High cost for large-scale applications

Sodium-sulfur Batteries

Sodium-sulfur (NaS) batteries are low-cost, high-capacity batteries constructed from molten elemental sodium and sulfur. Individual cells are typically tall steel cylinders, coated with chromium or molybdenum, and filled with the molten electrodes separated by a ceramic membrane, which selectively conducts Na+. Individual cells are packed in temperature-controlled modules and stacked on racks.

Advantages:

1) Rapidly dispatched and movable from site to site
2) 75-90 percent round-trip efficiency
3) Relatively easy to obtain permits
4) Triple the energy density of lead-acid batteries, longer lifespan, and lower maintenance

Disadvantages:

1) Substantial ancillary equipment required to maintain 290–360°C operating temperature
2) Sole supplier: NGK Insulators Ltd

Flow Batteries

Redox flow batteries (RFBs) represent one class of electrochemical energy storage devices. The name “redox” refers to chemical reduction and oxidation reactions employed in the RFB to store energy in liquid electrolyte solutions which flow through a battery of electrochemical cells during charge and discharge.

During discharge, an electron is released via an oxidation reaction from a high chemical potential state on the negative or anode side of the battery. The electron moves through an external circuit to do useful work. Finally, the electron is accepted via a reduction reaction at a lower chemical potential state on the positive or cathode side of the battery. The direction of the current and the chemical reactions are reversed during charging. The total difference in chemical potential between the chemical states of the active elements on the two sides of the battery determines the electromotive force generated in each cell of the battery. The voltage developed by the RFB is specific to the chemical species involved in the reactions and the number of cells that are connected in series. The current developed by the battery is determined by the number of atoms or molecules of the active chemical species that are reacted within the cells as a function of time. The power delivered by the RFB is the product of the total current and total voltage developed in the electrochemical cells. The amount of energy stored in the RFB is determined by the total amount of active chemical species available in the volume of electrolyte solution present in the system.

The separation of power and energy is a key distinction between RFBs and other electrochemical storage systems. As described above, the system energy is stored in the volume of electrolyte, which can easily and economically range from a few kilowatt-hours to tens of megawatt-hours, depending on the size of the storage tanks. The power capability of the system is determined by the size of the stack of electrochemical cells. The amount of electrolyte flowing in the electrochemical stack at any moment is rarely more than a few percent of the total amount of electrolyte present (for energy ratings corresponding to discharge at rated power for two to eight hours). Flow can easily be stopped during a fault condition. As a result, system vulnerability to uncontrolled energy release in the case of RFBs is limited by system architecture to a few percent of the total energy stored. This feature is in contrast with packaged, integrated cell storage architectures (Li-ion, NaS, lead-acid), where the full energy of the system is connected at all times and available for discharge.

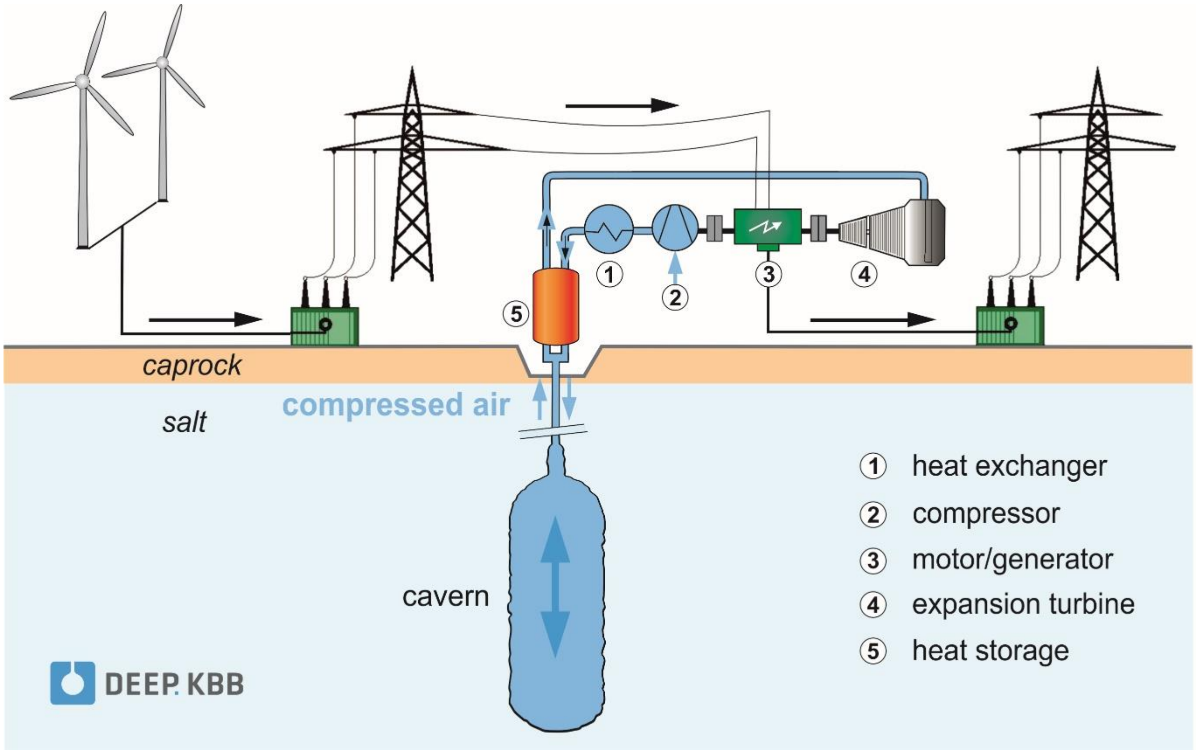
Flywheel Energy Storage

Flywheel energy storage (FES) works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy. When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of energy conservation; adding energy to the system correspondingly results in an increase in the speed of the flywheel.

Compressed Air Energy Storage

Compressed air energy storage (CAES) is a way to store energy generated at one time for use at another time using compressed air. At utility scale, energy generated during periods of low energy demand (off-peak) can be released to meet higher demand during peak-load periods (FIGURE 8.3).

FIGURE 8.3: Compressed Air Energy Storage



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Very large power systems favor storage from salt caverns, hard rock caverns, depleted gas fields, and aquifers. Sites that must be constructed are costly or take years to build (e.g. 1.5–2 years to create a cavern by dissolving salt).

FAULT CURRENT LIMITER

The upgrade of electricity supply (from new generation capacity or additional cross-connections, for example) increases the amount of power that can be supplied. To accommodate this, typically all of the branch circuits must have their busbars and circuit breakers upgraded to handle the new, higher fault-current limit. This is particularly challenging when distributed generation, such as wind farms and rooftop solar power, is added to an existing electric grid. It would of course be preferable to add additional power sources without the need for large, system-wide upgrades.

The fault current limiter (FCL) offers a simple solution by adding electrical impedance to the circuit. This limits the rate at which current can increase, thus limiting the level to which the fault current can rise before the breaker is opened. An FCL is a nonlinear element that has a low impedance at normal current levels but presents a higher impedance at fault current levels. This impedance change is extremely rapid and takes place prior to a circuit-breaker trip a few milliseconds later.

Industry Need

A fault condition creates a surge of current through an electric power system that can cause serious damage to grid equipment. Switchgear equipment, such as circuit breakers and switch disconnectors, is deployed within substations to protect equipment against fault conditions. Increasing fault levels, especially in power systems connected to large generating sources (like VRE), correspond to an increase in switchgear rating limits and personal safety issues. At several locations in a distribution system, employing some kind of fault-current limiting measures may be necessary to avoid costly system upgrades/upratings. Although the conventional methods currently in practice are effective to an extent, they have their limitations and disadvantages.

FCLs that are based on new technologies, such as solid-state and superconducting materials, are highly effective and efficient in preventing equipment damage during a surge of current. These new FCL technologies are still in various stages of development. Once ready for use, the next generation of FCLs is expected to find widespread application in transmission and distribution systems globally. The choice of a particular voltage level for new or expanded transmission and/or distribution systems is governed primarily by the desired power ratings. The objective is to keep rated current levels within the standard ratings of commercially available equipment, especially circuit breakers. These ratings typically provide enough margins with respect to short-circuit power at any given voltage level and for several fault conditions. Nevertheless, depending on the constraint of the applications (e.g. grid density, nearby generation, etc.), the short-circuit current may exceed the ratings of the available equipment. This may require choosing a higher voltage level based on the short-circuit capability of the equipment.

For existing systems, increasing the voltage level is more likely a viable option for medium-voltage systems where the increase in system voltage can be accommodated more easily within the same or similar space constraints by simply installing modern equipment. In high-voltage systems, because increasing the voltage level often is associated with major investments, it is often not the preferred option.

Functionality

The basic physical effect of FCL applications is an increase in impedance in series with the fault current circuit. The main subjects of impacts and interactions can be structured as follows:

1) Transient stability (rotor angle stability)
2) Protection system
3) Transient response
4) Power quality (voltage drop, fault recovery, harmonics, ferroresonances)
5) Thermal losses

Two types of commercially available FCLs are in use so far: current limiting reactors (CLRs) and pyrotechnic fault-current limiters. Recently, there has been a renewed interest in superconducting FCLs, since recent developments in high-temperature superconductors (HTSs) that use liquid nitrogen have sparked new possibilities in technical terms, although this is still not cost-effective as of yet.

The following encompasses some current and emerging technologies and methods of reducing the short-circuit levels in power systems.

1) **Bus splitting.** Bus splitting entails separating sources that could possibly feed a fault by opening normally closed bus-ties or splitting existing buses. This effectively reduces the number of sources that can feed a fault, but also reduces the number of sources that supply load current during normal or contingency operating conditions. This affects the reliability and security of the power system, and may require additional changes in the operational philosophy and control methodology.
2) **Splitting into sub-grids.** This refers to a measure applied to a grid (with one common voltage level) resulting in the original system being divided into smaller portions, which are then fed separately

from the next-higher voltage level. Splitting reduces the fault current level in each of the sub-grids to an allowable level. As with bus splitting, this affects the reliability and security of the power system, and may require additional changes in the operational philosophy and control methodology.

3) **Sequential breaker tripping.** Sequential tripping of circuit breakers is a special operational measure occasionally used in substations to manage higher fault-current levels (above equipment ratings) without replacing circuit breakers. A sequential tripping scheme prevents circuit breakers from interrupting excessive fault currents. If a fault is detected, a breaker upstream to the source of the fault current is tripped first. This reduces the fault current observed by the breakers within the zone of protection at the fault location, and these breakers can then open safely. A disadvantage of the sequential tripping scheme is that it adds a delay of one breaker operation before final fault clearing. Additionally, opening the breaker upstream to the fault affects reliability and protection zones that were not originally affected by the fault.
4) **Current limiting reactors (CLRs) and high-impedance transformers.** Fault-current-limiting reactors limit fault current due to the voltage drop across their terminals, which increases during the fault. However, current-limiting reactors commonly experience voltage drops under normal operating conditions and present a constant source of losses, if they are installed in feeders. When splitting a busbar, these disadvantages may not apply, depending on the power flow division among circuits connected to the busbar. A CLR is a passive FCL device that requires only a fixed and easy to determine redefining of protection settings after being installed in the network.

   The important guidance factors for CLR specification, which could even make the CLR application unfeasible, are voltage drop, joule losses, and high magnetic flux (larger distances/clearances required). CLR applications require analysis of the physical dimensions for the equipment, specifications of the electrical characteristics, and special attention paid to the influence of magnetic flux on personnel, either directly or through contact with metallic structures in the vicinity.

   The CLR can interact with other system components and cause instability, as well as an increase in transient recovery voltage (TRV), since the presence of a lumped inductance in an electric circuit from the CLR could lead to an increase in the severity of the TRV across the circuit breaker contacts associated with the interruption of the fault current. This may lead to increased requirements of the circuit breakers (CBs) for TRV issues. When conditions are right, air-core CLRs can be an economical and reliable solution to limiting high fault currents. Moreover, the installation of a suitable capacitor across the lumped air-core reactor and/or from the sides of reactor to ground can solve the problem of severe TRV without changing the CB requirements.

5) **Impedance grounding.** When the high fault currents are ground fault currents, solidly grounded systems can be converted to impedance grounded systems, such as low- or high-resistance grounding and inductance grounding.
6) **Pyrotechnic devices.** Pyrotechnic fault-current limiters (FCLs) are activated by a small, explosive charge that opens a link, diverting the fault current to a parallel current-limiting fuse for its limitation and clearing. Triggering is initiated by an electronic module that senses the instantaneous current or a combination of di/dt and the instantaneous current of the fault current. Pyrotechnic FCLs are typically employed as bus-tie limiters when the interrupting capability of the circuit breakers of a substation has been exceeded. The load current does not flow through the fuse but through a parallel path, which is opened by means of an explosive charge when a fault is detected by the trigger unit. Therefore, the thermodynamic requirements

of the standalone fuse no longer govern the design of the fuse element in the pyrotechnic fault-current limiter, allowing for significantly higher rated currents.

7) **Solid state technologies.** Utilities are reassessing fault-current mitigation methods and considering new, emerging technologies (solid-state, superconducting, etc.) as viable alternatives to existing methods – provided they can be shown to be the most cost-effective means of fault current management. Recently, there has been a phenomenal increase in R&D activities toward developing technically feasible and economically viable technologies, with the goal of designing a range of medium and high-voltage devices for fault-current-limiting applications in distribution and transmission.
8) **Superconducting FCLs.** The recent developments in high-temperature superconductors (HTSs) that use liquid nitrogen have sparked a renewed interest in superconducting FCLs. It is much cheaper and simpler to build and operate using cryogenic equipment (involving liquid nitrogen systems) than with the previously used liquid-helium systems. An FCL of this type can be applied to reduce the existing fault current to a lower, safer level, allowing the switchgear already in operation to continue to protect the grid. FCLs employing HTSs provide the necessary current-limiting impedance during a fault condition but have essentially zero impedance during normal grid operation. Therefore, HTS FCLs have no negative impact on overall system performance – in contrast to conventional current-limiting devices, such as the CLR, that produce voltage drops and energy losses.

   Superconducting FCLs may be broadly classified into quench and non-quench types. A quench-type FCL offers effectively zero impedance due to its superconducting state under normal conditions. A fault would trigger the superconductor to quench (i.e. suddenly lose its superconductivity), and the increased impedance would provide the desired limiting of the fault current. In a non-quench-type FCL, such as a saturable-core type, the superconductor is always in the superconducting state, and the fault-current limiting results from the change in magnetic saturation caused by the AC fault current.

The following considerations are important for FCL implementations:

1) **Interaction with protection systems.** Protection is a critical part of any power system, and possible interactions between FCLs and protection systems have to be investigated and understood. The various types of FCLs, protection functions, and network configurations may lead to a rather complicated investigation due to the multiple possibilities for interactions.
2) **Power quality.** A distinction must be made between power quality during the normal operation of a fault current limiter (i.e. without limiting action) and during the current-limiting process. The following three aspects of power quality are of importance in conjunction with the use of fault current limiters:

   a) Voltage drop (voltage regulation)
   b) Harmonics
   c) Ferroresonance

3) **Reliability.** From a reliability standpoint, FCLs can be broadly classified into two groups: those that require a control signal to operate and those that do not. For example, a solid-state FCL typically requires a current sensor and processing circuitry to determine when phase current exceeds a threshold (i.e. becomes a fault) such that the power semiconductor switches should be turned off to limit the fault current. A superconducting FCL needs no control signal as triggering and current limiting is inherent in the technology. "Active" versus "passive" is another way to classify FCLs. Active FCLs (i.e. those that require a control signal to perform their function) should be thoroughly

investigated to determine if the likelihood of a single point failure within the control signal path is sufficient to require redundancy. For example, if the current sensor and associated control circuitry is integrated within the FCL and its functionality is validated at the factory before installation, redundancy may not be required. System-level testing should still be performed to ensure other factors do not interfere with the proper operation of the controls. For example, if voltage sag resulting from a fault causes the power supply feeding the controls to collapse such that the controls do not respond to the fault, then a redundant (backup) source of control power is required.

4) **Availability.** High FCL system availability can be achieved through redundancy provided the failure is automatically detected and communicated so that corrective action can be taken. Tools such as a failure mode and effects analysis (FMEA) can be used in the design phase to determine (a) what equipment needs to be redundant and (b) what data acquisition and remote monitoring can be used to predict when preventative maintenance will be required.
5) **Environmental impact**. The environmental impact of FCLs has to be investigated on a case-by-case basis as there are many different locations and technology applications for them in power systems. In general, the following benefits can be achieved by using FCLs:
    a) Reduce losses
    b) Reduce space needed (small footprint)
    c) Preserve resources
    d) Keep the security for personnel at acceptable standards
    e) Use of liquid nitrogen

HIGH-VOLTAGE DIRECT CURRENT LINES (HVDC)

A high-voltage, direct-current (HVDC) electric power transmission system uses direct current for the bulk transmission of electrical power, in contrast with the more common alternating-current (AC) systems. An HVDC transmission link consists three main elements: a converter station, in which the AC voltage of the conventional power grid is converted into DC voltage; a power transmission line; and another converter station on the other end, where the voltage is converted back into AC. The electricity can be transported in both directions. The lines can go across land as overhead or underground lines, be installed in water as submarine cables, or a combination of the two. Transmission losses are lower than for AC voltage. DC voltage amounts to several hundred thousand volts. The higher the voltage, the lower the transmission losses are, and the more electricity can be transmitted via the line, which is economical for long-distance transmission. For underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle.

For shorter distances, the higher cost of DC conversion equipment compared to an AC system may still be justified, due to other benefits of DC links. HVDC allows power transmission to take place between unsynchronized AC transmission systems. Since the power flow through an HVDC link can be controlled independently of the phase angle between source and load, it can stabilize a network against disturbances due to rapid changes in power. HVDC also allows transfer of power between grid systems running at different frequencies. This improves the stability and economy of each grid by allowing power to be exchanged between incompatible networks.

Industry Need

It is expected that the transmission systems necessary to support the worldwide growth of electrical infrastructure will be a mix of HVAC and HVDC. In the past, these two technologies were differentiated by HVAC being used for interconnected short-length lines and HVDC for long-distance, point-to-point, bulk power transmission. New developments in HVDC conversion technologies are beginning to blur that distinction, with HVDC also being considered for shorter, multi-terminal applications.

TABLE 8.1 details the metrics (IID 2012) on systems that have been planned for commissioning from 2012 to 2020.

TABLE 8.1: HVDC Planned for Commissioning 2012–20

HVDC Systems Planned for Commissioning by Region, World Markets (2012–20) 18 Regions	Number of Systems	Overhead Line and Cable (km)	Total Capacity (MW)
North America	29	26,992	75,150
Europe	23	5,772	20,220
China and India	33	60,561	266,700
Rest of the World	12	25,120	37,110
Total	**97**	**118,445**	**399,180**

Source: IID (2012).

Some compelling reasons for high penetration of HVDC into transmission grid interconnection (IID 2012) are as follows:

1) **Asynchronous Connections**. HVDC is a constant current and is thus not subject to the stability issues of HVAC caused by variations in frequency. In addition to point-to-point, long-distance transmission, HVDC is also used in back-to-back operations to interconnect two HVAC systems whose frequencies are not synchronized – in North America, for example, where the western, eastern, and Texas interconnects are themselves interconnected via small DC interties. A back-to-back installation consists of two converter stations linked by a relatively short HVDC cable. Power flows between the two grid systems can then occur without threatening the stability of either system.
2) **Reactive power control**. HVDC also facilitates the integration of renewable-energy generation sources by preventing potential harmonic and frequency distortions from entering the AC grid network.
3) **System losses**. HVDC losses are greater than HVAC losses over very short distances, but as distance increases, HVDC always excels.
4) **Right-of-way requirements**. Right-of-way requirements are an important operational and economic consideration for route planning. For a given amount of capacity, HVDC lines require a much smaller footprint than the traditional AC transmission system.
5) **Cost**. Three-phase AC installations are the best choices for moderate distances. The breakeven distance for HVDC to become a more viable solution than its AC counterpart is where the cost of installing additional AC conductors exceeds the cost of the DC converter stations. This is especially true in undersea applications.

There are many different reasons why HVDC was chosen in the abovementioned projects. Some detailed discussions of HVDC project implementations are presented in (Rudervall et al. 2000), and the following key reasons are identified for the selected projects:

1) In Itaipu, Brazil, HVDC was chosen to supply 50 Hz power into a 60 Hz system, and to economically transmit large amount of hydro power (6,300 MW) over large distances (800 km).
2) In the Leyte-Luzon Project in Philippines, HVDC was chosen to enable supply of bulk geothermal power across an island interconnection, and to improve stability to the Manila AC network.
3) In the Rihand-Delhi project in India, HVDC was chosen to transmit bulk (thermal) power (1,500 MW) to Delhi to ensure minimum losses, least amount of right-of-way, and better stability and control.
4) For Garabi, an independent transmission project (ITP) transferring power from Argentina to Brazil, an HVDC back-to-back system was chosen to ensure supply of 50 Hz bulk power (1,000 MW) to a 60 Hz system under a 20-year power supply contract.
5) In Gotland, Sweden, HVDC was chosen to connect a newly developed wind power site to the main city of Visby in consideration of the project area's environmental sensitivity (an archaeological and tourist area) and to improve power quality.
6) In Queensland, Australia, HVDC was chosen in an ITP to interconnect two independent grids (those of New South Wales and Queensland) to enable electricity trading between the two systems (including change of power flow direction), ensure very low environmental impact, and reduce construction time.

Functionality

There are three major approaches to AC-DC conversion:

1) **Natural commutated converters (NCC), also called line commutated converters (LCC).** Natural commutated converters are mostly used in today's HVDC systems. The component enabling this conversion process is the thyristor, which is a controllable semiconductor that can both carry very high currents (4,000 A) and block very high voltages (up to 10 kV). By connecting the thyristors in series, it is possible to build up a thyristor valve, which is able to operate at very high voltages (several hundred kV). The thyristor valve is operated at a net frequency (50 Hz or 60 Hz) and by means of a control angle, it is possible to change the DC voltage level of the bridge, allowing the transmitted power to be controlled rapidly and efficiently.
2) **Capacitor commutated converters (CCC).** An improvement in the thyristor-based commutation, the CCC concept is characterized by the use of commutation capacitors inserted in series between the converter transformers and the thyristor valves. The commutation capacitors improve the commutation failure performance of the converters when connected to weak networks.
3) **Forced commutated converters (FCC), also called voltage-sourced converters (VSC).** This type of converter introduces a spectrum of advantages, such as passive network feed (without generation), independent control of active and reactive power, and power quality. The valves of these converters – built using semiconductors that can turn both on and off – are known as voltage source converters (VSCs), which commutate at high frequency (i.e. not with the net frequency). Two types of semiconductors are normally used: the gate turn-off thyristor (GTO) or the insulated-gate bipolar transistor (IGBT). Both have been in frequent use in industrial applications since the early 1980s. The converter's use of pulse width modulation (PWM) makes it possible to create any three-phase angle and/or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Thus, PWM offers the possibility to control both active and reactive power independently. This makes the PWM VSC an almost ideal component in the transmission network. From a transmission network viewpoint, it acts as a motor or generator without mass that can control active and reactive power almost instantaneously.

Classic HVDC solutions based on thyristor technology offer a power rating of up to 6 GW at a voltage level of ±600 kV and up to 10 GW at ±800 kV.

In terms of construction, whereas it can take three years to build thyristor-based large HVDC systems, it takes just one year for VSC-based HVDC systems to go from contract date to commissioning. The following is an approximate construction time for the aforementioned HVDC technologies:

1) NCC (LCC): three years
2) CCC-based: two years
3) FCC (VSC)-based: one year

The three main elements of an HVDC system are:

1) A converter station at the transmission and receiving ends,
2) A transmission line, and
3) Electrodes.

Because the converter stations at each end are replicas of each other, they have all the required equipment to go from AC to DC and vice versa. The main components of a converter station are:

1) Thyristor valves,
2) VSC valves,
3) Transformers,
4) AC filters and capacitor banks, and
5) DC filters.

There are different types of HVDC transmission system design. HVDC is normally deployed to transmit power from one location to the next, usually taking its electricity from an AC system or generator and converting it to DC and then converting it back to AC at the other end of the line. For bulk power transmission over land, the most frequent transmission medium is the overhead line, which is normally bipolar (i.e. made up of two conductors with different polarity). However, monopolar and homopolar HVDC links are also known in the industry. In the monopole system, one set of conductors is used for transmission and the current return path is through an earth; this system is used mainly for submarine cable transmission. In a bipolar system, two sets of conductors are used in a transmission line, one positive (with respect to the earth) and the other negative. The midpoint of the bipoles in each terminal is earthed via an electrode line and an earth electrode. In normal conditions, power flows through lines but only a negligible current (less than 10 A) flows through the earth electrode. The homopolar systems are rarely implemented in the industry.

In a typical back-to-back HVDC configuration, two independent neighboring systems with different and incompatible electrical parameters (in terms of frequency/voltage level and short-circuit power level) are connected via a DC link (i.e. an asynchronous tie between two different AC networks). Back-to-back connections are also used to stabilize weak AC links and to supply more active power where the AC system already is at the limit of its short-circuit capability. The back-to-back configuration has no HVDC transmission line; the converter and inverter are located at the same place. Power transfer for back-to-back HVDC can be carried out in either direction, usually using a bipolar-type design with two conductors.

Long, high-voltage undersea and underground cables have a high electrical capacitance compared with overhead transmission lines, since the live conductors within the cable are surrounded by a relatively thin layer of insulation and a metal sheath. The total capacitance increases with the length of the cable. When alternating current is used for cable transmission, additional current must flow in the cable to charge this cable capacitance. This extra current flow causes added energy loss via dissipation of heat in the conductors of the cable, raising its temperature. Energy losses also occur as a result of dielectric losses in the cable insulation. When direct current is used, the cable capacitance is charged only when the cable is first energized or if the voltage level changes; no additional current is required. For a sufficiently long AC cable, the entire current-carrying ability of the conductor would be needed to supply the charging current alone. This cable-capacitance issue limits the length and power-carrying ability of AC-powered cables. DC-powered cables are limited only by their temperature rise and Ohm's Law. This advantage of DC technology for cables transmitting power over long distances may become an important consideration for connecting offshore renewables.

In a multi-terminal system, three or more terminals are connected in parallel; some feed power and some receive power from the HVDC bus. Multi-terminal HVDC provides interconnection among three or more AC networks. At present, only a handful of HVDC systems are multi-terminal.

HVDC has the following advantages:

1) Lower overall investment cost for distances beyond the “breakeven” distance (long-haul overhead line longer than 500 km and bulk power transmission greater than 1 GW) and no limitation of stability (free from stability and capacitance limitation);
2) In terms of transmission lines, smaller right-of-way requirements and construction costs (HVDC two-phase; HVAC 3-phase);
3) Sole option for underwater transmission beyond approximately 100 km (approximately 60 miles),
4) Connection of asynchronous grids;
5) Interconnection of grids operating at the same frequency (back-to-back transmission);
6) Directional control of power flow;
7) Lower transmission loss because of no reactive loss;
8) Lower insulation/clearance of conductor (the DC voltage is about 71 percent of the AC peak voltage);
9) Power transmission between asynchronous AC systems;
10) Fast power-flow control;
11) Enhancement of AC system stability; and
12) Supplying more active power where the AC system is at the limit of its short-circuit capability.

HVDC has the following disadvantages:

1) HVDC is generally less reliable and has lower availability than HVAC, mainly due to the extra conversion equipment and maintenance difficulty.
2) Tapping for multiple grids is difficult.
3) HVDC circuit breakers are difficult to design. Some mechanism must be included in the circuit breaker to force current to zero.
4) Pollution deterioration of the outdoor insulator is faster (due to the static charge effect),
5) AC filters are required to absorb harmonic components.
6) The thyristor valve requires a clean (i.e. dust-free) room.

The essential differences between HVDC and HVAC transmission lines, which reflect the discussed advantages and disadvantages, are summarized in TABLE 8.2.

TABLE 8.2: Comparison of HVDC and HVAC

#	Item	HVDC	HVAC
1	Long-Haul OHL	High	Limited
	Bulk Transmission Capacity	> 1GW	
2	Long-Haul Transmission Stability	No limit	Limited
3	Right-of-Way for Bulk Transmission OHL	Low	High
4	Long-Haul Transmission Loss	Low	High
5	Insulation / Clearance	Low	High
6	System Connection	Asynchronous	Synchronous
7	Power Flow Control	Easy and fast	Difficult
6	Multiple terminal (Tapping)	Difficult and costly	Simple and easy
7	Short-Circuit Limitation	Effective	Not effective
8	Pollution Effect	More pronounced	Relatively less
		Higher insulator creepage distance is required	

In general, developing an HVDC system design requires the definition of basic parameters such as amount of power to be transmitted, distance of transmission, voltage levels, temporary and continuous overload, status of the network on the receiving end, and environmental requirements. For tendering purposes, a conceptual design is done following a technical specification or in close collaboration between the manufacturer and the customer. The final design and specifications are in fact the result of the tendering and negotiations with the manufacturers and suppliers. It is recommended that a turnkey approach to contract execution be chosen; it is standard practice even in developed countries (Rudervall et al. 2000). The market for HVDC equipment is currently dominated by a few large manufacturers, but more vendors are trying to penetrate the market.

There were no mature HVDC standards at the time of this document's preparation. However, several efforts are under way to develop technical concepts, guidelines, and common requirements for HVDC grid systems. With a focus on elaborating technical standards for HVDC grid systems, the CENELEC Technical Committee TC8X has started a new working group (WG06) to address the system aspects of HVDC grids. The first goal of this working group is to create a document describing clear functional specifications for different aspects for HVDC grid systems and associated equipment. Some technical papers have been published (EPRI n.d.) discussing the need for standardization and suggesting approaches to developing functional specifications.

9 | CONCLUSION

Traditional solutions to upgrading the electrical transmission system infrastructure have primarily come in the form of new transmission lines, substations, and associated equipment. However, over the past decade, these solutions have experienced an increasing number of problems to do with permitting, siting, and construction of new transmission lines – which have become extremely difficult, expensive, time-consuming, and controversial in the fast-growing world of large cities and developing urban infrastructure. High-voltage power electronics provide alternative and very cost-effective solutions to the modern grid's technical challenges, especially in the areas of transmission capacity and system stability, voltage control, power quality improvement, and prevention of cascading disturbances.

The potential benefits of FACTS equipment are now widely recognized by the power systems engineering and transmission and distribution industry communities. The first generations of classical voltage-regulation FACTS devices, such as mechanically switched reactors and capacitors and static VAR compensators, have been widely used in the industry for many years and proven to be very effective and relatively inexpensive; however, they lack the regulation speed and control flexibility currently required by power systems, which are expanding with deregulation while experiencing a high penetration of green energy. The new generation of FACTS equipment – based on voltage-sourced converter technology, which utilizes self-commutated thyristors/transistors such as GTOs, GCTs, and IGBTs – has been successfully applied in a number of installations globally for static synchronous compensators, unified power flow controllers, convertible series compensators, back-to-back DC ties, and VSC transmission.

The optimistic estimate of market share for FACTS devices in the next decade exceeds $40 billion. Regardless of the financial investment, industry demand for FACTS is definitely very strong and steadily growing worldwide, especially in North America and Europe. The strong demand for new FACTS devices dictates the necessity of a proper approach to a needs analysis of FACTS installation, determination of optimal location in the grid, and selection of FACTS type, rating, and characteristics. Although the IEEE and IEC working groups have developed detailed standards and guidelines for the first-generation FACTS devices, the development of industry standards for second-generation devices is still ongoing. This guidance note has collected, compiled, and presented information on a variety of FACTS technologies, identifying the basic design and functionality of FACTS, essential specification requirements, industry needs, applications, and benefits of implementation. Usually, it is the implementation benefits that drive the demand for change and for the procurement of new, advanced-technology equipment.

TABLE 9.1 summarizes this document's analysis in terms of impact on FACTS devices in the following key factors of a power system: load flow, system stability, and power quality. The FACTS devices are grouped into categories according to their general function. The HVDC lines and back-to-back technology were also included in the summary due to their important role and for comparison purposes with FACTS devices.

TABLE 9.1: FACTS Technology Summary

Principle	Device	Key Performance Factors				Cost
		Power Quality	Power Flow	System Stability	Control Speed	
Series Compensation	Fixed series compensation	L	L	M	L	L
	Thyristor protected series compensation	L	L	H	M	M
	Thyristor controlled series compensation	L	M	H	M	M
Shunt Compensation	Mechanically switched reactor, capacitor	M	–	L	L	L
	Static VAR compensator	M	–	M	M	M
	Thyristor controlled reactor	M	–	M	M	M
	Thyristor switched capacitor	M	–	M	M	M
	Static synchronous compensator	H	L	M	H	M
Power Flow Control	Unified power flow controller	H	M	H	H	H
	High voltage direct current	M	H	H	H	H

Note: L (low), M (medium), and H (high) are relative rankings.

APPENDIX A: ILLUSTRATIONS OF FACTS DEVICES

The illustrations provided in this section have been compiled from brochures and other documents published by large manufacturers of FACTS devices including (in alphabetical order) ABB, Eaton, General Electric, Hyosung, Mitsubishi Electric, NR Electric, and Siemens. This does not constitute or imply the endorsement, recommendation or approval of the World Bank.

REACTOR

FIGURE A.1: Reactor

CAPACITOR

FIGURE A.2: Capacitor I

FIGURE A.3: Capacitor II

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SYNCHRONOUS CONDENSER

FIGURE A.4: Synchronous Condenser

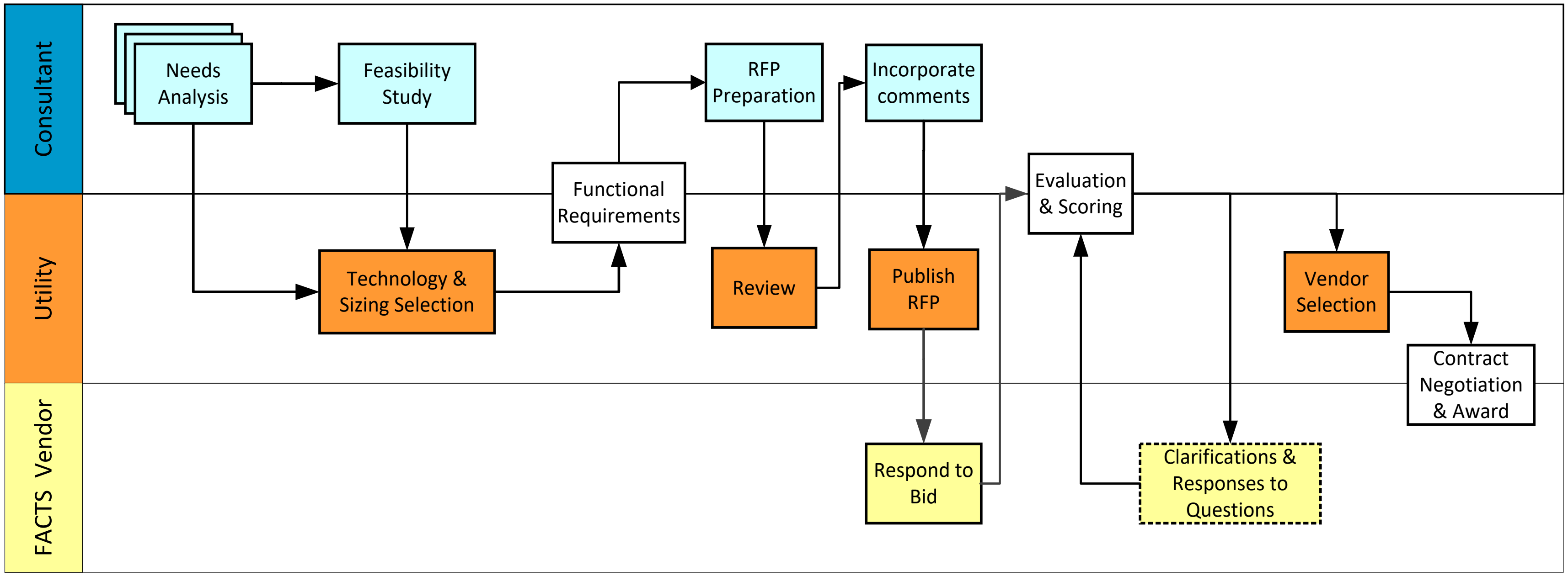
STATIC VAR COMPENSATOR

FIGURE A.5: Static VAR Compensator

APPENDIX B: PROCUREMENT

The following diagram represents a generic overview of the procurement process, with an emphasis on the extensive needs analysis, feasibility, and planning studies that precede the selection of technology, size, and location as well as the preparation of technical specification.

FIGURE B.1: Overview of procurement process



The following is a list of documents that represent good references for establishing a FACTS procurement process, including evaluation of bids and project implementation:

- IEEE 1052-2018, “IEEE Guide for the Specification of Transmission Static Synchronous Compensator (STATCOM) Systems” (2018)
- Recommendation 28, “10-400 kV oil-immersed shunt reactors” (Danish Energy Association 2005)
- “Principles for Efficient and Reliable Power Supply and Consumption” (FERC 2005)
- Directive 2004/17/EC of the European Parliament and of the Council (2004)
- CIGRE TB 663, “Guidelines for the procurement and testing of STATCOMS” (2016)

The last document in the list deserves a special mention. Its table of contents represents a useful checklist of items to be addressed during FACTS procurement in general, and SVC and STATCOM in particular, so we have presented it below.[12]

GLOSSARY OF ABBREVIATIONS AND SPECIAL TERMS
1 INTRODUCTION
  1.1 Background
  1.2 Technical Brochure (TB) Scope
2 SHUNT REACTIVE POWER COMPENSATION
  2.1 Basic operating principle
    2.1.1 SVC
    2.1.2 STATCOM
  2.2 Advantages/Disadvantages of STATCOMs
  2.3 References
3 STAGES LEADING TO DEVELOPMENT OF SPECIFICATION OF STATCOM
  3.1 Planning Specification
    3.1.1 Studies
    3.1.2 Information to be Included in the Planning Specification
    3.1.3 Connection Requirements
  3.2 Feasibility Studies
    3.2.1 Layout
    3.2.2 Interface to the ac system
    3.2.3 Auxiliary AC supply
    3.2.4 Audible noise
    3.2.5 Losses
    3.2.6 Other Items
  3.3 Internal Procurement Team
    3.3.1 Network Planning/System Development
    3.3.2 Technical Design
    3.3.3 Engineering Design
    3.3.4 Network Operations
    3.3.5 Project Management
    3.3.6 Finance and Legal
    3.3.7 Asset Management
  3.4 Data/Requirements after Planning Specification
    3.4.1 Site and environmental conditions
    3.4.2 General design requirements
    3.4.3 Primary plant equipment requirements
    3.4.4 Control, protection and monitoring system requirements
    3.4.5 Auxiliary systems requirements
    3.4.6 Other requirements
    3.4.7 Civil and building works requirements
    3.4.8 Spares, special tools and maintenance requirements
    3.4.9 Safety, health and environmental requirements
    3.4.10 Training requirements
    3.4.11 Site Security
    3.4.12 Interference Requirements
  3.5 Scope of Work

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[12] For additional details, the document is available at http://b4.cigre.org/Publications/Technical-Brochures/TB-663-Guidelines-for-the-procurement-and-testing-of-STATCOMS.

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