Programme Area: Energy Storage and Distribution

Project: Network Capacity

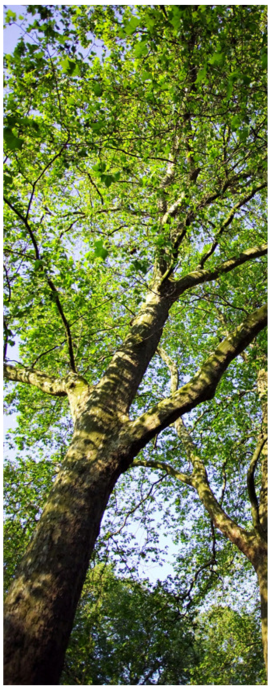
Title: Assessment of Power Electronic Technologies

Abstract:

This document reports the results of an initial literature review addressing the state of the art of power electronic (component) devices and of system technologies based on them. It also includes a brief assessment of other relevant technologies (such as special protection systems and phase shifting transformers). The report introduces each of the technologies and relates the claimed benefits to the actual state of the art of each, and it identifies initial gaps and opportunities which form the basis of further work throughout the project.

Context:

The Network Capacity research project identified and assessed new technology solutions that could enhance transmission and distribution capacity in the UK. It assessed the feasibility and quantified the benefits of using innovative approaches and novel technologies to provide improved management of power flows and increased capacity, enabling the deployment of low carbon energy sources in the UK. The project was undertaken by the management, engineering and development consultancy Mott MacDonald and completed in 2010.


The ETI Energy Storage and Distribution Programme - Network Capacity Project

Work Package 1 Task 1 Final Report
- Assessment of Power Electronic Technologies

August 2010
The Energy Technologies Institute (ETI)

Mott MacDonald

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Content

1. Summary

1.1 Background

Mott MacDonald has been commissioned by the Energy Technologies Institute (ETI) to carry out the ETI's Network Capacity Project. This project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals. Specifically the project will assess the feasibility of two potential areas of development to improve the operation and increase the capacity of the UK onshore T&D systems. The outcome will be a thorough, coherent and well presented analysis that will enable the ETI to make informed decisions as to where future work in the programme should be directed.

- The first area of the project is focussed on the feasibility of applying new and existing power electronic technologies to provide enhanced management of network power flows in order to release more capacity within the T&D system.
- The second area concentrates on the technical feasibility of multi-terminal HVDC in the context of operation within the existing UK T&D system.

The work associated with both areas comprises an assessment of the credible options from these technologies in the context of power flow management including the benefits and also associated impediments to their development and deployment, and will provide guidance in respect of technology development opportunities. The work has been structured into two packages;

- Work Package 1 concentrates on the novel technologies with the potential to release capacity in the UK T&D networks. The work in this package comprises a literature review and modelling of the various technologies integrated into the networks to determine their effectiveness and requirements for such integration. It will also include analysis of environmental and social impacts, and of the barriers to development and deployment.
- Work Package 2 concentrates on the use of multi-terminal HVDC transmission and its integration within the existing UK T&D networks. The work in this package will comprise a feasibility assessment and detailed modelling of multi-terminal HVDC to assess its performance, impact and potential interactions arising from its use. It will also include analysis of the requirements for such integration, the benefits case for conversion of existing AC lines, and of the barriers to development and deployment.

1.2 Work Package 1 Task 1 Final Report

Mott MacDonald commissioned the Power Electronics and Energy Conversion Group at the University of Strathclyde to carry out a review of the power electronic technologies covered by the Work Package 1 Task1 scope of work. The final report received from the University of Strathclyde is included as Appendix A. This report incorporates amendments to the report that have been made in response to ETI comments received on the draft report submitted in April 2010.

The report is provided as a separate stand-alone document at this stage. The final report for the project consolidates and updates the outputs from each of the individual task reports, including that covered by this document, in order to provide a coherent output that represents the integrated output from all of the work carried out.

Appendices

Appendix A. University of Strathclyde Report - Review of Flexible AC Transmission Devices and High-Voltage DC Transmission Systems

University of Strathclyde

Department of Electronic and Electrical Engineering

Power Electronics, Drives, and Energy Conversion

Review on

Flexible AC Transmission Devices

and

High-Voltage DC Transmission Systems

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26th March 2010

High Level Summary

Flexible AC transmission systems (FACTS) and high voltage dc transmission (HVDC) are techniques that increase power flow capacity of electricity transmission systems. Unlike conventional AC transmission systems, these devices rely on power semiconductor devices and associated control systems.

FACTS devices achieve power flow management by altering the reactive power flows in the network; this allows better utilisation of the AC transmission architecture. In general, FACTS have the advantage that the power electronics need only be rated at a fraction of the main power flow. HVDC systems may be used to avoid AC transmission losses, increase capacity and to buffer separate AC regions. Reduced transmission losses and increased capacity must be traded against increased loss, in the power electronics. HVDC has restricted deployment, to long distance transmission and subsea/underground lines where charging loss is increased.

For most applications, FACTS and HVDC may be implemented by established thyristor based converters or by means of newer voltage source converter systems. In general, voltage source FACTS achieve better power quality and control response at the expense of increased losses.

At present thyristor based systems have the advantage of lower losses and a proven track record. Where these considerations are paramount such systems will continue to be employed. However it is important to understand the circumstances under which the limits of this technology become significant. Changing patterns of electrical power generation and transmission make this understanding an important area for future research.

The power losses associated with voltage source converter technology have been a significant restriction to uptake into transmission applications. This is now a key area for research among manufacturers and their research partners.

There is now significant interest in the development of multi-terminal HVDC systems. This will require the use of voltage source converter circuits with extended functionality to manage DC side faults. The understanding of the potential benefits of multi-terminal HVDC and the technical developments required to support this are an important area for research.

The performance of FACTS and HVDC systems is dependant of power semiconductor device technology. At present this is dominated by silicon based thyristors and IGBT's, it is unlikely this technology will see significant increases in ratings. Wide band-gap devices include Silicon Carbide (SiC), Diamond, and Gallium Nitride. Of these, SiC is the furthest advanced

This report has focused on technologies that address near term (within 2020 time frame) enhancements to the existing transmission network. These changes are driven by the need to integrate increased renewables within a fairly stable pattern of electricity demand. In the longer term there will be a need to transfer the direct consumption of fossil fuels (transport and heating) to low carbon sources. This may lead to a significant increase in the demand for electricity and provide a substantial requirement for technical innovation, particularly in power dense urban centres where conventional reinforcements may prove difficult. In such environments the losses and complexity of power electronic systems can be traded against the ability to deliver clean energy. In this context, devices for distribution voltage connection (≤ 33kV) may see the greatest scope for innovation.

Conclusions

- Power electronic technologies are available which can increase transmission power flows for a given infrastructure base. It is important to establish the merits of this approach (technical, environmental, and economic) relative to conventional network reinforcement.
- In the near term, line commutated FACTS and HVDC have advantages in terms of losses and established ratings. Network studies, such as those conducted in work-package 2 of this project, are required to identify instances where the added performance of voltage source FACTS/HVDC is required. Continuing research may be required to establish if evolving patterns of generation and loading will require the use of more advanced technologies.
- Voltage source inverter technology has significant performance benefits relative to established line commutated thyristor systems. Designs which can achieve improvements in the efficiency and reliability of these systems will extend their potential deployment at the transmission level.
- Multi-terminal HVDC networks are currently receiving significant attention. The potential of this technology for reinforcement of the U.K transmission system is investigated in work-package 2 of this project. In the longer term, multi-terminal HVDC has been proposed for transnational 'supergrid' structures. Such ambitious applications remain in the early research and development phase.
- Multi-terminal DC networks are not a simple extension of point to point voltage source HVDC. Research and development is required to provide suitable hardware, protection and power management systems. Of

these, effective low loss DC side protection and fault management remain one of the main obstacles to deployment.

- Research into high-voltage power semiconductor devices has the potential to extend the application of FACTS and HVDC by reducing losses and device count. Despite early optimism, silicon carbide devices have yet to impact on high-voltage power semiconductors.

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List of Abbreviations

APF	Active power filter
CCC	Capacitor commutated converter
CSC/CSI	Current source converter/inverter
DVR	Dynamic voltage restorer
ESCR	Effective short circuit ratio
FACTS	Flexible AC transmission systems
HVDC	High-voltage dc
HVDC-Light/or Plus	ABB and SIEMENS names for VSC-HVDC systems
IGBT	Insulated gate bipolar transistor
IGCT	Insulated gate commutated thyristor
LCC	Line commutated converter
M2C or MMC	Modular multilevel converter
NPC	Neutral-point clamped
PCC	Point of common coupling
PST	Phase shifting transformer
PWM	Pulse width modulation
SCR	Short circuit ratio
SSR	Subsynchronous resonance
SSSC	Static synchronous series compensator
STATCOM	Static synchronous compensator
SVC	Static VAr compensator
SVC-Light and Plus	ABB and SIEMENS names for STATCOM
SVM	Space Vector Modulation
TCR	Thyristor controlled reactor
TCSC	Thyristor controlled series compensation
TSC	Thyristor switch capacitor
TSSC	Thyristor switch series capacitor
UPFC	Unified power flow controller
VSC/VSI	Voltage source converter/inverter

1. Introduction

The Energy Technologies Institute (ETI) identified the need for engineering studies to assess innovative approaches and technology solutions that could lead either to:

- the capability enhancement of the *existing* onshore UK electricity transmission and distribution networks, or
- the *expansion* of these networks by means other than the construction of new overhead line infrastructure,

and thereby enable the installation of substantially more renewable energy systems in the UK than the current T&D system can accommodate. The project is aimed at supporting the ETI's overall goal of accelerating the deployment of technologies that will help reduce greenhouse gas emissions and thus help achieve climate change goals.

This project has concentrated on the network reinforcement necessary to meet predicted challenges within the 2020 time frame. Within this time frame change to the U.K. electricity system will be driven by the development of bulk renewable generation at locations remote from principal load centres. Integration of these resources will require increased transmission capacity if generation constraints are to be avoided.

This report reviews the technologies available for network reinforcement of the U.K. transmission system. The report details discussion of Flexible AC systems (FACTS) and High Voltage DC transmission (HVDC) systems and their role in achieving increasing power flows for a given level of transmission infrastructure.

FACTS refers to a range of power electronic techniques that may be used to enhance the basic AC network, therein reducing capacity and stability constraints of conventional infrastructure. This is achieved by varying the effective impedance characteristics or reactive power consumption of sections of the ac network.

HVDC takes advantage of improved power transmission capabilities of DC lines and cables. This advantage is traded against the losses and capital cost of the converter stations. HVDC is an established technique for long distance and subsea transmission. It may also be used to may relieve network congestion and provide a degree of protection against wide area blackout. However, it may not be able to meet the current GB Grid Code, such as fault ride-through capability and reactive power contribution to support the grid voltage during AC faults. Voltage source HVDC overcomes many of the problems of conventional HVDC but suffers increased losses. Since

conventional HVDC transmission systems will not add sufficient flexibility to the UK, its selection based solely on loss criteria becomes questionable.
This report provides a review of the power electronic technologies available for network reinforcement and compares their relative merits and applications.

Methodology

The objective of this report is to review and assess the range of power electronic systems available for reinforcement of the U.K. electricity transmission network. The principal focus is on technologies appropriate to changes predicted for the 2020 time frame. Within this period increasing transmission capacity has been identified as the chief challenge.

The report is based on background knowledge resulting from the University of Strathclyde's ongoing industrial and academic research programs and a review of recent information from manufacturers, government, and academic publications.

Where appropriate, this report also contains observations relating to research and development opportunities beyond the period of the main study.

All pictures and non original diagrams used in this report have been taken from public access web sites as listed in the references section.

Report Structure

The report contains three main sections. Section 2 (Detailed Findings) provides an in depth summary of FACTS and HVDC technologies.

The background material supporting section 2 is given in sections 3 (Flexible AC Transmission Systems) and 4 (High Voltage DC Transmission) of the report. These two sections provide a more detailed description of the individual FACTS and HVDC technologies.

Supporting material is included in the appendices, including: a review of power semiconductor technology, emerging power semiconductor materials, and alternative network technologies for network reinforcement.

2. Detailed Findings

2.1 Summary

Within the 2020 time frame, reinforcement of the U.K. transmission system will be driven by the development of renewable generation at locations remote from principal load centres. Integration of these resources will require increased capacity if generation constraints are to be avoided. The use of power electronic technologies may allow increased power flows for a given level of transmission infrastructure.

Flexible AC transmission systems provide an enhancement to the basic AC network, reducing capacity and stability constraints of conventional infrastructure. The use of conventional point-point HVDC transmission systems may relieve network congestion and provide some protection against blackout. However, it may not be able to meet the current GB Grid Code, such as fault ride-through capability and reactive power contribution to support the grid voltage during AC faults. Voltage source HVDC overcomes many of the problems of conventional HVDC but suffers increased losses. Since conventional HVDC transmission systems will not add sufficient flexibility to the UK, its selection based on loss criteria only becomes questionable.

2.2 Power Semiconductor Devices for Transmission Applications

With few exceptions, flexible AC and high voltage DC transmission can only be implemented because of the existence of suitably rated power semiconductor devices. The type of device employed will determine the capability and performance of the FACTS or HVDC system. To achieve high efficiencies these devices are operated in a 'switched mode' where the device is either turned fully on or fully off.

Although there are a wide range of power semiconductor technologies, only two device families are extensively used in transmission and distribution applications.

a) **Thyristors.** These may turn-on under control but rely on the action of the ac network to turn-off. Such circuits are termed line commutated and are restricted to operation at the frequency of the ac network. Thyristor based systems have a long track record in transmission/distribution applications.
b) **IGBTs.** These devices may be controlled to turn-off and turn-on. This allows the use of high frequency (1 to 2kHz) pulse width modulation to synthesise the voltage or current that is to be applied to the network.

At present the voltage ratings of silicon thyristor and IGBT devices are limited to 8.5kV and 6.5kV, respectively; there is little scope for significant increase in these figures. For many transmission applications, series connection of devices is required in order to achieve the necessary operating voltage.

New wide band-gap materials such as silicon carbide and gallium nitride have the potential to deliver increased voltage ratings, reduce switching losses, and raise operating temperatures. Although low voltage SiC devices are available, advances are still required in order to achieve the high-voltage, high-power modules necessary for transmission applications. The key benefits that may be achieved are:

- Increased voltage rating leading to decreased device count and possible reliability gains
- Decreased system conduction loss due to reduced numbers of series devices and possible reduction in device on-state voltage (The realisation of reduced on-state voltage per unit of voltage capability remains to be proven.)
- Increased switching speed may give advantages in terms of reduced switching loss. However the benefits of this for transmission may be marginal since significant increases in *dv/dt* may prove problematic at these voltage levels. Furthermore, advances in circuit design have decreased the importance of switching loss in voltage source inverters.

2.3 Impact of Power Semiconductors on System Performance

Although there is a wide range of system level functionality, the basic circuits used for FACTS and HVDC show many common features. (The same power electronic circuit may be employed for different functions). Performance of these systems depends directly on the basic devices that are used for implementation.

2.3.1 Line Commutated Thyristor Systems

With the exception of multi-terminal HVDC, the basic steady state operation required of FACTS and HVDC systems may be achieved through the use of line commutated thyristor based systems. There are however limits on the performance/functionality that may be achieved.

2.3.1.1 Advantages

a) Thyristor devices give low losses and are available in robust high-current capacity single-wafer capsules.
b) Line commutated HVDC and FACTS have an established track record at transmission voltage and power levels.

2.3.1.2 Disadvantages

a) Line commutated systems inject significant low frequency harmonics which must be eliminated by large (physically and electrically) passive filter arrangements. The presence of these filters may lead to circulating harmonic currents which must be mitigated by damping networks. Filters and damping networks may have to be designed specifically for each location and may not be optimal for all operating conditions.
b) Line commutated systems are inherently limited in their response time (Limited to line frequency switching) and may face limits to their control ability. For example thyristor based HVDC:
    i. Cannot decouple the real and reactive power injected into the network.
    ii. May have limited operating range depending on the source impedance provided by the AC network at the point of connection.
c) Line commutated circuits tend to require large passive components leading to large footprint systems.

2.3.2 Voltage Source Converter (VSC) Systems

Voltage Source Converter systems are based around self commutating devices (typically IGBT technology). The use of these devices allows the application of high frequency (>1kHz) pulse width modulation techniques, which are common in the industrial drives sector, to the control of transmission (and distribution) level power flows. By the use of PWM, the Voltage Source converter may synthesise a fully controlled voltage at its output. This voltage appears as a power frequency fundamental with harmonics at the switching frequency. With appropriate feedback, the voltage source inverter may be controlled to act as a current source.

2.3.2.1 Advantages

a) The injection of low frequency harmonics is reduced, leading to smaller filter requirements and damping networks.
b) Systems can achieve better levels of control. In the case of IGBT based voltage source HVDC:
    i. The converters can independently control the real and reactive power injected into the network.
    ii. Operation is independent of the network characteristics. This facilitates connection to weak networks and black start.

c) The use of high frequency switching reduces both filter requirements and the size of passive energy storage components, leading to reduced installation size.
d) Faster response allows IGBT based converters to reject network distortion and transients.

2.3.2.2 Disadvantages

a) Improved control is achieved at the expense of increased losses in the power converter. Increased losses are the result of:
    i. The move to high frequency switching leads to increased switching loss.
    ii. IGBT devices exhibit significantly higher on-state voltage drop compared to thyristors with similar voltage ratings. For a given application, this will lead to increased conduction loss.
b) IGBT modules have lower power capability than available thyristor packages, leading to increased power component count.
c) Thyristor capsules fail short-circuit, whilst undesirably module IGBTs tend to fail open-circuit.
d) IGBT devices have lower current overload capability than thyristor based systems.
e) High *dv/dt* transitions may be present at the output.

2.4 Comparison of LCC and VSC Systems

FACTS and HVDC systems are currently implemented using both LCC and VSC technologies. Line commutated FACTS have the advantage of a well established technology but are subject to inherent performance limits. The use of VSC can overcome some of the inherent limitations of LCC based systems. The IGBT converters used in voltage source FACTS are still in a state of development with relatively limited operation experience. At present VSI systems have yet to match the established LCC technology in terms of capacity and losses.

- Despite technical limitations, line commutated FACTS provide a practical solution using robust devices and well proven circuits.
- IGBT based (voltage source) FACTS provide improved functionality but are subject to a number of limitations.
    - The technology is more complex and less mature.
    - Achieved capacities have yet to match that of line commutated FACTS.

- Increased losses.

2.5 Operation at High Voltages

In general power electronic systems for power transmission are required to operate at power levels and voltages significantly above that which may be sustained by a single power device. This presents challenges not normally faced in other applications. To meet this requirement, circuit topologies are required which allow voltage sharing between multiple devices.

In LCC systems this is achieved by series connection of devices, with static and dynamic voltage sharing necessary to ensure that voltage stresses remain compatible with device ratings.

Series device connection has been applied to self commutating devices to achieve two level voltage source converter systems. Series connection of devices in voltage source converters is more challenging due to the increased operating frequency and switching speed that is required. Recent advances have seen the use of multi-level converters to address the technical limitations of series connected devices in voltage source converters.

2.5.1 Series Connection of devices

With series connection a number of devices are connected to form a composite high voltage switch. This approach requires both static and dynamic voltage sharing between the constituent devices. In LCC based systems, voltage sharing issues are simplified by the inherently low switching frequency.

In the case of VSC systems, series connection of devices allows the direct application of two-level pulse width modulation. However there are significant challenges in achieving the transient voltage sharing at the required switching speeds.

2.5.1.1 Advantages

a) The basic power circuit is simple and allows the use of established control/modulation techniques.
b) With appropriate device choice (fail to short circuit), it is possible to implement series redundancy.
c) The circuit draws power from a single DC supply and is well suited to voltage source HVDC applications.
d) For balanced loading, the energy drawn from the DC supply is constant, allowing minimisation of capacitive energy storage.

2.5.1.2 Disadvantages

a) In order to achieve the necessary waveform quality, a switching frequency of 1 to 2kHz is required. Since each switch must switch at this rate, high levels of switching loss are introduced.
b) The need to balance the transient voltage between series devices leads to de-rating of devices in terms of blocking voltage and switching speed. This is reflected in increased losses.
c) The circuit will give rise to high *dv/dt* switching at its output terminals, leading to EMI emissions that must be contained.

2.5.2 Multilevel Circuits

Multilevel circuits address the problem of voltage sharing by means of a series of intermediate voltage steps. Each semiconductor switch is operated within its rated operating voltage without the need for series device connection. A large number of multi-level inverter circuits have been proposed, two of which are currently regarded as suitable for transmission applications, viz. neutral point clamped (NPC) converter and modular multilevel converter (M2C). Multi-level converters allow the modulation of the pulse width and magnitude of the output voltage where each individual device operates at low frequency, in the order of 150Hz in the M2C and half of the assigned carrier frequency in the NPC converter. This results in significant improvements in output waveforms and switching loss.

2.5.2.1 Advantages

a) Multi-level inverters give lower current harmonics resulting in reduced filter requirements, relative to two level systems. In general, the filter reduces to a single coupling inductor.
b) The switching loss of the inverter is greatly reduced such that losses in multilevel inverters become dominated by on-state conduction loss.
c) Reduced EMI due to lower switching voltages steps.

2.5.2.2 Disadvantages

a) There is a need to derive the intermediate voltage levels for the multi-level inverter. For transmission applications, multiple isolated power supplies are impractical, therefore capacitor clamping networks must be used to provide ‘virtual voltage sources’.
b) The clamping capacitors see full load current and must be sized to achieve acceptable voltage fluctuations. This results in a large capacitor requirement and a larger converter footprint.

c) The modulation of the inverter must be controlled to manage both the output voltage and the charge balance of the clamp capacitors. This leads to complex controllers.
d) Series redundancy is more complex than for series connection.

2.6 Flexible AC Transmission Systems

Flexible AC transmission systems make use of power electronic techniques to control power flow and dynamic response in AC networks. FACTS may provide either or both series compensation and shunt compensation. In principle, series compensation acts to directly modify the properties of the power transmission path whilst shunt compensation is used to modify the reactive power loading. FACTS devices may be implemented using either line-commutated or voltage source systems.

Line commutated FACTS will appear as controlled impedances that may be varied according to the thyristor firing pattern. This technology has the capability to provide steady-state compensation and the dynamic capability to contribute to the damping of subsynchronous oscillations. Line commutated FACTS devices switch at the power frequency, which limits their dynamic response and gives rise to low frequency harmonics. Mitigation of these low frequency switching harmonics through the use of passive filters may contribute to circulating harmonic currents.

Voltage source FACTS make use of high switching frequency modulation, giving improved dynamic response and reduced low frequency harmonics. This allows them to be controlled to appear as variable voltage or current sources. Due to limits on power semiconductor device technology, voltage source FACTS have yet to match the high power capability and low losses of line commutated FACTS systems. The additional loss associated with voltage source technology is a significant limitation for series compensation, since the FACTS device has to be placed in the principal power flow path.

A review of FACTS devices is provided in section 3 of this report

2.7 High Voltage DC Transmission

HVDC transmission is discussed in detail in section 4 of this report. Section 4 presents a review of high-voltage DC (HVDC) transmission systems with the main focus on their capabilities and limitations. It also discusses the current state of the art of the converter stations of HVDC transmission systems and their potential influence on power system operation in terms of voltage and power system stability, reactive power support, and resilience to AC and DC faults. Section 4 also presents comparisons between different HVDC transmission system technologies, such as, line commutated HVDC, capacitor commutated

HVDC, and voltage source converter HVDC (VSC-HVDC) based on two-level voltages, neutral-point-clamped and modular converters. The strengths and weaknesses of each technology are highlighted. Examples of recent projects, covering most of the HVDC technologies discussed in this report, are given in order to show the maturity of each technology. Also discussed is the potential use of point-to-point HVDC and multi-terminal HVDC transmission systems to relieve network congestion, improve system stability and reliability against system blackout, and provide ancillary functionality such as damping support and frequency stabilization of the AC networks.

The following bullet points summarise the features and limitations of the technology employed in current HVDC systems:

- Thyristor based high-voltage DC transmission is a well-established technology. The limits of this technology are well-known, namely high VAR consumption, large harmonic current emissions, and large installation size. Conventional HVDC transmission is based on current source principles; giving advantages in terms of DC link fault behaviour but is not readily adapted to multi-terminal systems.
- Voltage source converter HVDC is a more recent development. Voltage source HVDC exhibits increased losses relative to thyristor based systems but is suited for connection to weak networks where conventional technology would not be technically practical. There has been significant use of this technology with subsea links to circuits that could not support conventional HVDC (most notably offshore renewable generation clusters).
- Unlike conventional HVDC, voltage source converter systems do not require DC link voltage reversal in order to change the power flow direction; this allows the use of robust and flexible polymer insulated cables.
- Voltage source converter HVDC operates from a common DC bus with fixed polarity, facilitating more complex multi-terminal architectures.
- For power levels greater than 2400MW, conventional HVDC is the only option. In this case, suitable FACTS devices (such as SVC or STATCOM) are used on both AC sides to reduce the impact on the local network, improve fault ride-through capability and other transient performances.
    - The use of VSC-HVDC transmission systems in the UK Grid will potentially improve system stability and immunity against blackout.
    - The voltage source converter is capable of remaining connected to the grid during AC side faults.
    - Active current control limits the overload stress on the converter and limits current into the fault.

  - The converter stations of VSC-HVDC have inherent STATCOM capability, allowing voltage support during AC faults.
  - During AC faults DC the rise of DC link voltage may be limited by the converter station control or by the use of DC choppers. This limits converter voltage stress and acts to decouple the faulted and un-faulted ac networks.
- The VSC-HVDC transmission system can provide all the ancillary functionality available on conventional generating units based on synchronous machines, such as frequency support, local and inter-area oscillations damping, and voltage support as required in the GB Grid Code, at no additional cost. The functionality, such as power reversal, frequency support, AC voltage control, and recovery from DC fault within 0.5s, have been demonstrated in the Caprivi link based on the overhead line VSC-HVDC transmission system in Namibia. In the case of an OH line VSC-HVDC transmission system, a reduction in construction cost will be achieved compare to the cases where underground cable is used.
- The power electronics presently used in voltage source inverter circuits cannot block current flowing from the ac supply into a suppressed DC link voltage during dc faults. For point-to-point installations, protection may be on the AC in feed, but the low overload capability of power electronic components adds to the difficulty of providing protection in this way.
- DC link control is required to manage transient power flow during disturbance in the ac and dc sides without imposing the risk of device failure in the converters. This becomes of increased importance where HVDC is applied to overhead lines due to the increased likelihood of temporary DC side faults. For multi-terminal systems this control is necessary in order to minimize the risk of system collapse resulting from temporary dc line faults or permanent faults on individual sections. Research into suitable DC circuit breakers and reverse blocking HVDC converters, are areas of on-going research.

2.8 Other Network Technologies

Other, non power electronic, approaches to network reinforcement are possible. These include:

- Special protection schemes, in particular system-to-generator inter-trips, and
- Phase shifting transformers.

Phase shifting transformers may be employed in a similar manner to FACTS in order to improve power transfer. It can be argued that these systems will exhibit lower losses than power electronic FACTS. However, transient response and control characteristics are inferior.

Special protection schemes enhance the security of transmission systems by managing network events such that systems limit violations are prevented. Special protection techniques may be required for HVDC reinforcement in order to compensate for the limited overload capacity at converter stations.

Details of these approaches are given in Appendix D of this report.

2.9 Future Research and Development

This study focuses on technologies required for near-medium term reinforcement of the transmission system (up to say 2020). Within this time frame, established transmission system models remain valid and generation and load characteristics may be confidently defined. Beyond this period, requirements for the electricity supply network become significantly more uncertain. Table 1 summarises the key technology challenges identified in this report

Table 1: Summary of Technology Limitations and Challenges

	Limitations	**Challenges**
Applications of FACTS and HVDC	• System benefits must be traded against cost and losses in FACTS/HVDC converters • implications of large scale deployment remain uncertain	• Understanding systems level benefits • Operation of Systems with high levels of FACTS/HVDC
Line Commutated Converters (LCC)	• High harmonic emissions • Restriction of both static and dynamic control response	• LCC converters have advantages in terms of ratings, loss, and established track record. However network studies are required to identify instances where this technology is inappropriate
Voltage Source Inverter (VSI) Topologies	• High losses • Restricted voltage and capacity rating	• Identifying network instances where VSI is to be preferred to LCC • Increasing voltage rating • Increasing capacity • Reduced losses • Optimising cost, size and efficiency for particular applications
Distribution Level FACTS and HVDC	• System requirements still highly uncertain • Benefits of distribution FACTS unproven • Lack of proven medium voltage technology	• The drivers for distribution reinforcement (load and distributed generation) still need to be quantified. . • Identify the benefits of distribution HVDC/FACTS.
Multi-terminal HVDC Systems	• Technology still unproven • Protection and management of DC side faults • Increased voltage rating for VSI converter stations	• Protection and management of DC side faults • Increased voltage rating for VSI converter stations • Mores experience of MT-HVDC required
Power Semiconductor Devices	• Device ratings for transmission and distribution applications	• New semiconductor device materials may allow significant improvement in device rating and performance • Optimisation of devices/packaging for transmission applications

2.9.1 Future Transmission Systems

Research is required to understand the form that the transmission systems must take in order to

- Meet energy and 2050 climate change targets. The transfer of direct consumption of fossil fuels to clean energy may drive a significant increase in the demand for electricity. This will require increased transmission and distribution capacity.
- Quantify the effect that long term changes to generation and load types may have on the electricity supply system. This will have implications for any network technologies that are deployed. Drivers for this change include:
  - Increased levels of active loads (e.g. efficient variable speed drives and electric vehicle chargers).
  - Replacement of conventional generating capacity with inverter connected renewable generation.
- Accommodate large numbers of FACTS and HVDC devices. As discussed in the report, FACTS and HVDC devices may be used to improve transmission and distribution capacity. However, large scale deployment of such devices will significantly alter the way the power network behaves. Research is required to:
  - Quantify the potential benefits of high large scale FACTS/HVDC deployment and identify potential structures.
  - Understand the behaviour of power systems with high penetrations of power electronic devices.
  - Identify the functional requirements of FACTS and HVDC technology in future power networks. (e.g. will there be an increase in the transmission areas of the transmission that are unsuited to line commutated HVDC/FACTS).
- Facilitate increases in bulk transmission of energy for reasons other than increasing the transmission of renewable energy. There may also be requirements for significant reinforcement of distribution networks. In urban areas, conventional reinforcement may be difficult due to space constraints and alternative distribution architectures, including medium voltage FACTS and HVDC that may be required. Studies are required to understand long term changes in distribution networks and the potential for power dense distribution architectures.
- Facilitate trans-national pooling of generation. Such systems provide significant research and development opportunities at the system level.

It should be noted that this is the subject of a number of on-going state funded research programs (including EPSRC Supergen FLEXNET and the E.U. 'Twenties' consortium).

2.9.2 Converter Technology

IGBT based voltage source converter (VSC) FACTS and HVDC have been shown to provide improved performance but have yet to match the low losses and high ratings of established line commutated thyristor systems.

- Research is required to extend the ratings of VSC based FACTS/HVDC. It may be possible to achieve this through parallel operation of exiting systems; however this approach is unproven in transmission applications.
- The increased losses of IGBT based systems are currently regarded as a significant barrier to their use. Within the industry there is significant research into circuit techniques that will lower losses. (Whether it will be possible to match the losses of line commutated systems is dependent on multiple trade-offs and remains a matter of debate).
- Multi-level converters provide a means of reducing the losses and increasing the operating voltage of VSI systems. Indications are that this will become the dominant approach. Designs for multilevel converters are not fully mature, with high levels of ongoing industrial and academic research. Particularly for offshore applications, designs may be required which provide a compromise between power density and losses.
- Multi-terminal HVDC based around voltage source inverters will require development of new hardware systems.
    - The control of DC faults will require DC circuit breakers at converter stations that can block DC line faults. This hardware must have sufficiently fast operation to prevent secondary failure of converter power electronics.
    - Protection systems are required that can identify and isolate faulted sections of the DC network. These protection schemes must be integrated with hardware that can achieve rapid re-energisation of the DC network.

2.9.3 Power Semiconductor Devices

- Research into new semiconductor materials may achieve significant advances in voltage rating, operating temperature, and reduced switching loss. This may allowed improved performance and ratings of voltage source FACTS.
- There may be potential to increase the current rating of IGBT modules through the development of improved, multi-wafer packaging.

- In multi-level converters, device switching loss is no longer critical because of the reduced switching frequency. There may be opportunities to develop devices which are optimised for such applications (The optimisation between switching and conduction losses will differ from conventional applications).

3. Flexible AC Transmission Systems (FACTS)

3.1. Overview of FACTS Devices

Flexible AC Transmission Systems (FACTS) is the name applied to a range of power electronic systems deployed to manage power flow in electrical transmission and distribution systems. Unlike passive compensation, FACTS have the ability to continuously vary their operating point in response to changing system conditions [1]-[12]. Table 2 provides a comprehensive summary of FACTS devices; including applications, capabilities, and limitations. Further details of FACTS installations are included as Appendix A1 of this report.

Table 2: Summary of Flexible AC Transmission System (FACTS) Devices

Functionalities	Series devices					Shunt devices	
	TCSC [6]-[2],[30,56]	TSSC [2,12,30,56]	Dynaflow [30,56]	SSSC [12,19]	DVR [2,99]	SVC [1]-[5],[20,30,56]	STATCOM [13,19,20,30]
Main component	Fixed capacitor plus thyristor	Fixed capacitor, switched capacitor plus thyristor	TSSC combined with phase shift transformer	IGBT based voltage source converter	IGBT based voltage source converter	Thyristor, capacitor and reactor	IGBT based voltage source converter
SSR damping	good	good	Very good	excellent	possible	limited	limited
Inter-area oscillation damping	Very good	Very good	Very good	Very good (effective than PSS)	Is possible if configured	limited	limited
Active power control capability	Very limited	Small but better than TCSC	Better than TSSC and TCSC	Very limited	Very limited	no	no
Applications	Transmission system for SSR damping, extending steady-state stability limits and reactive power compensation	Transmission system for SSR damping, extending steady-state stability limits and reactive power compensation	Transmission system for SSR damping, extending steady-state stability limits and reactive power compensation	Transmission system for SSR damping, extending steady-state stability limits and reactive power compensation	Distribution system to reduce effect of imbalance loading	Transmission system for dynamic reactive power compensation, improving the fault ride-through capability of wind farms and flicker mitigation	Transmission system for SSR damping, extending steady-state stability limits, improved power quality and reduce voltage variation
Loss minimization	yes	yes	yes				
Ability to compensate for network harmonics.	no	no	no	No (only sub-synchronous)	no	Is possible, but in this case it called load balancer	Is possible, but in this case it is called APF
Ability to compensate for unbalanced network loading.	no	no	no	no	yes	Yes (depends on configuration)	no
Blackout prevention	no	no	no	no	no	no	no
Voltage instability prevention	limited	limited	limited	limited	limited	yes	yes
Voltage quality improvement	limited	limited	limited	limited	limited	yes	yes
Manufacturers	ABB, SIEMENS, GE	ABB, SIEMENS, GE	ABB	ABB	ABB, American Superconductor	ABB, SIEMENS, AREVA,	ABB, SIEMENS, AREVA,

						American Superconducto	American Superconducto

TCSC≡Thyristor control series capacitor, TSSC≡Thyristor-switched series capacitor, SSSC≡static synchronous series compensator, DVR≡dynamic voltage restorer, SVC≡static VAr compensator, STATCOM (sometimes called SVC-Light or SVC-Plus)≡static synchronous compensator, APF≡active power filter, PSS≡power system stabilizer. Note that SSSC and DVR have the same structure with different control objectives. Therefore, both control objectives can be combined in one device; the same is also valid for the STATCOM and APF

FACTS devices may be used to allow the network infrastructure to be operated closer to its thermal limits by compensating for voltage rise, reactive power, and line reactance. FACTS devices may achieve fast response times (technology dependant but typically less than 3 cycles), making them resistant to instability problems that can be associated with fixed passive compensation; notably sub-synchronous oscillations associated with series capacitor line compensation. Furthermore, with appropriate control, FACTS devices may be used to damp system oscillations. This active damping functionality can improve network stability margins, again allowing increased utilisation of the transmission infrastructure.

FACTS technology may be split into two principal families, namely line-commutated thyristor based devices and self-commutated IGBT/IGCT devices:

3.1.1 Line Commutated FACTS

Line commutated FACTS may be regarded as providing a means of inserting variable impedance either in shunt (static VAR compensators, SVC) or in series (thyristor switched and thyristor controlled series compensation TSSC/TCSC). The use of thyristor technology readily achieves high power handing capability with low losses and robust overload capability [4],[6],[11].

These devices have relatively long response times, of in the order of several power cycles, corresponding to the limits of line frequency switching and the inherent time constant of the controlled reactive component. Line frequency switching also imposes a requirement for filters and damping networks to eliminate harmonics at low multiples of the power frequency. The response of such systems allows for compensation of sub-cycle transients but lacks the bandwidth necessary for compensation of higher frequency disturbances.

3.1.2 Self Commutating FACTS Devices

Unlike line commutated devices, self commutating FACTS act as controlled sources which are capable of injecting voltage or current at the point of common coupling [4],[16],[17]. This provides better decoupling between the compensation function and network conditions. These FACTS devices employ devices that are capable of switching a high multiple of the power frequency (typically in the range of 1 to 2 kHz). This feature eliminates the low order harmonics associated with line-commutated systems. If required, this increased bandwidth may be used to achieve active management of harmonics and transients at frequencies above the power frequency (Active Power Filters, APF). Self-commutating FACTS operate as controlled sources that may inject parallel current (STATCOM) or series voltage (Dynamic voltage restorers, DVR). Series and parallel compensation may also be achieved through the integration of parallel and series devices (Unified Power Flow Controller, UPFC).

Systems are generally based around pulse width modulated (PWM) voltage source converter (VSC) technology, similar to that employed in variable speed drives. However, since FACTS do not contribute real power, no external power source is required.

VSC based FACTS devices achieve faster response times, improved transient response, and reduced size relative to thyristor based systems. (Size reduction results from the reduction in mains frequency rated reactive components). The use of PWM switched devices results in increased losses, both as a result of increased device conduction loss (relative to thyristors) and the increased loss associated with the high PWM switching frequency. Although low frequency power harmonics are absent from the output spectrum, the output of the PWM-VSI system contains harmonics at the switching frequency which must be removed with passive filters. These filters are smaller than those required for thyristor systems; however they may still contribute to system resonances and incur damping loss.

3.1.3 Advances in self-commutating FACTS devices

Since FACTS devices do not contribute to the principal power flow there is the option to use transformers to match between the network voltage and the ratings of power semiconductors. This allows the use of conventional two-level VSI technology, which differs from HVDC where the requirement is for high-voltage high-power conversion systems [13]-[15].

Raising the operating voltage of self-commutating FACTS has benefits in terms of increased VA capability and direct transformer-less connection. Increased operating voltage may be achieved though series connection of semiconductors or by means of multilevel converters.

Multi-level converters allow the synthesis of an output voltage that is comprised of a number of discrete steps, each of which is within the voltage rating of an individual power semiconductor device. This technique extends the achievable operating voltage, results in significant improvements in waveform quality, reduced filter size, and decreased losses. Intermediate voltage levels are provided by capacitors in a similar manner to the DC link capacitor of a conventional two level inverter. However these capacitors require charge balancing and must be sized according to the principal fundamental current (unlike a conventional two level inverter, where the capacitance experiences only switching frequency and unbalance components). Power circuits and control of multi-level converters are significantly more complex than those of two-level systems.

To date, a range of multi-level converters have been employed in FACTS applications. These include the three-level neutral point clamped (NPC) circuit, the Cascade Cell and M2C converters. These last two configurations provide full multi-level operation and the capacity to readily scale to transmission voltage levels.

3.1.4 Use of FACTS Devices to Improve Network Stability

FACTS devices have the ability to damp network oscillations through selective sourcing and sinking of reactive power. To achieve this, the ratings of the FACTS reactive storage components must be sized such that sufficient energy may be stored and released in anti-phase with the oscillation. A great many damping control strategies have been published [18]-[22]. Whilst FACTS have been used successfully to damp system oscillation, there is limited practical experience of the large-scale deployment of these devices.

Knowledge of the damping algorithms employed by FACTS installations is essential for accurate evaluation of their behaviour.

3.2. Static Reactive Power Compensation

In the steady-state, FACTS devices are used to manage power flow by manipulating the impedance and hence reactive power seen at different points on the network. There are a number of basic modes to affect static VAr compensation in a transmission system (figure 1):

i. shunt compensation -
   - thyristor controlled reactor (TCR)
   - thyristor switched capacitor (TSC)
   - hybrid parallel connect TCR and TSC, termed a static VAr compensator (SVC)
   - STATCOM (Voltage Source Inverter)

ii. series compensation -
   - thyristor switched series capacitor (TSSC)
   - thyristor controlled series capacitor (TCSC)
   - quadrature phase shift transformer

iii. static phase shift compensator (SPSC)

iv. dynamic voltage restorer (DVR)

v. combined shunt and series compensation, the unified power flow controller (UPFC)

Shunt compensation is defined as any reactive power compensation utilising either switched or controlled devices, which are shunt connected at a selected network node, called the point of common coupling, (PCC) of the transmission system.

Series compensation is defined as any reactive power compensation utilising either switched or controlled devices, which are series connected into the transmission line at a selected node, called the point of common coupling, (PCC) of the transmission system.

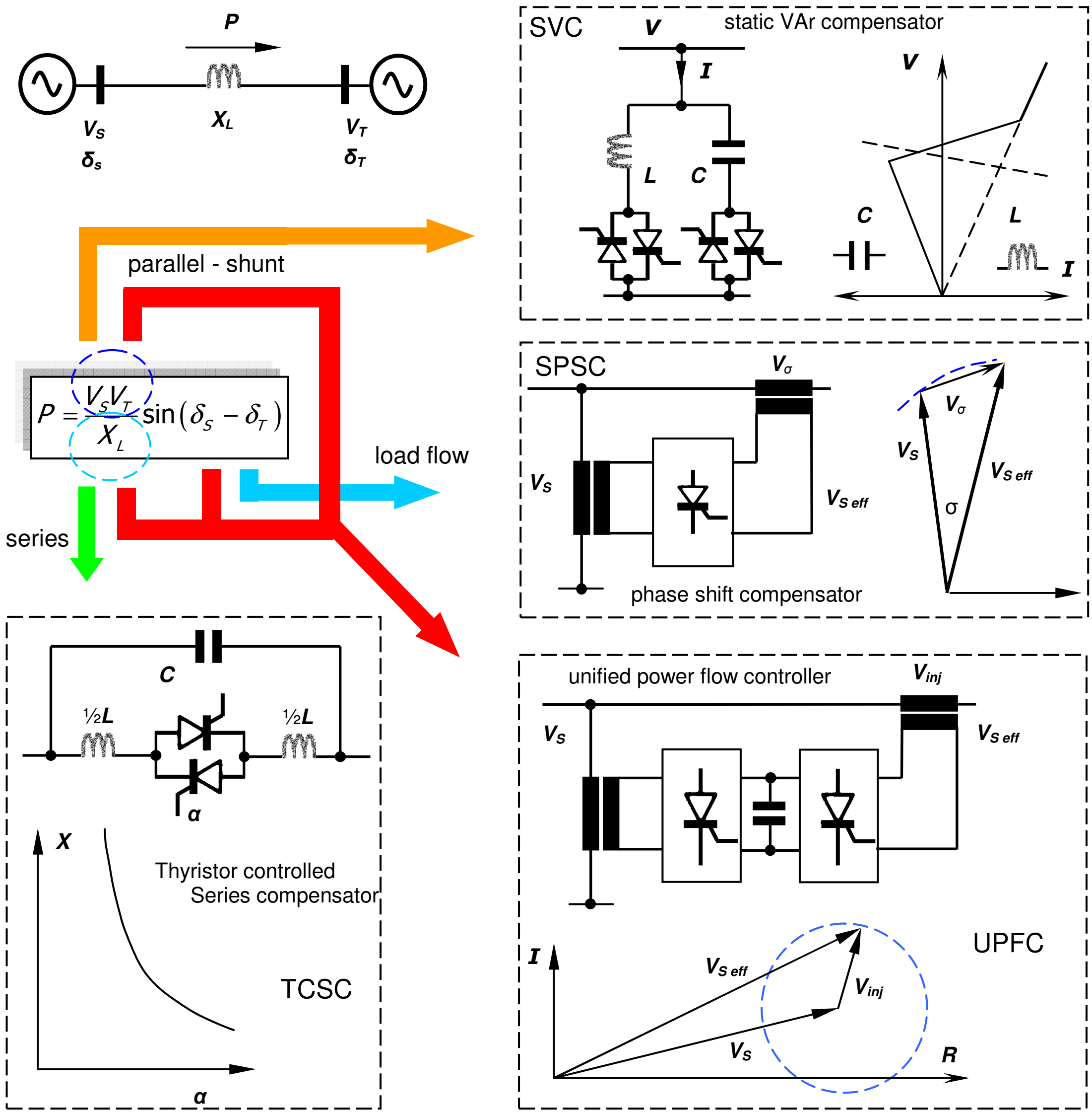


Fig. 1: The use of FACTS devices in power flow management

3.2.1. Thyristor Controlled Reactor TCR

The basic phase angle controlled TCR is shown in figure 2. If the thyristors are operated on an integral cycle basis, without phase angle control, the inductive arrangement is termed a thyristor switch reactor (TSR). Both modes are inductive thus are always associated with reactive power absorption.

Principle of TCR operation

The back-to-back connected thyristors conduct symmetrically on alternate half cycles of the ac supply.

$$i = \frac{\sqrt{2}V}{\omega L_{sh}}(\cos\alpha + \cos\omega t) \qquad \alpha < \omega t < \alpha + \sigma$$
$$= 0 \qquad \alpha + \sigma < \omega t < \alpha + \pi$$

where $\sigma = 2(\pi - \alpha)$.

It may be shown that continuous conduction occurs at a delay angle of 90° and partial symmetrical decreasing current (decreasing inductive VAr) results for delay angles increasing from 90° to 180°, as shown in figure 2. As the delay angle increases the fundamental current component decreases from a maximum, with the introduction of harmonics.

The power factor of the fundamental component lags by 90°, always absorbing reactive power. The odd order rms harmonics shown in figure 2 vary with delay angle according to

$$I_n = \frac{4}{\pi}\frac{V}{X_{Lsh}}\left[\frac{\sin(n+1)\alpha}{2(n+1)} + \frac{\sin(n-1)\alpha}{2(n-1)} - \frac{\sin n\alpha}{n}\cos\alpha\right] \qquad \text{for} \quad n = 3, 5, 7...$$

and the 90° lagging fundamental rms is given by

$$I_1 = \frac{2}{\pi}\int_{-(\pi-\alpha)}^{\pi-\alpha} \frac{V}{\omega L_{sh}}(\cos\alpha + \cos\omega t)\cos\omega t \; d\omega t$$
$$= \frac{2}{\pi}\frac{V}{X_{Lsh}}\left[\tfrac{1}{2}\sin 2\alpha + \pi - \alpha\right] \qquad \text{where} \quad X_{shL} = \omega L_{sh}$$

for $\frac{1}{2}\pi \le \alpha \le \pi$ with respect to zero voltage cross-over.

If the delay angles of both thyristors are not equal, even harmonics are produced, including a dc component. The total harmonic current distortion is increased.

As the delay angle increases the current conduction angle σ decreases and the current decreases, as if the inductance were increasing, so that the TCR effective acts like controllable shunt reactance.

$$L_{eff} = \frac{V}{\omega I_1}$$

$$Q_1 = VI_1 = \frac{V^2}{\omega L_{eff}}$$

As the delay angle *a* increases and the current decreases, the thyristor and inductor conduction losses decrease. The maximum fundamental rms current component of $V/\omega L_{sh}$ occurs at $\alpha=\frac{1}{2}\pi$

If the three-phase TCR is configured in a delta arrangement, then the third harmonic current does not appear in the source line voltage. If two separate reactors are used in each phase as in figure 2, then conduction up to 360° is possible resulting in the maximum possible fundamental with lower total harmonics, although energy cycling between the two inductors occurs. Alternatively, if transformer coupling is used, then the 5^{th} and 7^{th} order current harmonics can be eliminated if two three-phase delta connected TCR are used with a 12 pulse star-delta transformer secondary-tertiary arrangement. (Alternatively, two discrete transformers can be used.)
The use of a transformer allows voltage matching between the transmission network and TCR. Typically a voltage step-down transformer is used to match the TCR operating voltage to that of the semiconductor thyristor devices; thereby avoiding the need for series connection. High leakage inductance minimizes the necessary TCR discrete inductance required. Two discrete TCR's also offers redundancy possibilities. Further, a transformer offers the possibility of reducing the inrush current if used in conjunction with the capacitive TSC.

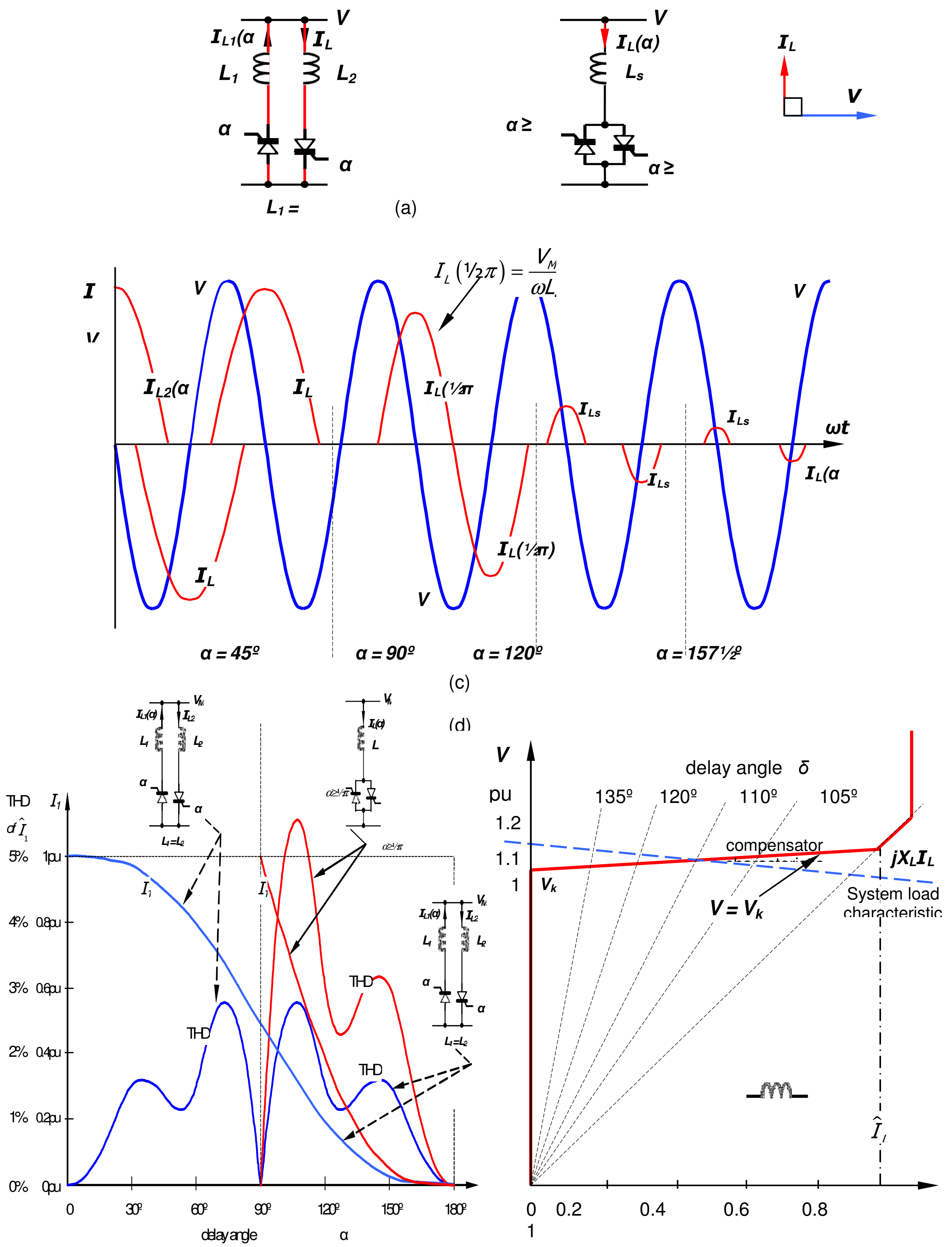


Fig. 2: TCR compensation: (a) dual reactor TCR compensator; (b) single reactor TCR compensator;
(c) line voltage and current waveforms for delay angles α=45°, 90°, 120° and 157½°;
(d) harmonics (delta connected - no triplens); and (e) fundamental I-V TCR characteristics.

3.2.2. Thyristor switched capacitor TSC

The basic shunt phase angle controlled TSC is shown in figure 3, where the thyristors are usually operated either continuously conducting or off. Normally capacitor banks are switched in parallel to give line susceptance discrete level adjustment, since phase angle control is not possible because of the uncontrolled capacitive turn-on currents that would result. Beneficially, no harmonics are produced with continuous thyristor conduction. Transformer coupling can be used for voltage matching, the leakage inductance of which helps control the initial current inrush. The capacitive VAr produced is determined by the capacitive current and the resultant system midpoint voltage, V_M:

$$I = \frac{V_M}{X_c} = \omega C V_M$$

$$VAr = Q_p = V_M I = -\omega C V_M^2$$

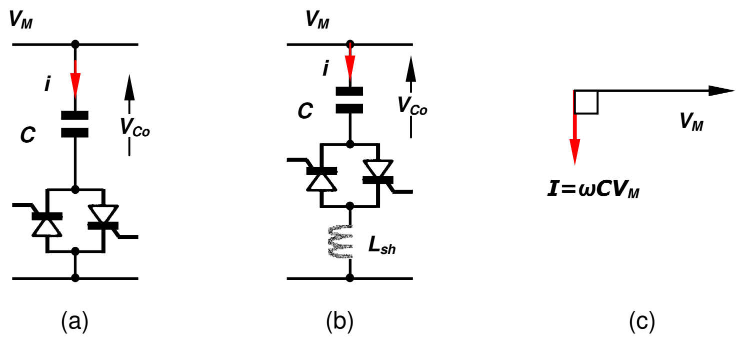


Fig. 3: Thyristor switched capacitor compensation: (a) ideal capacitor TSC compensator; (b) capacitor TSC compensator with line/leakage inductance; and (c) I-V TSC characteristics.

3.2.3. Shunt Static VAr Compensator SVC (TCR//TSC)

A static VAr compensator is comprised of a thyristor controlled reactor compensator and a thyristor switched capacitor compensator as shown in figure 4. The leading reactive power is provided in discrete equal steps (or 2^n steps) by banks of thyristor switched capacitor compensators (TSC) and precise continuous VAr adjustment is affected by a thyristor controlled reactor compensator (TCR). The maximum lagging current from the TCR is equal to the incremental capacitive leading current, such that the two can cancel to zero giving zero net reactive VA. As the phase angle of the TCR is increased, the net leading VAr increases. At zero TCR conduction, a capacitive bank is decremented and the TCR starts with full conduction, that is zero delay angle.

Ideally, no active power is drawn from the system and the reactive power depends on the net fundamental impedance of the parallel capacitor-reactance combination, which is TCR delay angle dependent.

$$P_{SVC} = 0$$
$$Q_{SVC} = -\frac{V_M^2}{X_{SVC}}$$

The SVC is usually transformer coupled for voltage matching of the thyristors. The compensator bus usually incorporates permanent LC notch filters to minimise the injection of 5th and 7th order harmonics, produced by the TCR, back into the HV system.

An alternative to the SVC is the shunt voltage source converter, called static synchronous compensator (STATCOM).

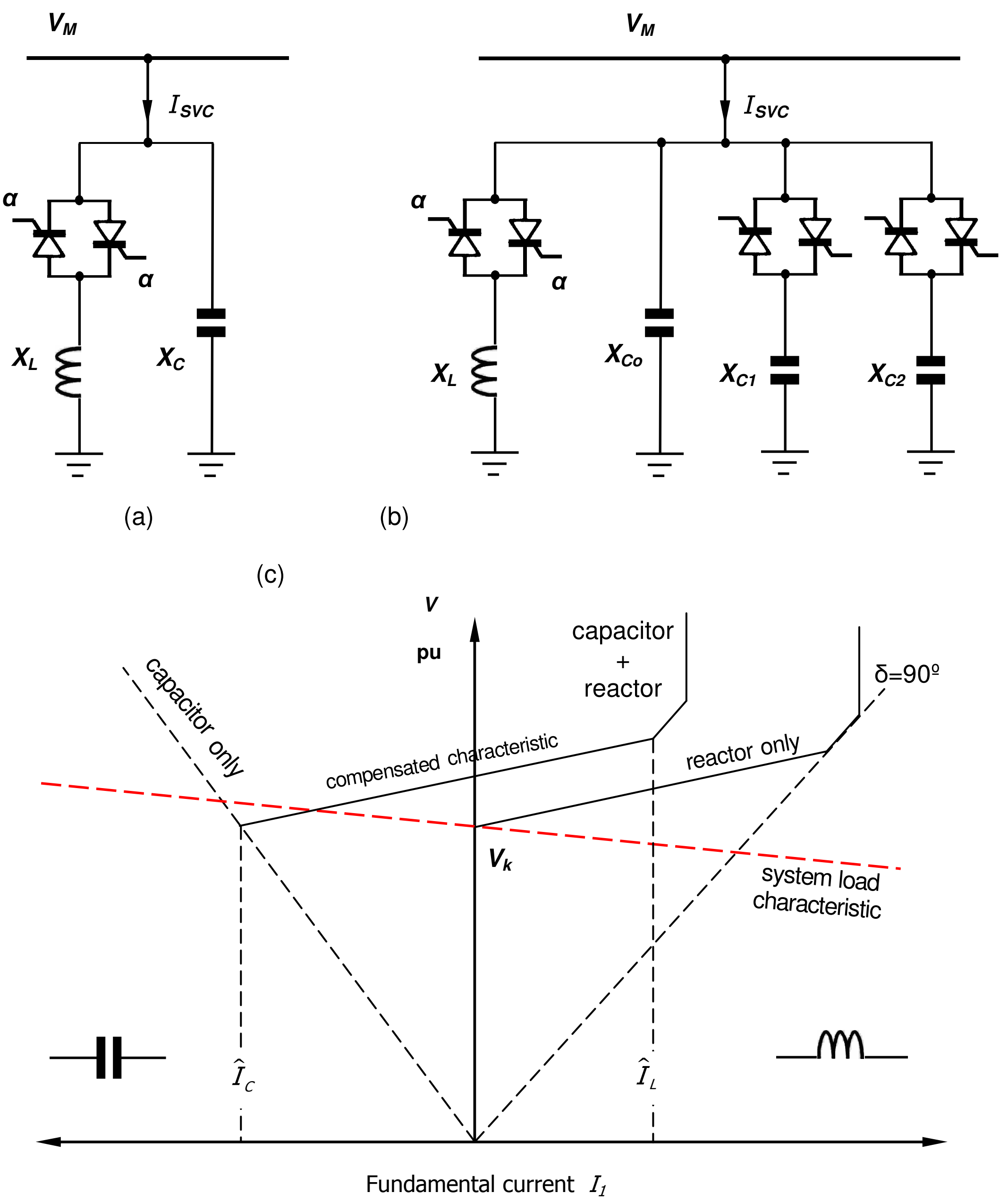


Fig. 4: Static VAr compensator (SVC):
(a) basic SVC; (b) SVC with capacitor banks; and (c) I-V SVC characteristics.

3.2.4. Static Series Reactive Power Compensation

Transmission line capability can be increased by installing series compensation in order to reduce the transmission line net series reactance. Line impedance will tend be dominated by inductive components. The insertion of additional inductance decreases transmission capability, and may be used to limit fault levels or divert power flow. The insertion of additional series capacitance will act to cancel the inductive voltage drop, reducing net line impedance and increasing power flows:

- increases power flow capability and stability margins;
- reduces the transmission load angle;
- increases the virtual load; and
- provides a means of damping power oscillations.

Normally, series compensation is capacitive. Since distributed compensation along the line is impractical, as with shunt compensation, series compensation is normally inserted at the reactance midpoint. Series compensation is normally only used on very long ac transmission lines, thereby making long distance ac transmission viable.

Principle of series compensation

The ideal series compensator is effectively pure reactance, without any power loss. The ideal series line compensation of a transmission line is shown in figure 5, where the compensator voltage is at quadrature to the line current

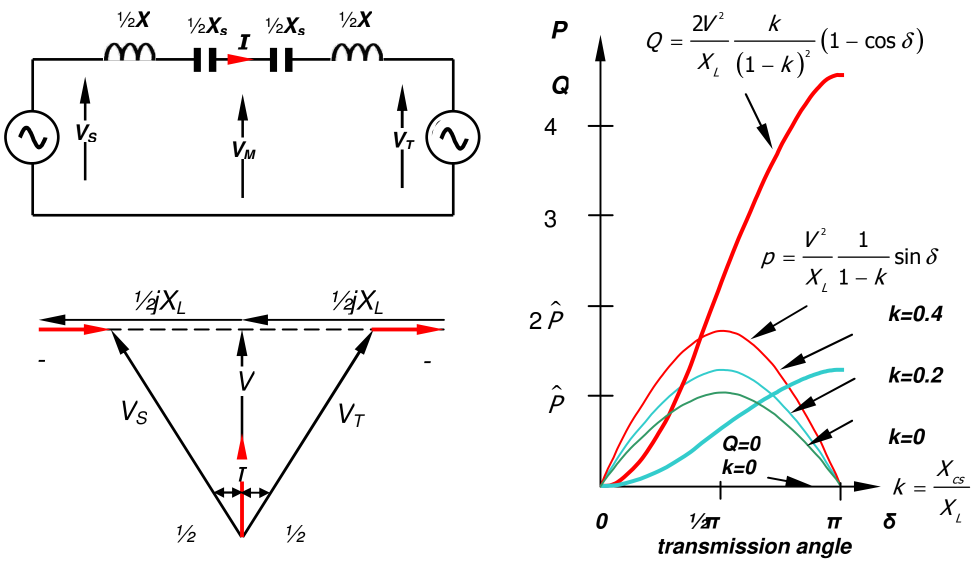


Fig. 5: Midpoint static series compensation: (a) two source power system model; (b) phasor diagram for | Vs | = | VT | = V; and (c) power versus load angle

3.2.5. Thyristor switched series capacitor TSSC

A thyristor switched series capacitor compensator TSSC consists of a least one series capacitor, each shunted by a back-to-back pair of anti-parallel connected phase control thyristors, as shown in figure 6. Thyristors may be continuously triggered to provide a path for the line current to by-pass the series compensating capacitors. When the thyristor trigger is removed natural turn-off commutation occurs at the subsequently line current reversal. With this commutation process, the series capacitor charges with a dc bias as shown in figure 6b. Subsequent thyristor turn-on should only occur at the line zero current points in order to avoid high initial anode *di/dt* currents.

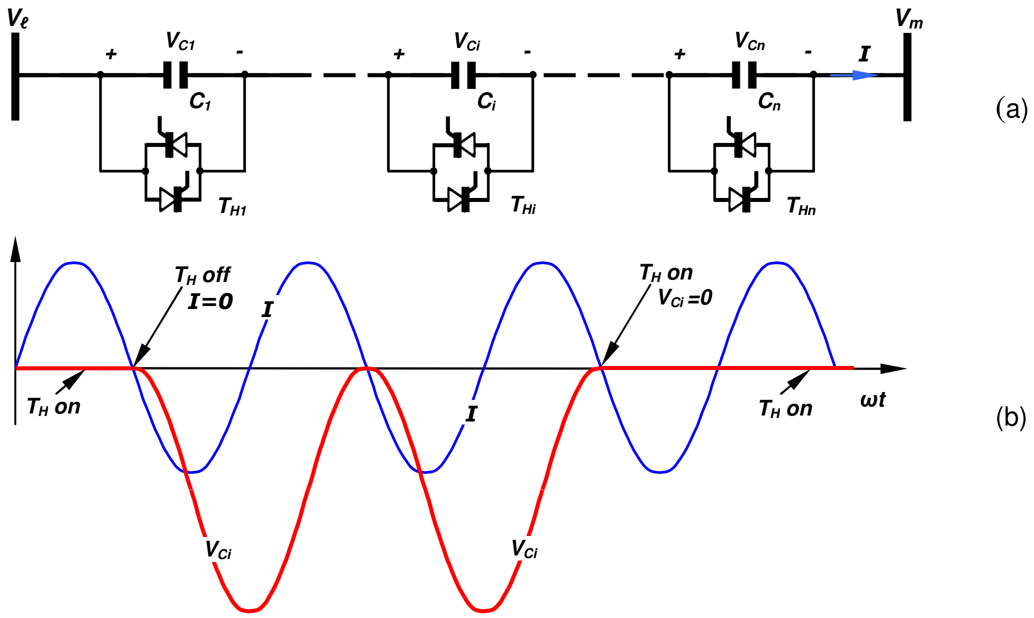


Fig. 6: Thyristor switched series capacitor compensation TSSC:
(a) series connected capacitors and (b) zero current activation and zero voltage deactivation

3.2.6. Thyristor controlled series capacitor TCSC

Better capacitor series voltage control is obtained if the thyristors in figure 6a are self-commutated, such as with symmetrical voltage blocking Insulated Gate Commutated Thyristors (IGCT). This series TCSC compensator is the dual to the shunt TSR in figure 3.

- Instead of thyristors in series with inductance, thyristors are in parallel with capacitance.
- Instead of unidirectional voltage blocking, naturally commutating switches, the capacitive series compensator uses bidirectional voltage blocking, self-commutatable switches.
- In the series compensator, compensation occurs when the series thyristors are on, while compensation is active in the series compensator case when the parallel IGC thyristors are off.
- The shunt compensator supports a sinusoidal voltage and produces current harmonics, while the series compensator conducts the sinusoidal line current and produces voltage harmonics.

Typical series TCSC waveforms are shown in figure 7c, while the harmonics produced are shown in figure 7d. It will be noted that the same equations as in section 2.2.4i for the TCR hold, except that voltages and currents are interchanged, and capacitive reactance is used instead of inductive reactance.

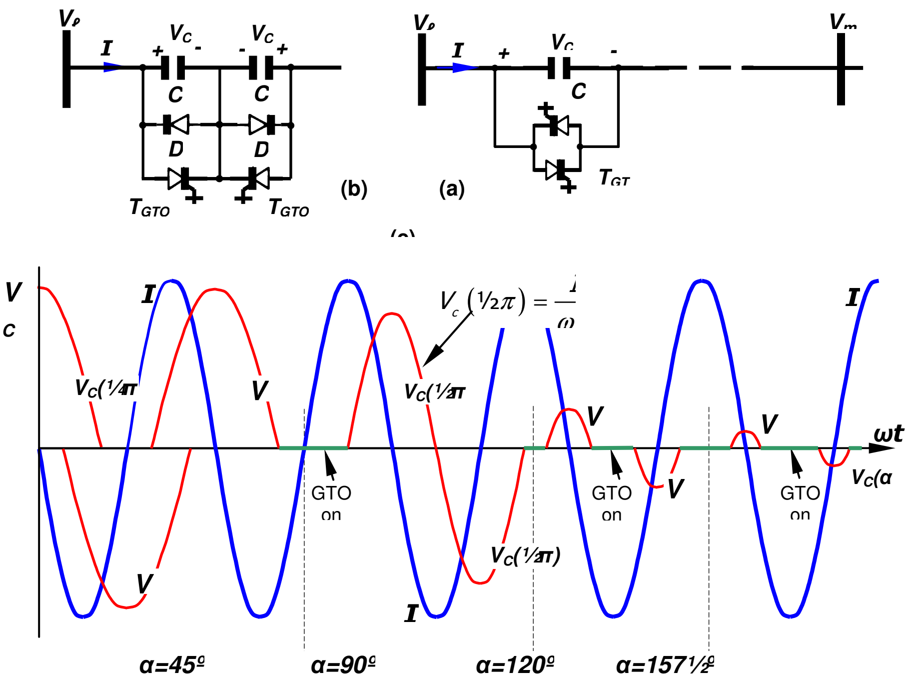


Fig. 7: Thyristor controlled series capacitor compensation TCSC:
(a) series connected capacitors with shunt self-commutable GTOs for α≥90° and (b) for α≥0° and
(c) line current and current waveforms for delay angles α=45°, 90°, 120° and 157½°.

3.2.7. Series Static VAr compensator SVC (TCR//C)

The TCR//C consists of a line series compensating capacitor in parallel with a thyristor controlled reactor (TCR), as shown in figure 8. By varying the delay angle of the TCR thyristors, the capacitive reactance can be decreased, since the fundamental reactance of the parallel combination is given by

$$X_{eff}(\alpha) = \frac{X_C X_{L1}(\alpha)}{X_C - X_{L1}(\alpha)}$$

The reactance at the fundamental frequency is

$$X_{L1}(\alpha) = \frac{½\pi}{½\sin 2\alpha + \pi - \alpha} X_L \qquad \text{where} \quad X_L = \omega L$$

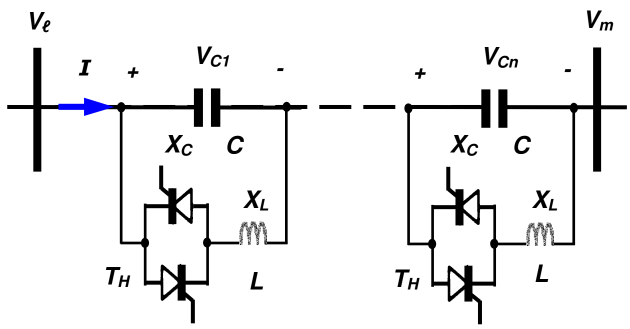


Fig. 8: Thyristor controlled reactance and series connected capacitance, SVC compensation.

The voltage harmonics produced by the reactor tend to be trapped in the parallel connected capacitor due to its low capacitive reactance X_C which is inversely proportion to harmonic frequency (relative to line reactance X_s which increases proportional to harmonic frequency).

Accounting for the line reactance X_s and compensator fundamental reactance X_{eff}, the active and sending reactive powers are given by:

$$P_T = \frac{V_S V_T}{X_L + X_{eff}} \sin(\delta_S - \delta_T)$$

$$Q_S = V_S \times \frac{V_S - V_T \cos(\delta_S - \delta_T)}{X_L + X_{eff}}$$

The signs in these equations are appropriately changed for capacitive operation.

3.2.8. Thyristor Controlled Phase Shift Series Compensator (The quadrature boost phase shift compensator)

The tap controlled phase shifting transformer may be extended by the use of a thristor controlled secondary. The configuration shown in figure 9a uses a delta connect line transformer to feed a naturally commutating thyristor tap changing circuit which transfers power to the line through the series line transformer. The transformer phase arrangement ensures that the series injected voltage is always at quadrature to the line voltage. Since the effective line voltage $V_{S\ eff}$ is now greater than the line sending voltage V_S, as shown in the phasor diagram in figure 9b, the converter forms a quadrature boost compensator. The tap changer is not reversible, that is, power can only flow from the shunt excitation transformer to the series compensating transformer in the transmission line.

The series compensator can be controlled in two ways:

- Phase angle control of the thyristors in one bridge
- Fewer harmonics are generated by either switching in or out the different excitation windings shown in figure 9a, which gives 27 different output voltage possibilities.

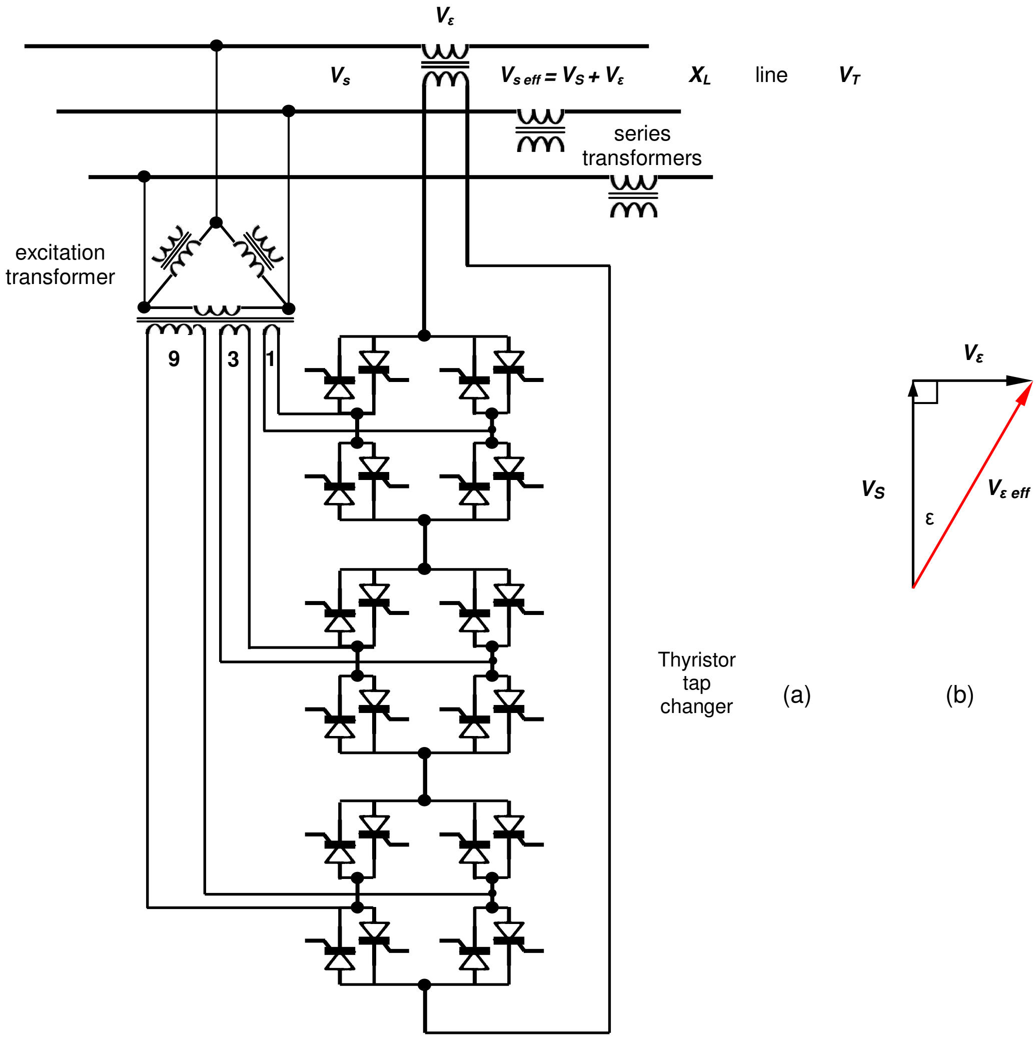


Fig. 9: Series phase angle compensator with quadrature boosting: (a) thyristor transformer tap changer and (b) phasor diagram for phase shift ±ε giving quadrature boosting, $\Phi=\frac{1}{2}\pi$.

3.3. Self Commutating FACTS Devices

Thyristor based FACTS compensators are based on the more robust but slower line commutated technology. Whilst the high device rating and overload capability makes thyristors well suited to transmission applications, the slow switching frequency incurs significant limitations:

- Large values of inductance/capacitance are required in order to inject the necessary fundamental reactive power into the network. This results in physically large installations.
- High levels of low order harmonics may be injected into the network. This requires the installation of passive harmonic filters. These filters result in additional size and may lead to circulating harmonic currents due to interaction with other non linear loads. Damping networks for the filters may require matching to particular locations and may not achieve optimal performance over the full set of operating conditions.

Self commutated converter systems allow the use of pulse width modulation (PWM) to inject controlled voltage or current into the power network. Representative single phase circuits for these devices are shown in figure 10. The systems are based on less robust (but faster responding) devices (IGCT thyristor and IGBT), and have historically been deployed at lower voltage levels where more sensitive equipment and embedded generation may be connected. Recent advances in voltage source inverter technology have made self commutated FACTS systems viable for transmission applications.

Self Commutating FACTS devices include the dynamic voltage restorer - DVR, shunt compensator - STATCOM, and the unified power flow controller - UPFC. They are based on high voltage IGBT, IGCT PWM inverter/converter bridge topologies which use a dc link reactance (a dc-side capacitor or a dc-side inductor) to act as an intermediate energy store.

The use of PWM modulation allows high levels of control of the VArs injected at the point of common coupling (PCC). The high switching frequency (in addition to minimising its own low order harmonics) may provide active filters functionality and compensate low order harmonics from other installations.

Active (self-commutating IGCT Thyristor and IGBT) inverter based topologies provide compensation for:

- Voltage and current harmonics
- Reactive power
- Neutral current
- Unbalanced loads
- Unbalanced phase voltages

The PWM inverter approach adopted can be:

- Inductive dc-link, current source PWM inverter, CSI, which acts as a controllable sinusoidal current source to compensate for non-linear load harmonics.
  - requires ac output shunt capacitance to filter current harmonics from the generated square-wave current waveform
  - self-supporting, large dc-link reactor
  - high reliability
- Capacitive dc-link, voltage source PWM converter, VSC, which acts as a controllable sinusoidal voltage source
  - requires output series inductance to filter voltage harmonics from the generated square-wave voltage waveform
  - self-supporting, large dc-link capacitor
  - applicable to multilevel inverter topologies for better system voltage

matching

The CSI or VSC inverter based compensators can be connected to the system, usually through voltage matching transformers (where in the case of the VSC, the transformer leakage inductance may provide voltage output harmonic filtering), in any of three ways, as shown in figure 10.

- Series inverter compensator – called a dynamic voltage restorer, DVR – compensating for:
  - Line voltage harmonics
  - Notches and sags and swells
  - Balance and regulate load or line terminal voltage
  - Static VAr generator to stabilise and improve voltage profile
- Shunt inverter compensator – called a STATCOM – compensating for:
  - Line current harmonics
  - Reactive power compensation
  - Balancing of three-phase loads
- Series plus shunt inverters/converters – called a unified power flow controller, UPFC
  - Performs the functions of both the shunt and series compensators
  - Two inverters share a common dc current or voltage link

Each of these three compensators belongs to the generic family of static synchronous compensators.

The classification matrix for custom power devices is shown in figure 10. For ease of comparison and understanding, single-phase versions are show, with specific three-phase configurations considered in the sections to follow. Three-wire (floating neutral) and four-wire (connected neutral) PWM inverter topologies are extensions to the basic single-phase topologies considered.
Given the switching frequency limitations of 6.5kV IGBT and IGCThyristor technology (<1 kHz), synchronous selective harmonic elimination SHE is used for switching modulation rather than standard pulse width modulation (PWM) or space vector modulation (SVM). (SVM tends not to used since its derivation assumes three symmetrical balanced phases.) If transformer coupling is adopted, low-voltage IGBTs (3.3kV) allow a higher switching frequency (2.5kHz). The trade-off is that the transformer core must transmit with minimal attenuation, the highest required compensation harmonic. Thinner transformer laminations (0.1mm and 0.05mm, as opposed to 0.3mm for 50/60Hz) allow a higher operating frequency, but at the expense of reduced flux density and higher core losses/kg. The best trade-off is 0.1 mm lamination thickness

compensating for harmonics up to and including the 17th and 19th. Higher harmonics (the 23rd, 25th and higher) are more effectively attenuated with passive *L-C* notch (with long term drift problems) and low pass filters. When only harmonic distortion correction is required, as opposed to any 50/60Hz VAr compensation, nano-crystalline amorphous core materials are an effective alternative the silicon grain orientated steels.

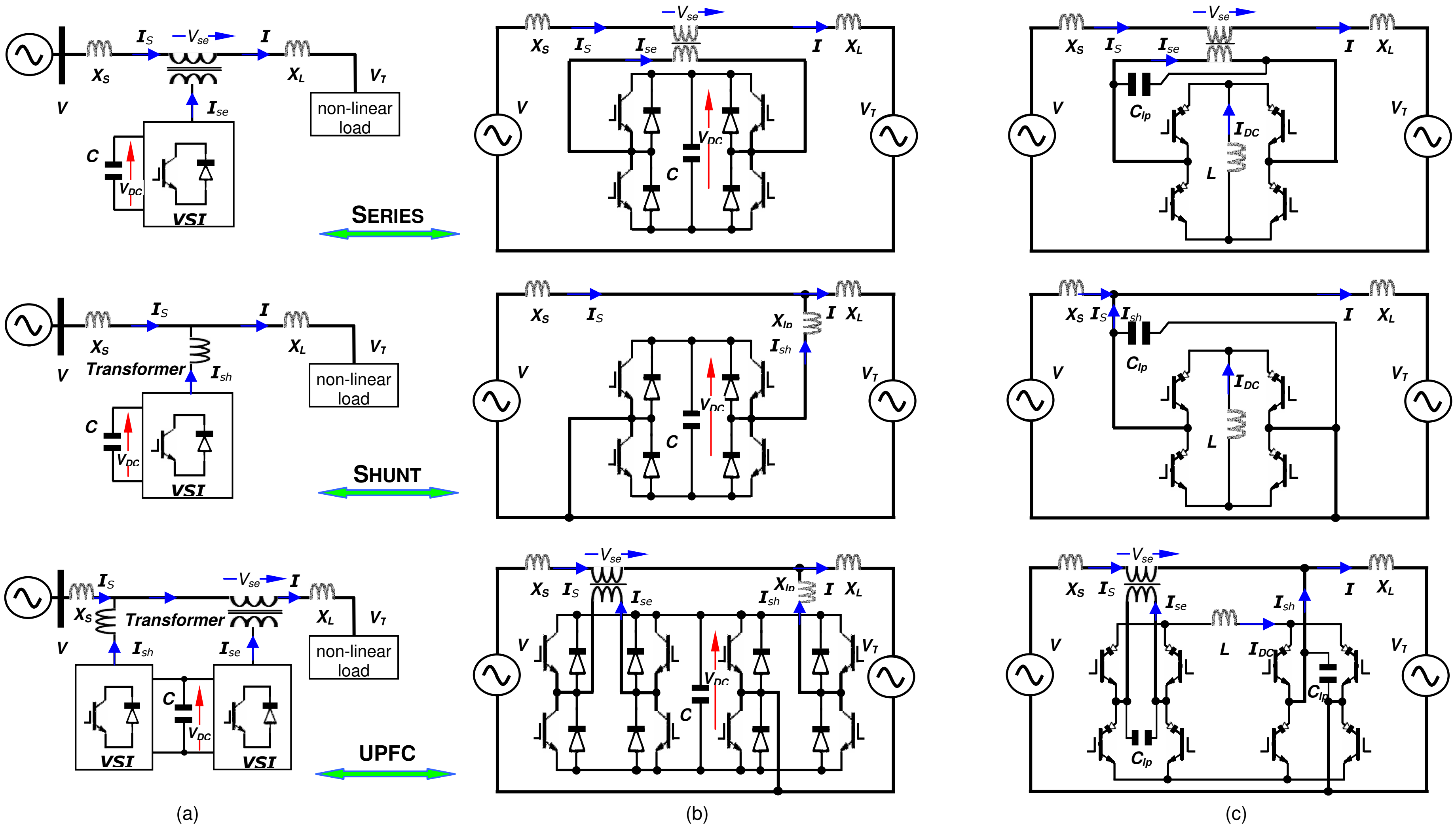


Fig. 10: Static synchronous compensator family: (a) transmission schematic of voltage source compensators (as power filters) transformer coupled to the ac network; (b) single-phase static synchronous compensators using dc-link capacitor voltage sources; and (c) static synchronous compensators using dc-link inductor current sources.

3.3.1. Static synchronous series compensator or Dynamic Voltage Restorer - DVR

The static synchronous series compensator (dynamic voltage restorer) DVR is a transformer coupled, PWM voltage source inverter that functions in series with the distribution line as shown in figure 11. Theoretically, it draws no power from the line since it uses a capacitor on its dc link which provides only reactive power. This makes the DVR a versatile regulating compensator. In steady-state it functions as a series phase shifter SPS, injecting a variable magnitude and angle voltage at one line end in order to control both the active and reactive power flow. The phase angle (which controls the real power if a suitable bidirectional dc-link source exits) is controllable between 0 and 2π, as shown in the phasor diagram in figure 11. The magnitude of $\boldsymbol{V_{DVR}}$ is controlled by the inverter PWM modulation depth.

In general:

$$\begin{aligned} V_{DVR} &= V_T - V_S \\ &= \left|V_{DVR}\right|(\cos\varphi + j\sin\varphi) = V_d + jV_q \end{aligned}$$

If the DVR does not involve any active power source and the only real power drawn from the ac line is that necessary to maintain the capacitor voltage so as to compensate for inverter and coupling transformer power losses, then V_d = 0 and V_q is in quadrature to the compensator line current. By varying the magnitude of V_q, the DVR performs the function of a variable reactance compensator, where

$$V_d \approx 0$$

$$\text{if } \begin{cases} V_q > 0 \text{ the DVR is capacitive} \\ V_q < 0 \text{ the DVR is inductive} \end{cases}$$

Within its energy limits, the DVR is suited for dynamically compensating any line feeding sensitive or critical equipment for:

- voltage harmonics
- power factor correction

and for a short duration:

- voltage sags and swells
- voltage imbalances
- outages

In the standby mode, the output voltage is zero and the inverter losses are low since no switching occurs. By turning on all the upper (or lower but not both) switches in the VSI inverter, the three single-phase transformers and inverter are seen in the line as a short circuit (as for a current transformer). Given a transformer connection, voltage matching of the VSI devices facilitates the use of standard IGBT technology that allows modulation frequencies above 2kHz, which is necessary for active filtering. Specific single-phase transformer coupling can be avoided if the DVR is connected at the opened star point of the main ac supply Y configured transformer or autotransformer. Alternatively, access to the transformer star point allows the use of a three-phase autotransformer rather than three single-phase transformers. A CSI is well suited for series application (with an outer voltage loop) since it is normally operated with the switches in an on-state, thereby ensuring that the DVR is seen as a short-circuit in the standby/fault mode.

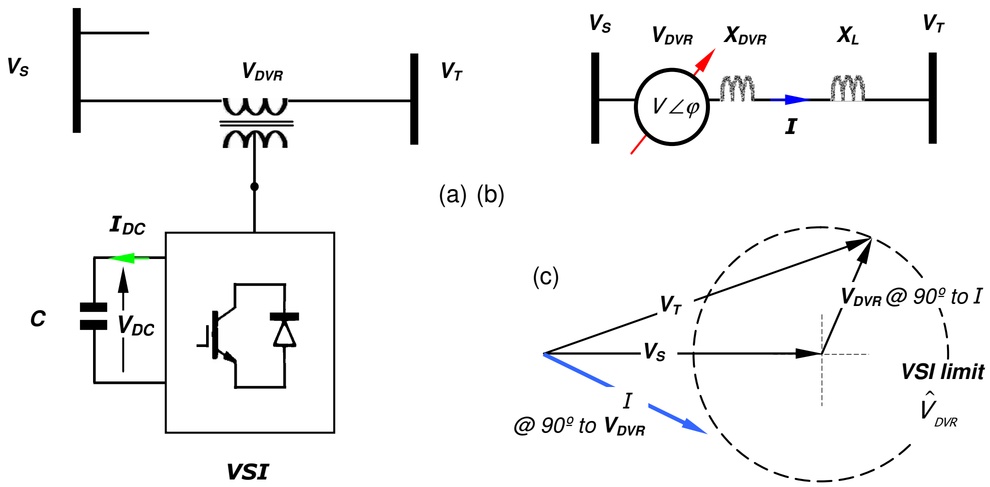


Fig. 11: . Static synchronous series compensator or dynamic voltage restorer DVR:
(a) schematic of a voltage source inverter, transformer coupled in series with the ac network;
(b) series connected DVR shown as a variable magnitude and phase angle voltage source; and
(c) 50/60Hz operating phasor diagram, where V_{DVR} is always perpendicular to the line current, I.

3.3.1.1 Series Voltage Regulation

The terminal voltage V_T in figure 12 draws a lagging current I_T and the series compensator V_{DVR} is to maintain the load voltage V_T constant, but at any angle with respect to V_S. From Kirchhoff's voltage law

$$V_S = jI_T X_R + V_{DVR} + V_T$$

The series compensator can deliver any voltage up to the maximum shown by the circle outer locus with centre O, for the series regulator in figure 12. If V_T is held constant then the source V_S can have a magnitude and angle that lies anywhere within the circle. If V_T sags and swells (changes length) then provided the variation is within the circle, V_{DVR} can compensate to maintain a constant voltage V_S. Maximum and minimum voltage compensation needed from V_{DVR} occurs when the source V_S forms a tangent to the circle as shown. In each case the current is not in phase with the compensation voltage, hence the compensating converter must transfer real power. The effective sending voltage $V_{S\,eff}$ is phasor N-O. The phasor O-W represents the case when power is delivered from the compensator in an effort to compensate for the sagging (reduced) V_T voltage phasor N-W, while the phasor O-X represents the case when V_T has swelled to phasor N-X and power is drawn by the compensating converter whilst attempting to decrease the line voltage. The inverter in figure 11 creating V_{DVR} must have a bidirectional dc voltage supply maintaining the dc-link voltage.

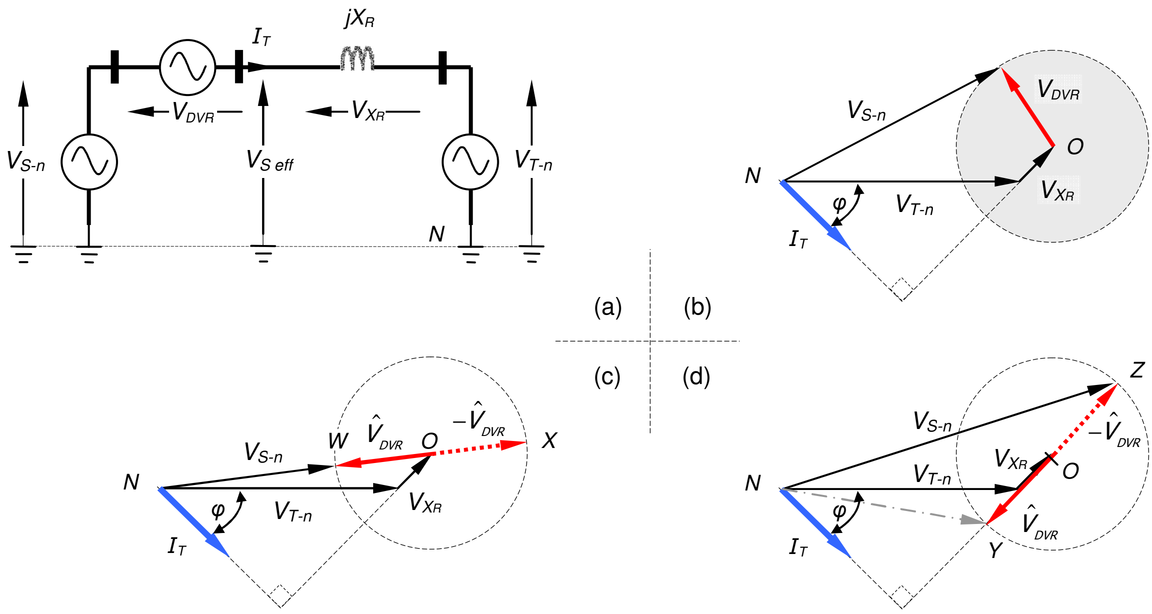


Fig. 12: Static series voltage compensation:
(a) series compensated network; (b) general series voltage compensation; (c) voltage sag and swell real-power compensation; and (d) quadrature reactive-power series voltage compensation.

The converter dc-link voltage can be self-supporting if no energy is lost or gained by the dc-link when the line current is at quadrature to the compensator voltage, as shown in figure 11. In this case, the source voltage V_T can be compensated when its voltage phasor lies along the line W-O-X. The magnitude range of the voltage V_T that can be compensated, is reduced.

The series compensation is effective for a wide range of line impedances, including low impedance stiff feeders, provided the line impedance phasor is within the compensating circle. The basic series converter arrangement can also be using for voltage distortion compensation.

3.3.2. Static synchronous shunt compensator - STATCOM

The STATCOM (***stat***ic synchronous shunt **com**pensator) is a shunt compensator comprising a current or voltage source converter, shunt connected to the ac system through a first order passive filter, as shown in figure 13.

The STATCOM function is to:

- Regulate the line at the point of connection when functioning in a SVC mode and/or
- Minimizes current harmonics by anti-phase current injection action – as an active filter.

Whist current STATCOM systems based on CSI topologies are feasible, the VSI is widely used for practical STATCOM systems. For a VSI based STATCOM, the dc reactive energy storage element is a dc capacitor in which case the interconnect filter comprises series line inductance for attenuating VSI output voltage harmonics. Since the STATCOM does not participate in real power exchange, no net energy is needed, except to replace the energy dissipated in the inverter and filter components.

Figure 13 shows the STATCOM system model including the simplified VSI circuit. The series voltage harmonic filtering inductance can be the leakage inductance associated with the three single-phase line voltage matching transformers or three auto-transformers. A dc chopper, with a dumping resistor as load, may be used across the dc-link capacitor to limit VSI over-voltage during intermittent transients when the STATCOM acts as an uncontrolled rectifier, created by the VSI freewheel diodes. The phasor diagram in figure 13, for the line to neutral voltage, illustrates the STATCOM operating principles.

$$P = \frac{V_{SC} V_T}{X_{SC}} \sin(\delta_T - \delta_{SC}) = 0$$

$$Q_{SC} = V_T \times \frac{V_T - V_{SC} \cos(\delta_T - \delta_{SC})}{X_{SC}} = \frac{V_T}{X_{SC}}(V_T - V_{SC})$$

$$I_{sc} = \frac{V_{T-n} - V_{sc-n}}{X_{sc}}$$

By controlling the inverter voltage, the STATCOM may behave like a shunt inductor (*I* lags V) without a physical inductor or magnetic field, and like a shunt capacitor (*I* leads V) without a physical capacitor or electric field.
Since the STATCOM does not process real power, no voltage energy source is required for the inverter. The dc link capacitor is initially charged through the VSI freewheel diodes which form an uncontrolled three-phase line rectifier. Subsequently the real power reference of the STATCOM is controlled to self regulate its dc-link voltage. The dc-link voltage will always be greater than the rectified ac grid voltage due to the rectification action through the six inverter bridge freewheel diodes. Since it behaves as a controlled source rather than impedance, the SATCOM can generate more reactive power during a fault than the SVC which is limited by its minimum reactance value.

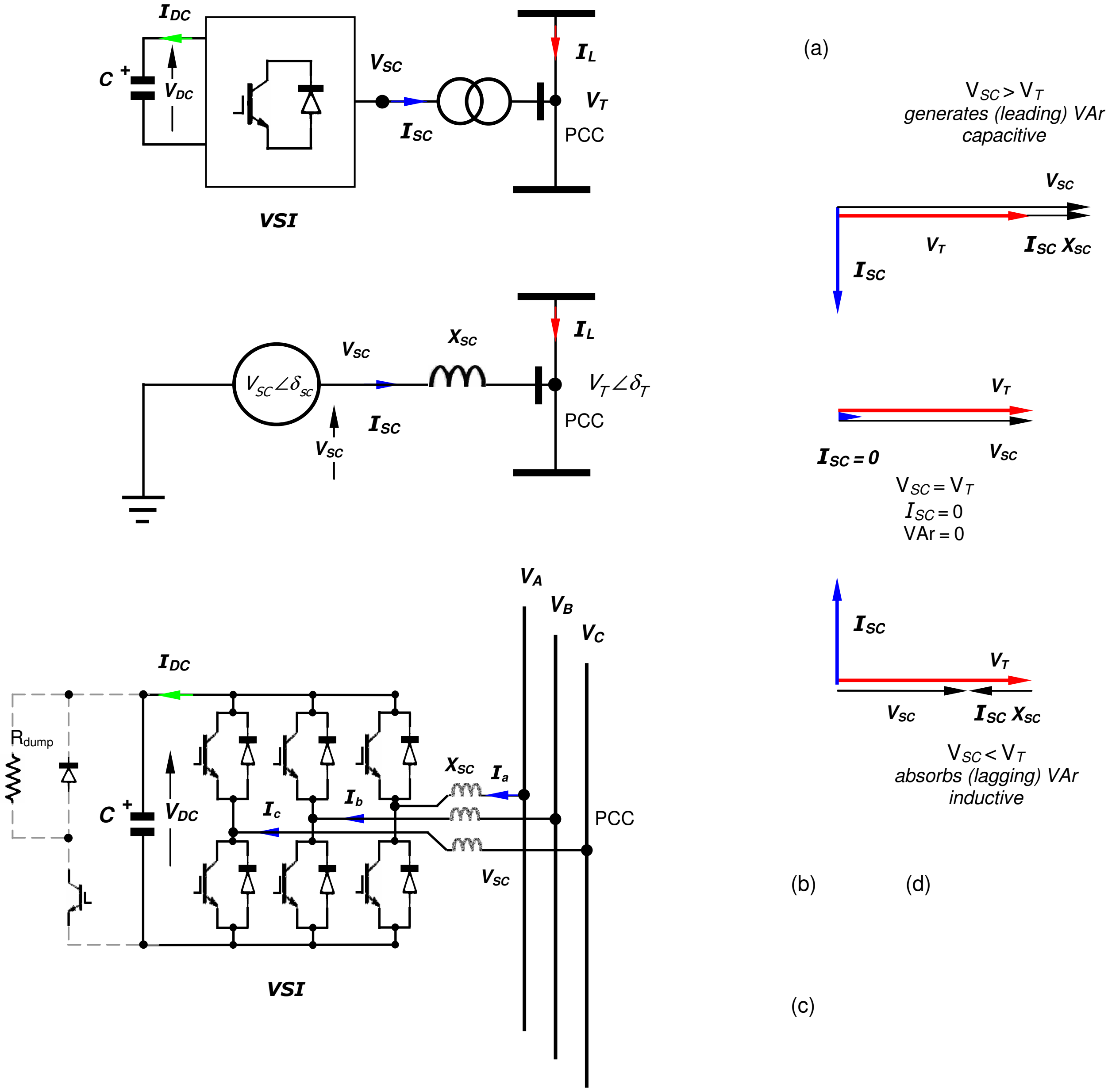


Fig. 13: Active shunt regulator - STATCOM:
(a) a voltage source inverter VSI, inductively shunt connected (transformer coupled) to the ac network; (b) shunt connected STATCOM shown as a variable magnitude and phase angle voltage source; (c) main VSI circuit; and
(d) phasor diagrams for leading (upper phasor diagram) and lagging (lower phasor diagram) modes of operation.

3.3.2.1 Shunt Voltage Regulation

Shunt compensation may also be used to control the voltage seen at the PCC. In this case the STATCOM current may be controlled so as to manage the voltage drop across the network inductance. The shunt compensator operates in a type of current push-pull or sourcing-sinking mode.

- When the source voltage is too high, voltage swell, the shunt draws or sinks current additional to the load current in order to increase the voltage across the line reactance X_R, thereby tending to decrease the load voltage V_T.

- When the source voltage sags, the shunt compensator sources current to the load network, thereby reducing the source current which decreases the voltage across the line reactance X_R, making a higher component of the source voltage available across the load network V_T.

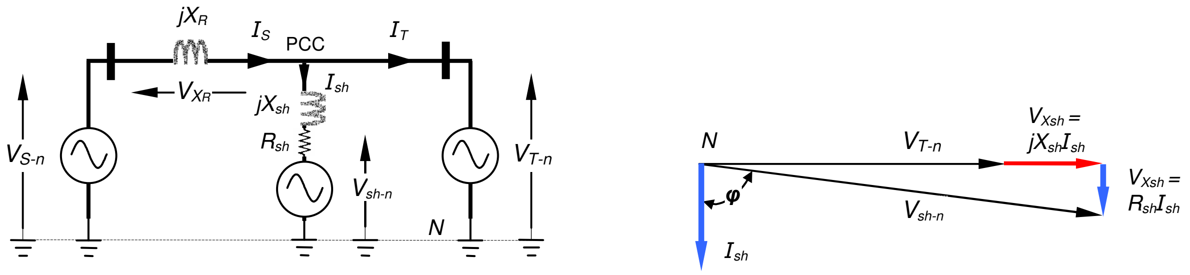


Fig. 14: Active shunt compensator used for power factor correction: (a) shunt compensated network and (b) phasor diagram.

3.3.2.2 Power factor correction

The shunt compensator can be used for power factor correction at the PCC. The compensator current I_{sh} is set to be 90° behind the PCC voltage V_{T-n}, with the magnitude of the current I_{sh} determining the magnitude of the compensation. This is achieved by ensuring that the load voltage and shunt regulator voltage are in phase, but the relative magnitudes are varied ($V_{sh-n} > V_{T-n}$). Since only VAr are involved from the shunt regulator, no shunt regulator dc voltage supply is needed to maintain the dc-link capacitor, except inverter losses must be accounted for. By ensuring the shunt voltage V_{sh-n} slightly lags the line voltage V_{T-n}, the necessary inverter losses can be provided from the grid. If the inverter losses are incorporated, as represented by the resistor in figure 14, then the resultant phasor diagram in figure 14 complies with the following output loop voltage equation.

$$V_{sh-n} = I_{sh}R_{sh} + jX_{sh}I_{sh} + V_{T-n}$$

The reactive power provided to the ac system from the shunt power factor controller is $Q = I_{sh} V_{T-n}$, while $P = V_{sh-n} I_{sh} \cos\varphi$ real power is drawn from the line to cater for the inverter power losses.

Table 1 summarises the different features of the IGBT based static synchronous compensator and thyristor based static VAr compensator, previously discussed.

Table 2: Comparison of STATCOM and SVC

Property	STATCOM	SVC
I-V characteristic	Current source Good under-voltage performance	Impedance source Good overvoltage performance
Control range	Symmetrical Otherwise hybrid solution	Adjustable with cascaded TCR/TSC
Modularity	Redundancy Compensated aging degradation Common inverter to other applications	Redundancy Aging degradation TCR/TSC branches common additions to SVC
Response time	1 to 2 cycles No natural commutation delays. Sub-cycle harmonic filter (APF) response feasible.	2 to 3 cycles Limited by supply frequency
Transient behaviour	Self protecting on critical system faults	Active before, during and after transient conditions
Volume requirements	40% to 50% of SVC	100%
On-line availability	96% to 98% of time	>99% of the time
Capital costs	120% to 150% that of SVC	100%

3.3.3. Unified power flow controller - UPFC

The unified power flow controller shown in figure 15 consists of a shunt and a series static synchronous compensator, where the two compensating inverters are connected back to back, and are decoupled by sharing a common dc link energy storage element (inductor or capacitor). As such, the two converters can operate independently, giving a versatile compensator that can simultaneously perform the function of either or both of the static synchronous series and shunt compensators, namely:

- Active power flow
- Reactive power flow
- Voltage magnitude control
- Voltage harmonic elimination
- Current harmonic elimination
- The shunt compensator provides voltage regulation at the point of connection by injecting reactive power into the line, and
- Balance of the real power exchanged between the two compensators when providing for inverter and transformer losses and any real power transferred by the series compensator.

The series compensator is used to

- Control the real and reactive power by injecting a controllable magnitude and phase compensating voltage in series with the line.

The UPFC thereby fulfils the functions of reactive shunt compensation, active and reactive series compensation, and phase shifting. Additionally, the UPFC can provide transient stability control by suppressing system oscillations.

Because line energy can be transferred readily between both converters in compensating for converter and transformer losses, the dc-link capacitor can be small, yet be maintained at the necessary rated link voltage. A consequence of the back-to-back connection is that the dc-link capacitor decouples the two converters and the shunt and series converter reactive powers can be controlled independently. Both converters can provide reactive power, and power for the series converter can be provided through the shunt converter. Because the series converter can now provide (and absorb) real power, the injected shunt voltage magnitude and relative phase are unrestricted, within the *I-V* limits of the two inverters. This is shown by the circle in the phasor diagram in figure 15, where unlike for the DVR, as shown in the phasor diagram in figure 11c, the line current I_L and the series compensation voltage V_{se} are not restricted to be at quadrature (that is, real power transfer can be involved with UPFC operation).

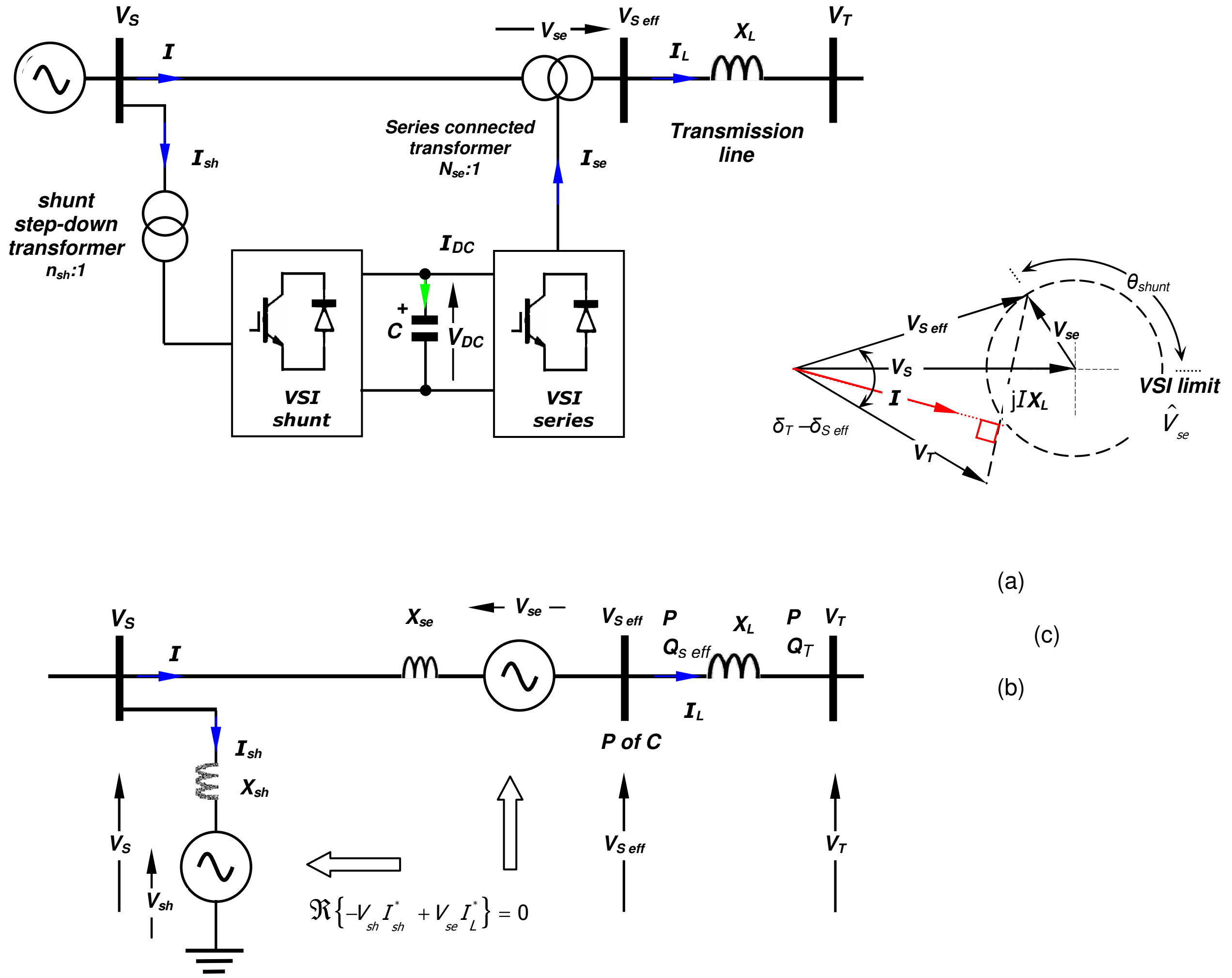


Fig. 15: Unified power flow controller - UPFC:
(a) single line diagram of the UPFC showing decoupled back to back connected inverters and matching transformers; (b) UPFC equivalent circuit; and (c) phasor diagram for system voltages an line current, I_L.

3.3.4. Active Power Filters

At the fundamental frequency, static synchronous compensators (shunt - STATCOM and series - DVR) can be used to manage power flow through the appropriate injection of fundamental current or voltage at the PCC. Because of the modulation employed, these systems are able to control at frequencies above the fundamental and may contribute to harmonic filtering. In the harmonic filtering mode, the compensators basically inject anti-phase current and voltage harmonics. Harmonic cancellation capability is set by the switching frequency (and coupling network) of the converter. The PWM frequency of the compensator inverter must be at least twice that of the highest frequency harmonic to be cancelled.

(a) Current compensation – shunt filtering

As shown in figure 16a, the static synchronous shunt compensator can be used to shunt inject equal but opposite magnitude harmonic compensating currents such that

$$I_S = I_{shunt} + I_L$$

The load current I_L is non-linear, as with rectification for highly inductive loads. The compensator shunt injects a current I_{shunt} such that the supply current I_s is a pure sinusoid at the fundamental frequency. The sending voltage source V_L sees the transmission system as a purely resistive load, if STATCOM normal VAr compensation is also operational.

Additional passive filtering may be necessary to prevent PWM carrier components from being injected into the ac system and to eliminate high order components beyond the bandwidth of the APF. These filters will have a cut off frequency significantly above that need for mains harmonic filtering, resulting in reduced size and reduced possibility of resonant effects.

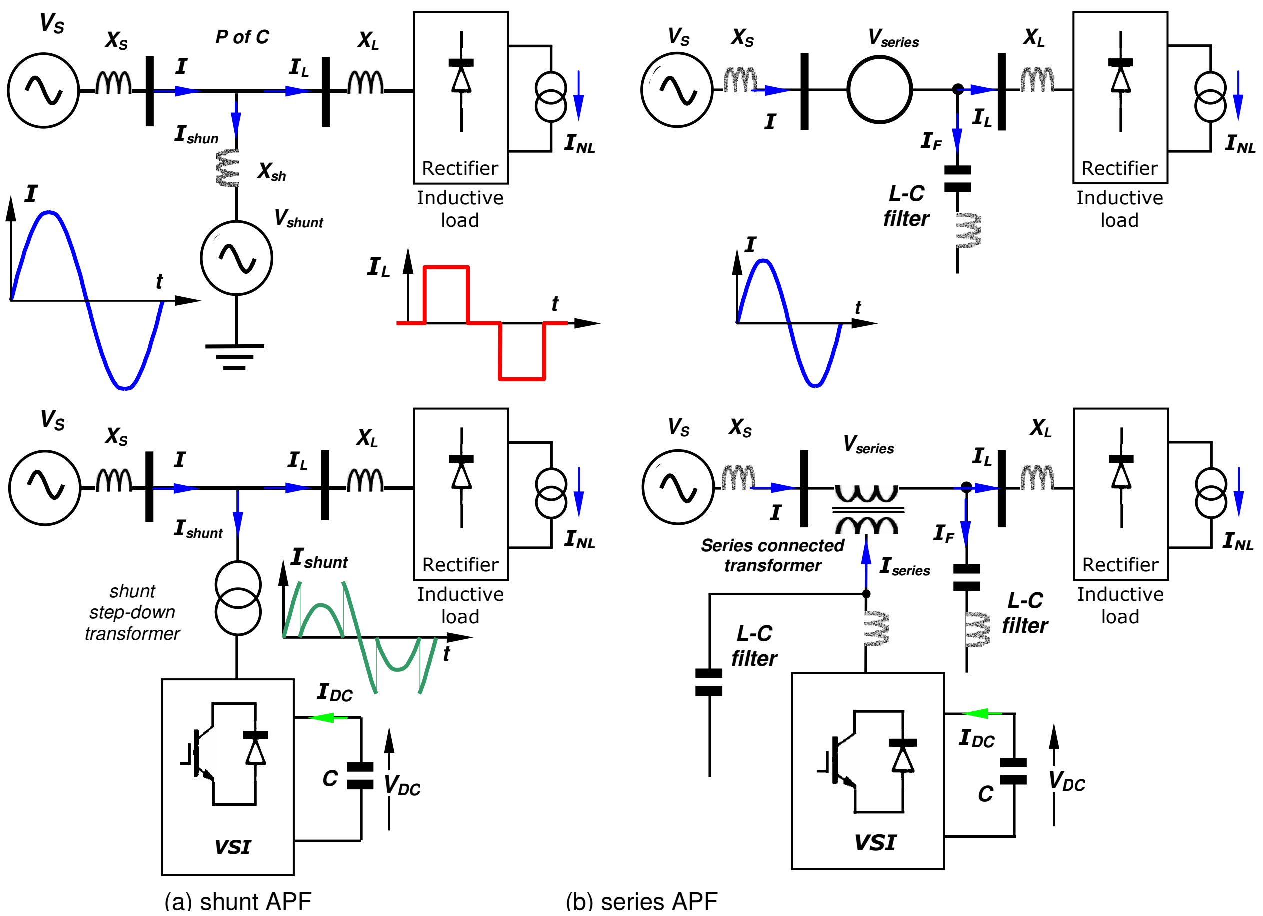


Fig. 16: Combined active and passive filters:
(a) transformer voltage matched shunt APF and (b) transformer voltage matched series APF

(b) Series filtering

As shown in figure 16b, the static synchronous series compensator can be used to series inject equal but opposite magnitude harmonic compensating voltages on the line such that

$$V_S = V_{series} + V_L$$

The load current I_L and voltage V_L are both non-linear, since the non-linear current associated with the rectification of highly inductive loads produces non-sinusoidal voltages across the series line inductance, normally around the peaks and troughs of the three-phase sine-waves. The compensator series injects a voltage V_{series} such that the sinusoidal supply voltage V_s delivers a more sinusoidal current into the transmission line. Since the loads still draws a non-linear current, passive notch-shunt and high-pass shunt second order *L*-*C* filtering are needed to provide a bypass path for the current harmonics. The series compensator output is second order *L*-*C* low pass filtered to prevent PWM carrier components from being injected into the ac system.

3.4 Distributed FACTS Devices

The use of multiple, dispersed, low capacity FACTS devices to control power flows has been proposed as an alternative to conventional concentrated systems. These distributed devices employ similar topologies to conventional FACTS, however the proposed ratings are several orders of magnitude lower (10kVA). Units may be made self powering and physically light, making for easy installation. Increased levels of compensation may be achieved by deploying many such devices, whose action may be coordinated through the use of distributed communications and control techniques. Advantages claimed for distributed FACTS devices include [23-27]:

- The modular structure can limit the impact of component failure leading to improved reliability.
- Individual FACTS modules may be designed around conventional, low voltage power electronics.
- Large scale use of identical modules will result in cost reduction similar to that seen in the variable speed drives sector.
- The approach is compatible with incremental modification of the power system.

Initial research focused on low capacity series compensation devices for the purpose of balancing power flows in meshed/interconnected networks. In such systems, relatively small injection of series reactive power can achieve useful redistribution of line currents. These units were designed to be directly coupled to the power line via a clip on transformer. This transformer provides a means of injecting compensation and providing unit power supplies. The device is designed to be self contained and light enough to be supported by the power lines. [23,24,27] More recently there have been proposals to implement more complex distributed FACTS architectures including Unified Power Flow Controllers. UPF operation requires energy transfer between the series and shunt compensators which presents challenges for distributed modules architectures. [26] Distributed FACTS devices remain largely at the research and development phase, with some reports of prototype and demonstration projects [27].

The fundamental function of distributed FACTS is the same as that of conventional FACTS. The argument for distributed FACTS is strongest for systems requiring low levels of compensation or where the exact positioning of compensation is important. Typically this would apply to highly interconnected systems where small FACTS devices may be used to balance power flows and optimise thermal capacities. The use of FACTS to mange bulk transmission may require devices with significant reactive power capacity. In such circumstances the use of the distributed FACTS approach becomes debateable since a large number of devices must be deployed to match the capacity of a single conventional installation.

4. High-Voltage DC Transmission (HVDC) Technologies

4.1. Introduction

The AC system has proven effective in generation, distribution and transmission of electrical energy. However, there are some performance limitations to the basic AC system, such as, transmission over long distances using overhead lines and cables, connection of AC systems with different frequencies, and input of additional power at the point in the AC network with high fault levels. These tasks can be performed economically and effectively using HVDC technology. The choice between a high voltage AC and DC transmission system is usually made based on economical and technical factors such as, transmission distance and medium (overhead line or cable), and fault levels and purpose of the line [28]-[34]. Fig. 17 shows the economic related choice between AC and DC transmission systems. The exact breakeven distance will vary according to project specific factors. For overhead line systems, breakeven distances in the region of 600-800km are typical, excluding the cost of compensation equipment. For submarine cables, increased AC losses give breakeven distances in the region 50km-100km (this distance may vary with voltage, power rating and type of HVDC technology employed). As a result, HVDC remains the only feasible solution in cases where the transmission line crosses the sea with a distance of more than 50km [28]-[31]. Another significant advantage of HVDC transmission is, it can carry 2 to 3 times the capacity of an AC line of similar voltage [34], [35]. The HVDC link between Xiangjiaba and Shanghai is the largest DC overhead line in the world, with a capacity of 6400MW at a ±800kV DC link voltage [33]- [37].

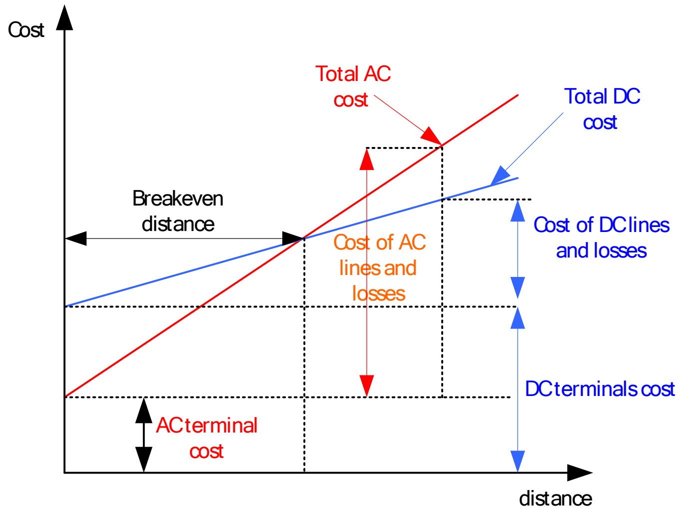


Fig. 17: HVAC and HVDC transmission cost versus distance

The technical aspects that may dictate the technology choice are [28], [38]-[40]:

- In environments that necessitate the use of underground or submarine cable to transfer the electrical energy over long distances, an AC transmission system cannot be used because of the high stray capacitance of the AC cable. This capacitance causes large charging currents along the line in addition to the useful load current. This reduces the line load carrying capability and increases the I^2R losses. Also, the AC cable transmission system requires complex and expensive reactive power compensation at both ends of the line to avoid over-voltage problems. This significantly increases the overall cost of the line.
- AC transmission systems do not allow the input of additional power at any point in the AC network with a low short circuit ratio, without causing power and voltage stability problems. Such connection changes the fault level and increases the rating of the switch gear at the connection point (adding cost).
- Two networks connected using an AC transmission system require synchronous connection. Because of synchronisation, a fault in part of the network affects the whole system. This increases the risk of blackout and other stability problems as each network loses autonomy.

The high-voltage DC (HVDC) transmission systems can be used as a complement, or the only alternative in some cases, to the traditional high voltage AC transmission system. It has several advantages over AC transmission systems when it comes to power transmission over long distances. These advantages can be summarized as follow [38]-[47]:

- low net transmission losses;
- enables asynchronous connection of two AC systems (two grids with different frequencies);
- reduces the dependency on the short circuit ratio, which is critical in the connection of AC systems with low short circuit ratios, such as with offshore wind farms;
- power flow is fully controlled (magnitude and direction);
- provides frequency and voltage regulation to the AC network through active and reactive power modulation;
- decouples and improves the stability of the AC network (as the AC fault in the one network will not be seen by the other network); and
- does not change the fault level at the connection point and contributes limited current to any AC fault.

The HVDC transmission systems can be built using current or voltage source converters.

4.2. Current Source Converter HVDC Transmission Systems

The thyristor current source converter approach is well established and its reliability has been proven. The converter configuration is based around line commutated thyristor rectifier/inverter circuits and is subject to inherent limits of this technology. Operation is limited by a lack of decoupled real and reactive power control and practical design constraints on the minimum allowable DC link current. Most existing DC transmission systems are based on current source converter technology [47]-[49]. Table 4 summarizes the most recent projects based on current source technology. HVDC transmission systems based on current source technology can use line-commutated converters or capacitor commutated converters. Fig. 18 shows the line and capacitor commutated converter HVDC transmission systems.

The main issues associated with HVDC transmission systems based on current source converters are [47]-[57]:

- Requires large reactive power for filtering purposes and to aid thyristor commutation. This reactive power is supplied using switch capacitors and reactors, because the amount of reactive power needed varies with the active power magnitude and operating mode (inversion or rectification). As an example, the 2×500MW back-to-back HVDC Chandrapur link in India is equipped with 2×426MVAr shunt capacitors in each terminal, configured as four switchable units of 106MVAr for each

500MW converter. As a result, a HVDC converter station based on current source technology is bulky and has a large foot print.

- The power reversal necessitates the DC link voltage polarity to be reversed. In practice, the power reversal is not instantaneous. The time required to reverse the power flow varies from 0.5s to several seconds, depending on AC system characteristics and DC cable design constraints [45], [57]. This problem does not exist in a voltage source converter based HVDC transmission system, because power reversal is achieved with a change of current direction (not voltage polarity).
- Lack of independent real and reactive power control presents difficulties for low real power transfers. Low real power transfer can be achieved either by the use of firing angle control or by controlling the dc link current. The former can result in high reactive power flows whilst the latter faces restrictions due to inductor sizing and minimum dc link current. The practical minimum power limit is typically in the order of 10% rated capacity. This limit can be extended using dynamic reactive compensation devices such as SVC and STATCOM.
- Only suitable for connection of the AC networks with a high short circuit ratio.
- AC faults or voltage distortion can result in commutation failure in which a thyristor fails to turn-off. The DC link voltage at the affected terminal will collapse and power transfer capability is lost. If uncorrected, commutation failure will require the link to shut down. (See Appendix B) [30],[36],[49],[55],[56]
- The presence of DC link inductance gives resilience to DC side short circuit faults (likely), However the converter topology is vulnerable to DC side open circuit faults (less likely).
- The inductive DC link of LCC HVDC systems behaves as a current source and is not well suited to multi-terminal connection. Power reversal requires a change of polarity at the converter terminals. The result is that the HVDC lines cannot appear as a common DC bus. Although theoretically possible, complex control strategies are required to achieve a multi-terminal configuration. In practice the achievable number of terminals has been limited to 3 [57].

The capacitor commutated converter was developed by ABB with the objective to extend the applications of the HVDC transmission systems based on current source converters to systems with low short circuit ratio. This converter improves system immunity to the risk of commutation failure; replaces the switched capacitors by a combination of fixed capacitors and reactors for filtering purposes only; and reduces transformer rating and size

[29], [35], [36], [49], [58]. As a result, the size of the converter station in CCC-HVDC transmission systems is greatly reduced compare to a LCC-HVDC system with the same power rating. The capacitor-commutating converter can be connected to AC systems with a short circuit ratio as low as 1.0 without the need for a synchronous condenser or static synchronous compensator (STATCOM) that can provide additional reactive power and maintain constant voltage at the point of common coupling. Fig. 19 shows the schematic diagram of the current source HVDC transmission system. According to IEEE Standard 1204-1997, the system short circuit ratio (SCR) and effective short circuit ratio (ESCR) are defined as follow:

$$SCR = \frac{S}{P_{dc}}$$

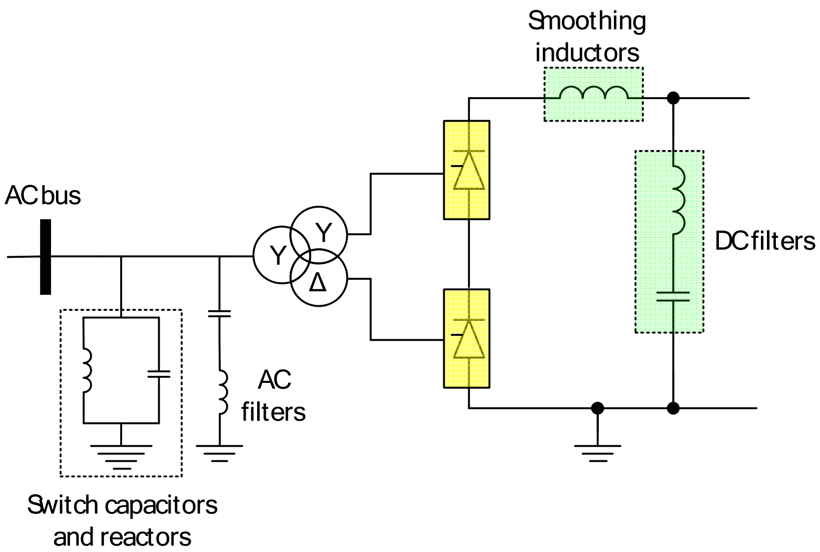
$$ESCR = \frac{S - Q_C}{P_{dc}}$$

where S is the ac system three-phase symmetrical short circuit level, MVA, at converter terminal (ac bus) calculated at rated terminal voltage (1.0 pu), P_{dc} is the rated dc power of the terminal, MW, and Q_C is the three-phase fundamental MVAr at rated P_{dc} and rated terminal voltage. This includes ac filters and shunt capacitors. The system strength is classified as follow:

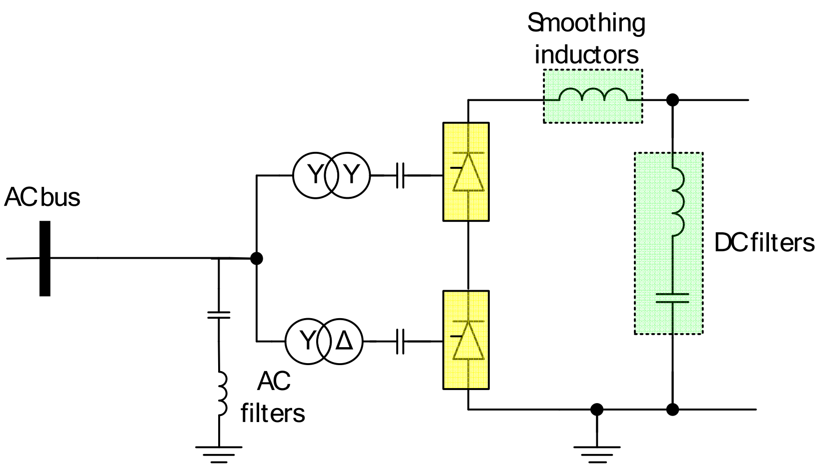
- System is strong if SCR>3 or $ESCR$>2.5
- System is weak if 3> SCR >2 or 2.5> $ESCR$ >1.5
- System is very weak (very low SCR) if SCR <2 or $ESCR$ <1.5

Table 4: Examples of the HVDC transmission systems using current source converter technology
[29], [35]-[36], [58]-[59]

Project	Rating	Application	distance	Commissioning year
Neptune (USA)	660MW, mono-polar 550kV DC	Interconnection of two area	82km submarine cable+ 23km land cable	2007
Guizhou-Guangdond II (China)	3000MW, bipolar ±500kV DC	Interconnection of two areas	1225km	2008
Rapid city DC tie (USA)	200MW, bipolar ±13kV double circuit	Asynchronous connection (using back-to-back configuration) provides voltage and frequency support	0	2003
The world longest transmission line (Brazil)	2×3150MW HVDC line and 800MW back-to-back converters, both at ±600kV	Asynchronous connection of two areas	2500km	2012
Chandrapur	2×500MW 205kV DC	Asynchronous connection using back-to-back HVDC link, provides frequency and voltage support	0	1997
Cross Channel HVDC between UK and France	2×1000MW ±270kV DC link	Interconnection of two areas as power trading facility	73km	1986



(a) Converter station of a line commutated high voltage DC (LCC-HVDC) transmission system



(b) Converter station of a capacitor commutated high voltage DC (CCC-HVDC) transmission system

Fig. 18: Converter technologies for a current source based HVDC transmission system

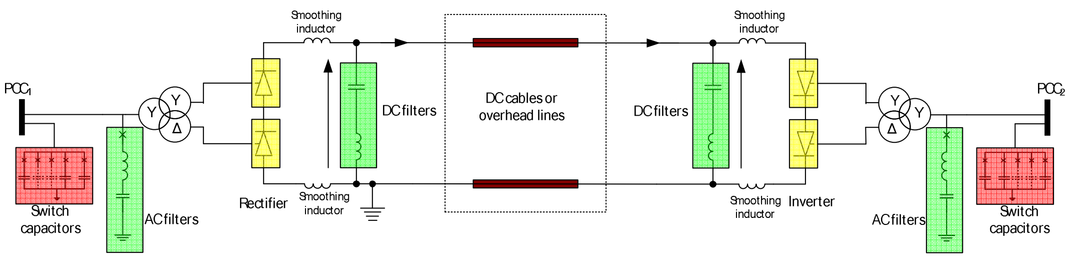


Fig. 19: Schematic diagram of a mono-polar LCC-HVDC transmission system

4.3. Voltage Source Converter High-Voltage DC (VSC-HVDC) Transmission Systems

The high-voltage DC transmission systems based on the voltage source converter (VSC-HVDC) was developed to address the shortcomings associated with HVDC transmission systems based on current source converters. The benefits of the voltage source technology are [61]-[69]:

- active and reactive power can be controlled independently;
- the use of pulse width modulation with a switching frequency in the of range 1 to 2kHz is sufficient to separate the fundamental voltage from the sidebands, and suppress the harmonic components around and beyond the switching frequency components. This significantly reduces filtering requirements;
- power flow can be reversed instantaneously without the need to reverse the polarity of the dc link voltage (only DC current direction is reversed);
- as the voltage source converter is capable of generating leading and lagging reactive power, the converter station can be used to provide voltage support to the AC network while transmitting active power, at no additional cost;
- since the voltage source converter actively controls the output current, the VSC-HVDC contribution to the fault current during AC faults is limited to rated current or less, and the converter can remain in operation to provide voltage support to the AC network, provided the AC network remains stable;
- black-start capability, which is the ability to start or restore power to a dead network (network without generation). This feature eliminates the need for a start-up generator in applications where space is critical or expensive, such as with offshore wind farms;
- in cases where there is no need to transmit active power between the two ends, VSC-HVDC can operate in sleep mode (zero active power exchange) and both converter stations operate as two independent STATCOMs to regulate AC network voltages;
- VSC-HVDC can be configured to provide fast frequency or damping support to AC network through active power modulation. This feature can be used to stabilize future power systems, with increased penetration of renewable energy and lightly damped systems. Also, it may facilitate the development of smart grids, especially during

transition from the grid mode to an intended or unintended islanding mode; and
- reduces converter size and delivery time, significantly.

However, the voltage source converter is more vulnerable to DC side short circuits than the thyristor based current source converter, which is likely if a system with a large number DC links is to be realized.

The VSC-HVDC transmission system can be realised using two-level voltage source converters or multilevel voltage source converters.

4.3.1. VSC-HVDC transmission system based on the two-level voltage source converter

This approach uses two-level voltage source converters in the HVDC transmission system, as adopted by ABB. Series connected IGBTs are used to increase the voltage blocking capability of the switching devices. The main advantages and disadvantages of this approach are [61]-[70]:

- simple in construction and requires a simple control strategy to guarantee stable operation over the entire operating range;
- capable of riding through different types of the AC faults without significant increase in device voltage and current stresses.
- high switching losses and relatively high filtering requirements (as a result requires relatively large AC filters with damping, which adds losses);
- high *dv/dt* due to the switching with a large voltage step, with a relatively high switching frequency and high common mode voltage. These impose high insulation requirements on the interfacing transformers; and
- poor DC fault ride-through capability. This represents a major obstacle to the development of multi-terminal HVDC, especially with the absence of reliable and proven DC circuit breakers.

A voltage source converter that produces output voltage levels 0 or V_{dc} is called a two-level converter, where V_{dc} is the dc link voltage referred to negative bus. To produce high quality output voltage or current with this type of converter requires relatively high switching frequencies. Practically, the maximum switching frequency used with two-level converters in high voltage DC transmission systems is 1.95kHz.

Fig. 20 shows a two-level voltage source converter that uses self-commutated switching devices, mainly IGBTs. The capacitor C of the voltage source converter must be sized to maintain a constant dc link voltage. The LC filter is tuned to attenuate the high frequencies, mainly, the most significant switching frequency components and their sidebands. The filter resistance is selected to damp possible oscillations that may arise, whilst introducing minimum power losses. Typical AC filters for the converter station, based on two-level converters, range from 10% to 20% of the converter rating [66], depending on the strength of the AC system. The power loss in the AC filter depends on the quality factor. The size of the VSC-HVDC transmission station system, based on two-level converters, is 30% to 50% that of the line commutated HVDC station, which requires 50% to 60% reactive power for filtering purposes and to aid valve commutation [35]-[37], [71]-[73].

The first DC transmission system based on the VSC in the UK was the East-West Interconnector between the UK and the Republic of Ireland. It has a capacity of 500MW and a ±200kV DC link voltage and is the largest single-circuit VSC-HVDC transmission system in the world. The main reasons for choosing this technology was its length (75km of underground cable and 186km of submarine cable), controllability, black-start capability, and its superior active and reactive power capabilities. This line is to be connected at 400kV AC on both sides and is expected to be commissioned in 2012. However, the converter topologies used and modulation strategy are not known.

A few examples of VSC-HVDC transmission systems based on two-level converters are summarized in table 5. Fig. 21 shows a schematic diagram of a voltage source converter based DC transmission system.

Table 5: Examples of the VSC-HVDC transmission systems based on two-level converter [34, 68, 71, 85, 86]

Project	Rating	PWM strategy	Applications	Distance	Controllability	Losses	Commissioning year
Gotland HVDC Light	50MW, ±80kV DC link fc=1.95kHz	SPWM	Connection of wind farm and power quality improvement	2×70km	high	high	1999
Direct link HVDC Light	3×60MW, ±80kV DC link,	SPWM	Interconnection and grid re-	6×59km	high	high	2000

	fc=1.95kHz		enforcement				
Estlink (Estonia-Finland)	350MW, ±150kV DC link, fc=1.15kHz	Optimum PWM	Interconnection and grid re-enforcement	105km	moderate	moderate	2006
Nord E.ON 1 Germany	400MW, ±150kV DC link	-	Connection of offshore wind farm	203km			2009
Caprivi link Namibia	300MW, 350kV DC link	-	Grid re-enforcement	970km O.H			2009

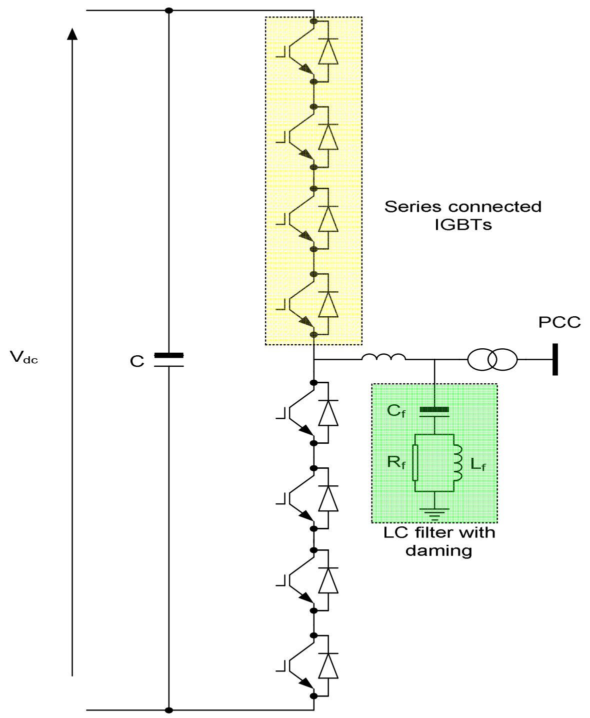


Fig. 20: Converter station of the VSC-HVDC transmission system based on the two-level converter

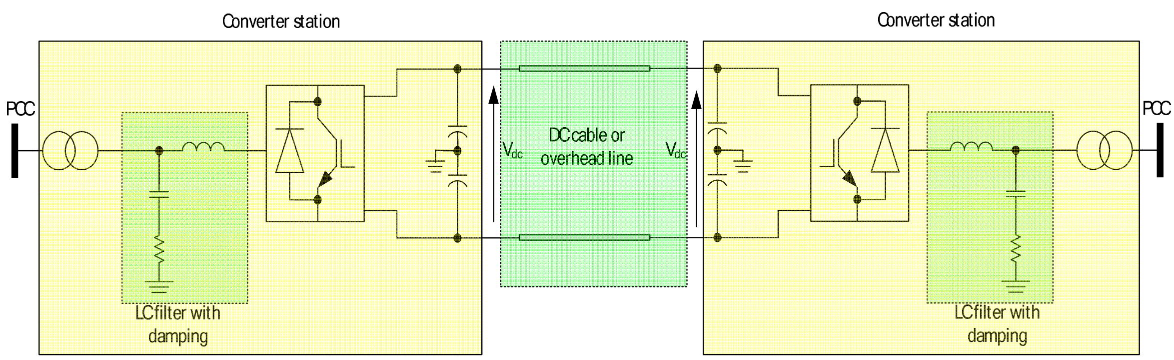


Fig. 21: Bipolar VSC-HVDC transmission system based on the two-level converter

4.3.2. VSC-HVDC transmission system based on multilevel converters

(a) Neutral-point clamped converter

Fig. 22 shows one phase of the neutral-point clamped (NPC) converter, where the converter produces a three-level waveform between point a and 0 (DC link mid-point shown in Fig. 22). The voltage levels are +½Vdc (when output phase leg 'a' is connected to the positive bus), 0 (when output phase 'a' is connected to the DC link mid-point) and -½Vdc (output phase 'a' is connected to the negative bus).

In order to achieve a reduced effective switching frequency per device (consequently, low switching losses), low *dv/dt* (allows the use of a transformer with reduced insulation requirements), and low voltage total harmonic distortion at the PCC (achieves a further reduction in filter size), ABB developed VSC-HVDC based on the three-level diode clamped converter [59], [72]-[76] (also known as neutral point clamped (NPC) converter). Fig.22 shows one-phase leg of the neutral-point clamped converter, which halves the voltage stress and effective switching frequency per device compared to the two-level converter. As a result, the conversion loss of the converter stations is reduced significantly. However, with the NPC converter, it is difficult to meet some grid code transient requirements, such as, the converter must remain in operation during grid faults to provide reactive power to support the grid voltage [76]. This is because the NPC converter DC link capacitor voltage cannot be maintained balanced at ½V_{dc} during asymmetrical AC faults, such as, a single-phase open circuit fault, single-phase-to-ground, and line-to-line faults. V_{dc} is the total dc link voltage of the NPC converter. As evidence, ABB has abandoned the NPC converter based HVDC transmission systems, while continuing to deliver VSC-HVDC transmission systems based on the two-level converter, despite its shortcoming compare to the NPC converter. Both the VSC HVDC transmission systems developed by ABB are called HVDC Light. The maximum rating for the HVDC Light is 1200MW with a bipolar DC link voltage of ±320kV.

Table 6 summarises VSC-HVDC transmission systems based on neutral-point clamped converter, and currently in operation.

Table 6: Examples of the VSC-HVDC transmission systems based on the NPC converter [34, 68, 71, 85, 86]

Project	Rating	PWM strategy	Applications	Distance	Controllability	Losses	Commissioning year
Cross Sound (USA) Cable	330MW, ±150kV DC link fc=1.26kHz	SPWM	Grid re-enforcement	40km	high	moderate	2002
Murray link	220MW, ±150kV	SPWM	Grid re-	180km	high	moderate	2002

(Australia)	DC link, fc=1.35kHz		enforcement				
EAGLE PASS (USA)	36MVA, ±15.59kV DC link, fc=1.26kHz	SPWM	Power trading and power quality	0 (back-to-back)	high	moderate	2000

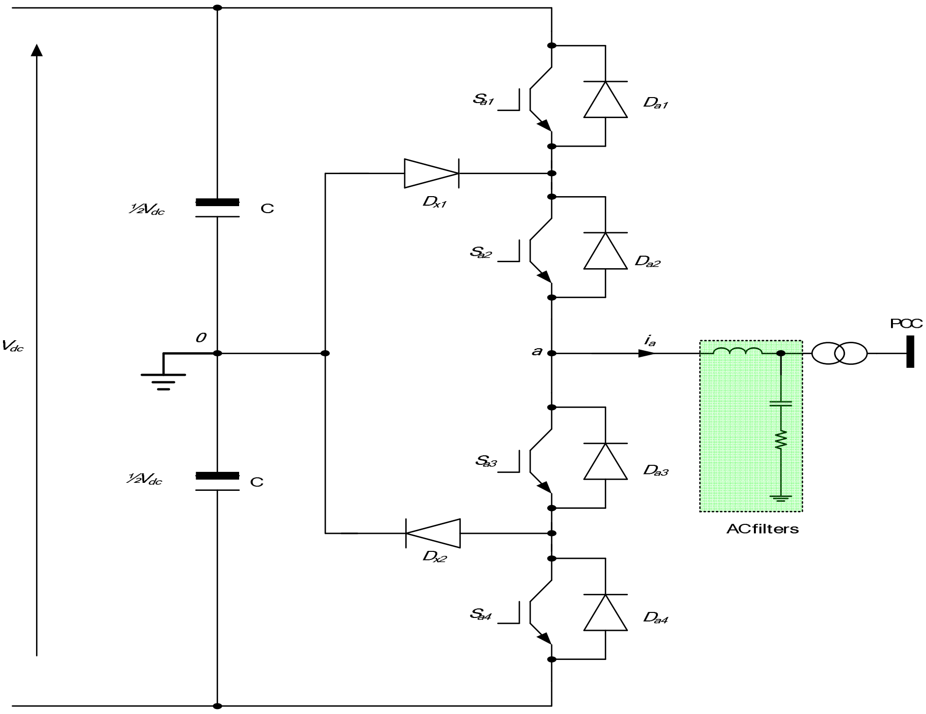


Fig. 22: One-phase of the neutral-point clamped (NPC) voltage source converter

(b) VSC-HVDC transmission systems based on the modular multilevel converter

This approach uses the full potential of the multilevel structure and pulse width modulation. The filtering requirements are greatly reduced due to the generation of high quality AC voltage (small filters are required) [76]-[80]. The use of a large number of levels with small voltage steps, results in low *dv/dt* and reduced voltage stress on the insulation of the interfacing transformers (this allows the use of standard transformers without need to withstand the DC link voltage or harmonic currents) [73], [76]. The effective switching frequency per device is low, which reduces the switching losses and overall conversion losses, and does not produce significant high frequency noise [81], [82]. This approach has been adopted by Siemens in their VSC-HVDC transmission system called HVDC Plus [76]. Fig. 23 shows one-phase of a 7-level modular converter. This converter relies on the cell capacitors to create a multilevel voltage waveform at the converter terminal. As the number of levels increases, it can generate high voltage with extremely low harmonic content, using medium voltage devices (2.5kV or 4.5kV). DC link capacitors are not required, which significantly reduces the space requirement for the converter station. As the converter depends on phase voltage redundancy to maintain approximately constant voltage across the cell capacitors, the modular multilevel converter performs better than the NPC converter during unbalanced operation, and symmetrical and asymmetrical faults, without increasing the risk of device failure or system collapse. The ability of the modular converter to ride through different types of AC faults makes it attractive in power system applications where it can meet the requirements of the different grid codes. The absence of DC link capacitors in a VSC-HVDC transmission system based on the modular converter, make sizing the cell capacitors critical. They are sized to be able to store enough energy to support the converter dc link during transient events. Otherwise the system may fail to meet transient requirements. The first commercial modular multilevel converter based HVDC transmission system project is the Trans Bay cable project in the USA, rated at 400MW active power transfer and ±170MVAr STATCOM functionality with a bipolar DC link voltage of ±200kV. The line is 85km of submarine cable, and it is expected to be commissioned in 2010 [83].

For this type of multi-level converter, the cell capacitors experience the full load current (un-like the rail capacitor of a two level system). High capacitance and large physical size result. This capacitance appears to be the dominant factor in the size of this type of converter. But the main DC link capacitors in both ends of the line are eliminated.

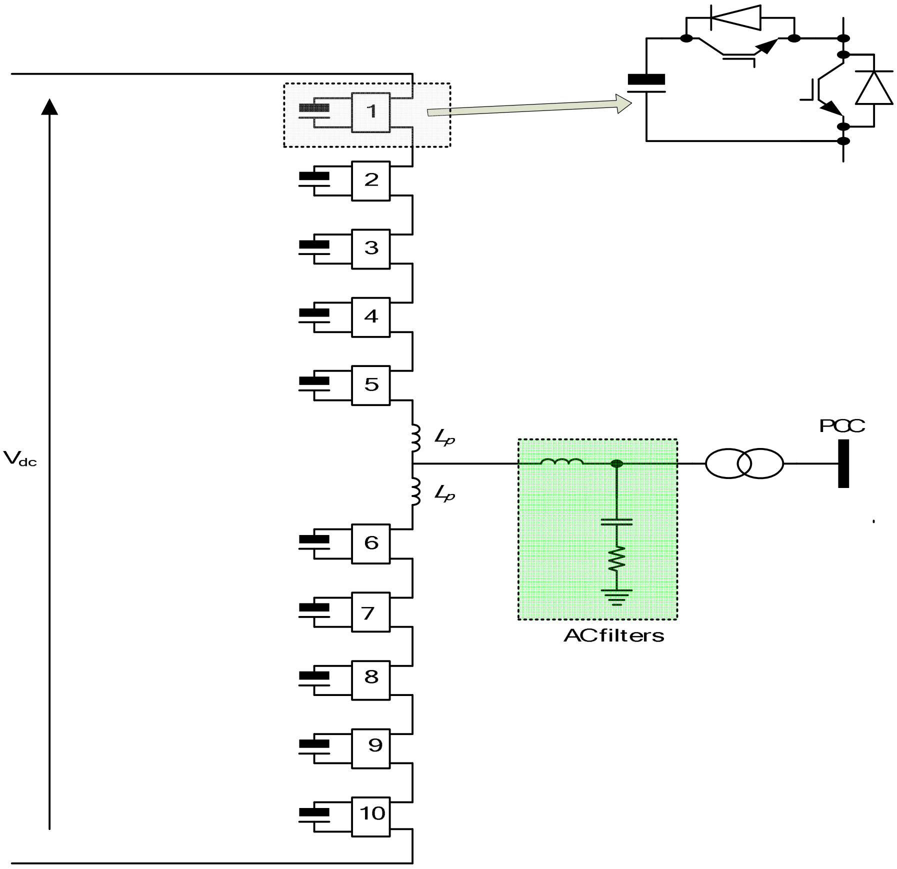


Fig. 23: One-phase of 7-level modular converter used as basic building block of HVDC Plus

Table 7 provides a detail comparison between high-voltage DC transmission system technologies. The comparison focuses on several issues, such as, control flexibility, fault ride-through capability, conversion losses, electromagnetic compatibility (EMC) issues, and provision of auxiliary functionality such as voltage, frequency, and damping support.

Table **7:** Comparison between different HVDC technologies

	Current source converter based		**Voltage source converter based**		
	LCC [28,30,31,32,49,55,57,58,65,74,88]]	CCC [28,30,31,32,49,55,57,58,65,74,88]	Two-level [68,85,86]	Neutral-point clamped [68,85,86]	Modular (M2C) [104]
Switching device	Thyristor	Thyristor	IGBT	IGBT	IGBT
switching losses	Negligible	Negligible	High	Moderate	Low
On-state losses	Low	Low	Moderate	Moderate	Moderate
Station size	large	Reduced due elimination of switch capacitors and their circuit breakers	Significantly reduced (30% to 50% of LCC)	Significantly reduced (30% to 50% of LCC)	Significantly reduced (30% to 50% of LCC)
Active power control	Discontinuous from ±10% to ±100%	Discontinuous from ±10% to ±100%	Continuous From 0 to ±100%	Continuous From 0 to ±100%	Continuous From 0 to ±100%
Active power reversal	DC voltage polarity must be changed and not instantaneous	DC voltage polarity must be changed and not instantaneous	Instantaneous and no change of DC voltage polarity	Instantaneous and no change of DC voltage polarity	Instantaneous and no change of DC voltage polarity
Independent control of	No	No	Yes	Yes	Yes

active and reactive power					
Reactive power demand	50% to 60%	50% to 60%	No	No	No
Reactive power capability	Limited (lagging VAr only) and discontinuous using switch shunt capacitors for leading VAr	Limited (lagging VAr only)	Continuous and inherent within the converter control at no additional cost	Continuous and inherent within the converter control at no additional cost	Continuous and inherent within the converter control at no additional cost
Achievable power levels (based on current technology)	Up to 6400MW	Up to 6400MW	Up to 1200MW	Up to 1200MW	Up to 1200MW
controllability	Low	Low	High	High	High
AC filters	Large	Large	small	Smaller than 2-level converter	no
DC filter	Yes	Yes	No	No	No
Converter transformer	Expensive with high insulation requirement to withstand voltage stresses during power reversal	Expensive with high insulation requirement to withstand voltage stresses during power reversal, but with reduced MVA rating	Expensive with high insulation requirement to withstand switching of large voltage steps with high frequency	Expensive with high insulation requirement to withstand switching of large voltage steps with high frequency	Cheap with standard insulation
DC cable	Expensive with high insulation requirement to withstand voltage stresses during power reversal	Expensive with high insulation requirement to withstand voltage stresses during power reversal	Cheap and light weight extruded cable	Cheap and light weight extruded cable	Cheap and light weight extruded cable
Commutation failure	Due voltage distortion and lack or reactive power during AC fault	Significantly reduced	No	No	No
Applications	Connection of strong systems only, connection of weak system is possible but at additional cost by using STATCOM or synchronous condenser	Connection of strong and weak systems with SCR>=1	Independent of systems strength and network without generation	Independent of systems strength and network without generation	Independent of systems strength and network without generation

	Current source converter based		Voltage source converter based		
AC fault ride-through capability	Possible with high risk of commutation failure	Possible with reduced risk of commutation failure	Excellent	Very good, but its ability to cope with asymmetrical faults depends on capacito voltage balancing strategy used	Excellent
DC fault ride-through capability	Possible with inherent inductance in the DC side	Possible with inherent inductance in the DC side	Possible with increasing the interfacing reactor>0.25pu	Possible with increasing the interfacing reactor>0.25pu	Possible with combinations of inherent inductances within each arm and interfacing reactors
Multi-terminal configuration	Limited to 3 due to increase complexity of the control system to achieve current balancing and power reversal	Limited to 3 due to increase complexity of the control system to achieve current balancing and power reversal	Extendable to any number of terminal practically feasible	Extendable to any number of terminal practically feasible	Extendable to any number of terminal practically feasible
Delivery time	36 month	36 month	24 month	24 month	Not yet known
Redundancy	yes	yes	yes	yes	yes
Manufacturers	ABB, SIEMENS and AREVA	ABB	ABB	ABB	SIEMENS

Note: Controllability is a general term used to describe several features such as: fast dynamic response, ability to mitigate flickers and inter-area oscillations, fast active and reactive power modulation in order stabilized ac system frequency and damping of low frequency oscillations, and fast power run-back and ramp up during loss of load or generation.

The ratings of the LCC-HVDC, CCC-HVDC, and VSC-HVDC systems shown in table 6 can be achieved at present only by using multiple converters per terminal. This has been practically implemented in the Three Gorges-Shanghai HVDC transmission link in China, with two 3000MW converters and a 1200MW converter, all configured to be bi-polar, with dc link voltages of ±500kV. The future trend from the main manufacturers, such as ABB, SIEMENS and AREVA, is to produce power levels up to 6400MW using ultra-high-voltage dc (UHVDC) system with dc link voltages greater than ±600kV to 800kV using only one converter per terminal.

For VSC-HVDC, the limited voltage and current ratings of the IGBT, restrict the capability of individual converter stations. Present VS-HVDC systems are limited to the order of 2400MW (Reported by ABB) This can be achieved using multiple converters with dc link voltages of ±300kV (or ±320kV). Significant increases in the link voltage of two level VSC-HVDC are unlikely due to inherent technology limitations. Manufacturers are working to increase the operating dc link voltage of VSC-HVDC transmission systems by using multilevel structures in order to increase the power carrying capability of single converters to 600MW or higher without significantly increasing the device current capability.

VSC-HVDC transmission systems are known to have higher conversion losses, dominantly switching losses [34]. But the manufacturers currently claim conversion losses almost equivalent to conventional HVDC transmission systems, where each device switches once per fundamental period. In the authors' opinion, the VSC-HVDC transmission conversion losses will be higher than LCC-HVDC or CCC-HVDC transmission systems, as the IGBT on-state voltage will always be higher than that of the thyristor for the same voltage and current rating. The topologies influence the switching losses, which represent only part of the conversion losses.
Examples of converter stations based on different HVDC transmission technologies and their components are given in Appendix A2.

4.4. Multi-terminal HVDC Transmission Systems

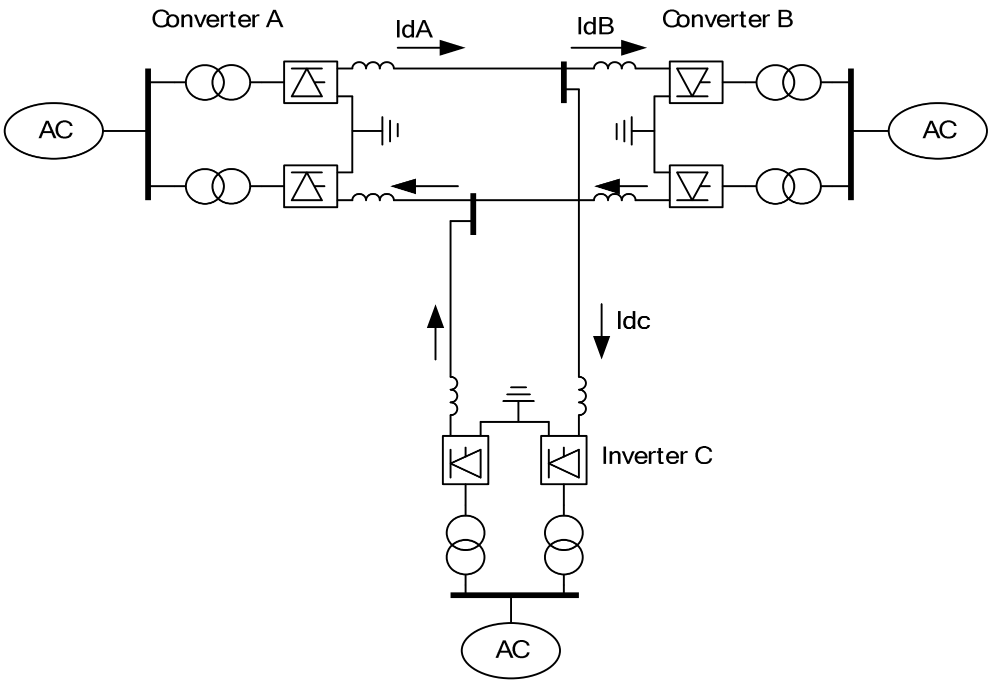
HVDC transmission systems based on current source or voltage source converters can be configured as point-to-point or multi-terminal. Currently the use of a current source converter in a multi-terminal HVDC system configuration is limited to three terminals due to technical difficulties such as increased control system complexity and DC current balancing between the converters [84]-[87]. Examples of constructed multi-terminal HVDC transmission systems using the current source approach are summarized in table 8.
Because of previously discussed advantages of VSC-HVDC transmission technology, it is the most suitable in many applications, including multi-terminal DC transmission systems for the integration of offshore wind farms to the grid, grid re-enforcement, and power trading [87]-[91].

The multi-terminal VSC-HVDC transmission systems can be extended to any number of terminals without increasing the system complexity significantly. Fig. 24 shows some of the possible multi-terminals configurations based on current and voltage source converters. Fig. 24a shows a three-terminal system based on a classical HVDC transmissions system. It is observed that a change in operating mode of one of the converters, such as 'C', in order to reverse the power flow, necessitates converter DC link polarity reversal as well as a change in control mode [84]. This one example highlights the complications that may arise from the use of LCC or CCC-HVDC in multi-terminal DC transmission systems. The limited reactive power capability of multi-terminal systems based on conventional HVDC transmission systems, increases the risk of voltage and power system instability due to the lack of reactive power available to maintain the system voltage at acceptable levels in a weak AC system. Instability is more likely to occur during constant power control, restricting the amount of power that can be transmitted, and during operation with constant extinction angle γ at the inverter [84]. A more detailed discussion about the implications of using HVDC classic for multi-terminal DC transmission systems, is given in references [54],[55],[78]-[89].

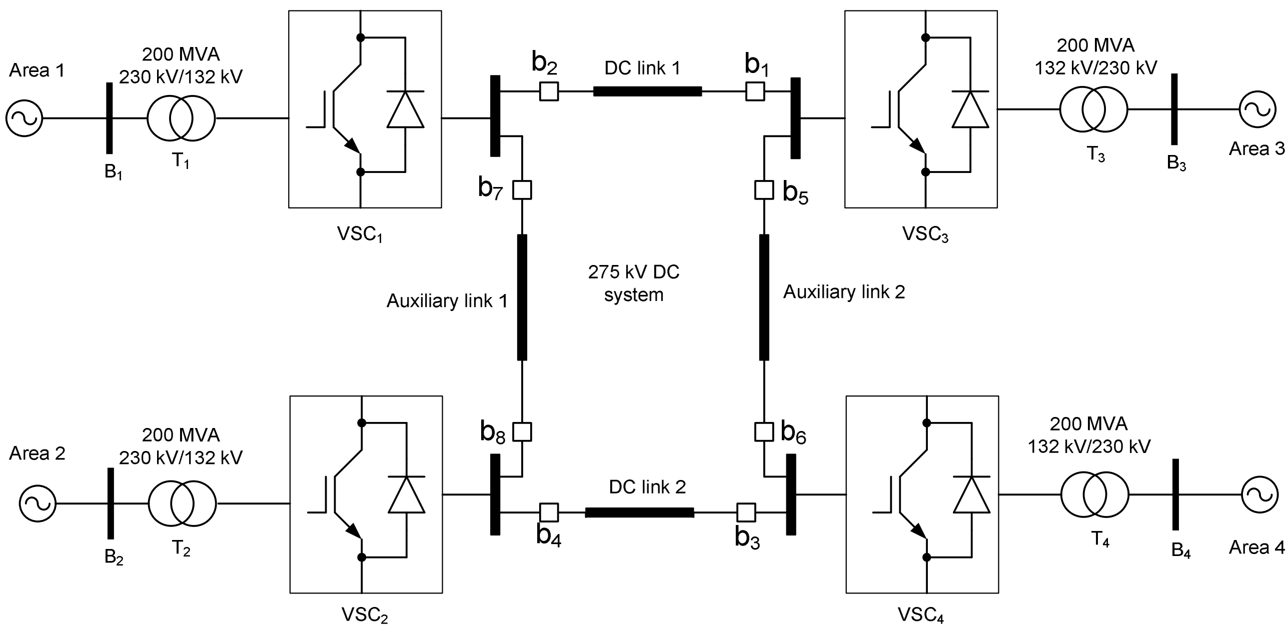
Fig. 24b shows examples of possible multi-terminal HVDC transmission systems based on VSC-HVDC. It can be observed that active power reversal at any terminal can be achieved by changing the DC current direction without the need to change the DC link voltage polarity and operating mode. This results in instantaneous power reversal without increasing the stress on the DC cable and interfacing transformer, as occurs in conventional HVDC. The active power sharing between the converters in a multi-terminal VSC-HVDC system can be achieved using combinations of direct active power control in converters that control active power, and DC voltage droop in the converters used to control the DC link voltage, as demonstrated in references [80],[91]. This increases the flexibility of multi-terminal VSC-HVDC transmission systems to respond to any network alteration resulting from AC faults and active power imbalance due to loss of major load or generation, and participate in stabilization of AC networks.

The ability of multi-terminal VSC-HVDC to fully control the active power flow (magnitude and direction) makes it suited to reduce network congestion and extend the steady-state stability limits of the AC networks. Unlike conventional HVDC, the inherent reactive power capability within the converter stations of multi-terminal VSC-HVDC transmission improves voltage and power system stability of weak AC networks at no additional cost. It also allows active power injection into any AC networks regardless of their strength. This feature is vital to improve the energy availability at any terminal of the AC network.

However, a highly coordinated control system is required between the converter stations and robust DC circuit breakers to improve the possibility of system recovery from DC faults or loss of converters [55],[78],[87]-[91]. Decentralized Dynamic Voltage Controlled Recovery (DDVCR), developed for the Hydro Quebec-New England Hydro scheme, is an example recovery scheme for a conventional HVDC multi-terminal transmission system [54]. The common DC bus architecture of VSC-HVDC is fundamentally different from previous LCC based multi-terminal HVDC. This architecture will require protection and fault management systems to protect un-faulted converter stations and ensure rapid recovery of the network. The recovery strategy of VSC-HVDC multi-terminal transmission system from a dc side fault will require the ability to interrupt the DC fault current, isolate the faulted line sections, and reenergise the line. These functions may require special functions including , dc fault blocking converter stations, dc breakers, and fault location systems.



(a) Three-terminal system based on current source converter (LCC- or CCC-HVDC)



(b) Four-terminal VSC-HVDC system

Fig. 24: Examples of possible multi-terminal configurations

Table 8: examples of multi-terminal HVDC transmission system in operation [54]

Project	Rating	Length	Configuration	Commissioning year
SACOI Italy/France	250MW 200kV DC link	406km	Three monopolar terminals in series (extension of existing two terminal monoploar HVDC)	1967 and 1986
Pacific Intertie USA	3100MW, ±500kV DC link	1360km	Four bipolar terminals in parallel, rated at 2×2000MW and 2×1100MW (built in three stages, 1600MW 2 bipolar terminals with ±400kV using Mercury arc valve, upgrading of existing terminals by 400MW and DC link voltage is increased to ±500kV using thyristor valve converter, and 1100MW 4 bipolar terminals at ±500kV)	1970, 1984 and 1989
Hydro Quebec-New England Hydro Canada/USA	2250MW, ±450kV DC link	1480km	Three bipolar terminals in parallel rated at 2250MW, 2130MW and 1800MW (constructed in three stages)	1990 1991 1992

4.5. High-Voltage DC Circuit Breakers

The high-voltage DC circuit breaker is a key system component, the availability of which is key to the exploitation of multi-terminal DC transmission systems, especially since an increased number of terminals and lines increase the risk of a DC fault. An unavoidable consequence of a DC side fault is that the power transfer in whole system will be interrupted [55]. Therefore, fast dc fault clearance is essential. DC systems have no natural current zero at which the fault current may be extinguished. Circuit breakers must therefore provide sufficient voltage to drive the current to zero and absorb the fault energy. [92] [94] This must be achieved without incurring excessive steady state loss in the protection device. Circuit breaker technology for VSC based multi-terminal HVDC faces additional challenges resulting from the low impedance DC bus architecture and in-feed from the converter stations (which currently lack reverse blocking capability). In these systems the circuit breaker may be subjected to high fault levels and must achieve clearance times compatible with protection of the semiconductors in the converter stations.

The academic and industry research approaches [92]-[99] use passive or active circuits, in parallel with the actual current interruption circuit, to create an artificial zero crossing in order to minimize the resulting over-voltage following the interruption [92],[95]. The first proto-type of a 500kV DC circuit breaker was developed by BBC in 1984, reported in reference [93] and shown in Fig. 25. References [92]-[94] reported recent DC breakers development by ABB and Areva. Practical DC circuit breakers have been reported for use with LCC based HVDC [92],[94]. Circuit breakers for use in VSC-HVDC remain at the development stage (including state funded programs e.g. E.U FP7 'Twenties Project') with no clear consensus on technical solutions.[95] The use of reverse blocking converter technology is also being actively investigated as a means of controlling DC faults. [105]

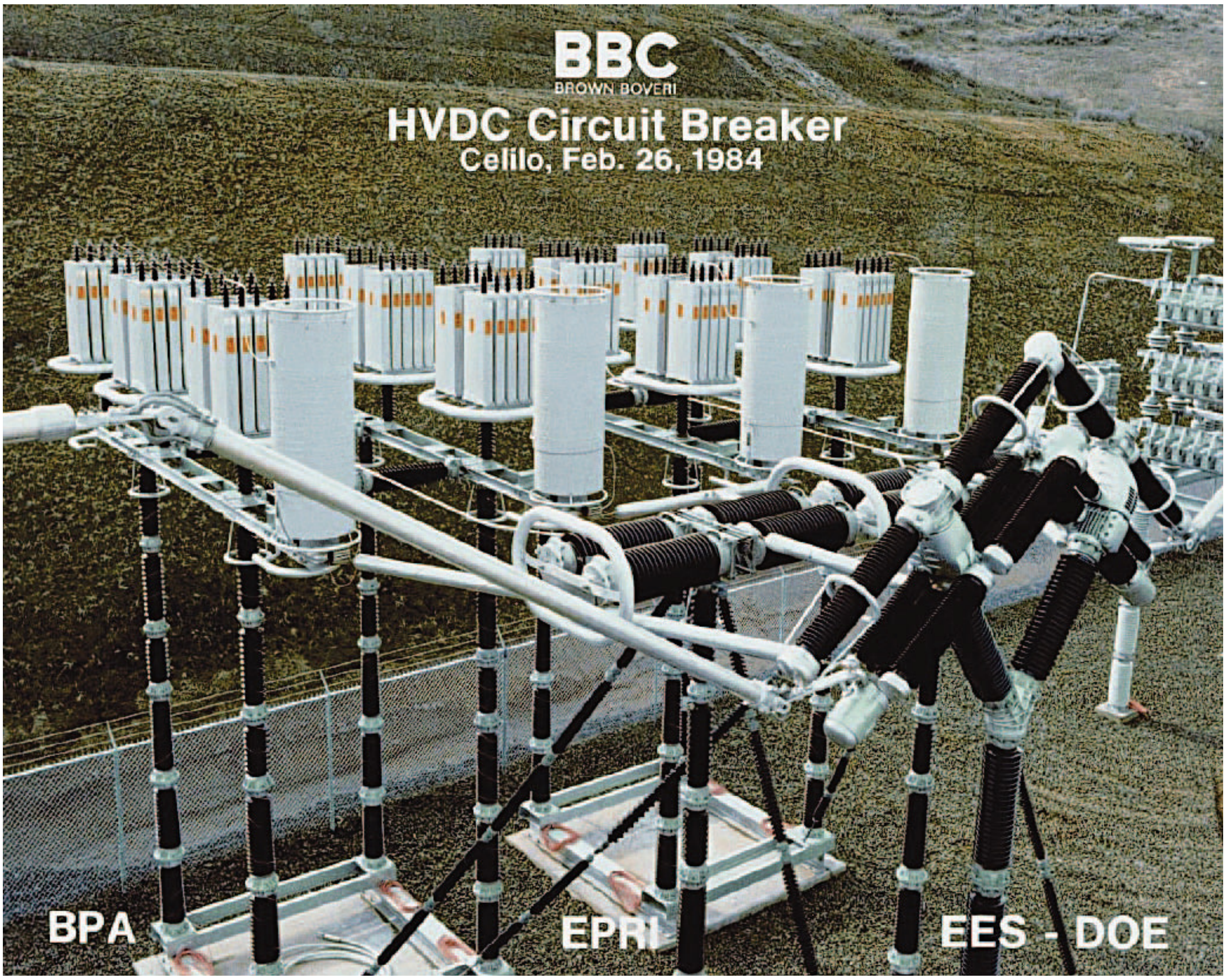


Fig. 25: 500kV DC circuit breaker at Cellilo [93].

4.6. Summary of HVDC Application to the UK Transmission System

- LCC-HVDC transmission technology has a large space requirement and visual impact, in the context of the UK where the right of way is extremely expensive; these significantly increase construction cost and the difficulty to obtain planning permission. It is also vulnerable to commutation failure from asymmetrical faults close to the PCC and severe voltage distortion. However, the risk of commutation failure can be reduced by using a STATCOM, but this adds losses and cost. Despite LCC-HVDC technology being well established and proven in terms of reliability, it will not be able to fulfil UK National Grid code requirements, such as:

  - fast power ramping during major transient events in order to improve system transient stability,
  - fast power reversal due to dc cable and converter transformer limitations, and
  - it will not meet many requirements such as reactive power support and fault ride-through capability without additional cost.

- In the context of the UK, CCC-HVDC transmission system technology can minimize the risk of commutation failure and reduce station size significantly, and reduce converter transformer rating. As a result, system construction cost may be reduced while improving transient performance. CCC losses are expected to be less than the 1.6% those associated with the LCC approach, especially as transformer losses represent about 37% of the station losses. When the capacitors associated with CCC-HVDC transmission are replaced with a TCSC, as implemented in the Stöde substation in central Sweden, the converter station will offer addition functionality, such as voltage and damping support to the AC network. This modification adds losses and cost.
- VSC-HVDC transmission system technology is relatively new but with a proven track record in terms of its functionality. For example, black-start capability, connection of dead networks with no generation, and weak AC systems, such as offshore wind farms have been demonstrated by the Valhall offshore oil platform operated at variable voltage and variable frequency, and in NORD E.ON 1 offshore wind farm, Germany. The fast response of VSC-HVDC transmission, instantaneous power reversal and reactive power capability could provide additional flexibility to the UK Grid in terms of improved system steady-state and transient stability, improved voltage and frequency stability and accommodation of additional generation from the planned onshore and offshore wind farms without the need to further upgrade the current AC transmission system or install new FACT devices to improve power flow and power quality. The low space requirement of the VSC-HVDC transmission system may reduce project capital expenditure and encourage local government to issue planning permission within a short

period of time because of minimal public objection as the visual and other environmental impact is relatively low. Also, it can meet most, if not all, the GB Grid Code at no additional cost. However, all these features and flexibility are achievable at the expense of higher losses than with LCC or CCC-HVDC. The risk of subsynchronous resonance with rotating machines in close proximity is minimal. In the current UK Grid, the precise active and reactive power control of the VSC-HVDC transmission system can relieve network congestion, and provide grid access to large amounts of potential onshore wind farms without having to worry about fault level and undesirable power flow. Additionally, it can be used in parallel with HVAC to reduce losses and provide reactive power compensation at no additional cost. With reference to multi-terminal HVDC transmission, the use of VSC technology may result in a simple control strategy. However, the risk of a DC side fault is much greater in multi-terminal configurations than a point-to-point system. Practical realization of DC grids can be expected when a reliable DC current interruption technique is available. The present point-to-point VSC-HVDC transmission system technologies are unable to block the excessive current that may flow in the converter switches/diodes during DC side faults. Therefore, the phase interface reactors must be sized to limit the fault current level to a safe level for the converter switches.

- The lifetime of conventional HVDC and VSC-HVDC is 30 years and 35 years respectively, as claimed by the manufacturers, each with a reliability of 98%.

4.7. Economic Benefits and Environmental Impact

The features of HVDC transmission, such as fast response, precise power flow control, and reactive power capability are essential to improving market integration, grid integration of renewable power, and improving security of supply. However, as with any other technology, there is an environmental impact associated with construction of new HVDC transmission systems, such as [100]-[101]:

- Generation of magnetic fields from large converters and DC cables range from 5μT to 30μTesla. These magnetic field levels are not harmful to humans, and marine life in the case of submarine cables.
- Converter stations generate audible noise. This can be minimized using a multilevel converter approach, AC and DC filters, and indoor converter stations.
- Visual impact can be minimized using oil-free under ground or sub-sea cable.

- The use of oil-free polymeric extruded cables eliminates the risk of pollution as a result of oil leakage, and reduces the cost of laying cable as the cable is robust and light-weight.
- Improves transmission efficiency by 25% in applications necessitating the use of submarine cable. This reduces CO_2 emission, maximizes the use of available generation, and defers construction of new transmission systems and power plant.
- Low space requirements and short delivery time may encourage local authorities to ease issuing planning permission and may also reduce public opposition to its construction.

4.8. Conclusions — HVDC Transmission System

This report presented a comprehensive review of high-voltage DC transmission systems. The review emphasizes the potential impact of the HVDC transmission systems on AC power system networks. The report explores the features of different HVDC transmission systems technologies to improve AC network performance. The comparison between conventional HVDC transmission systems based on current source converters (mainly, line commutated and capacitor commutated types) and voltage source converter HVDC transmission systems (mainly, two-level, neutral-point-clamped, and modular converters) are presented. The features and shortcomings associated with each technology are highlighted. Based on this review the following conclusions are drawn.

- Conventional HVDC transmission based on current source converter technology remains the viable option for transmission of large amounts of power (over 2400MW) between two strong AC networks over long distances. In this case, the choice between line and capacitor commutated converters must made based on several factors, such as, network strength, risk of commutation failure, cost, space requirement, etc.
- The use of voltage source converter based HVDC transmission systems can provide additional functionality at virtually no additional cost. However this technology is presently limited to capacities below 2400MW. In theory, higher capacities could be achieved through the use of parallel connection of converters. However, the technical and cost considerations of this approach are uncertain.
- For connection of weak networks or networks without generation, the voltage source converter remains the only feasible option. This is due to its inherent reactive power capability and independent control of

active and reactive power, and its fast dynamic response to network alteration.

- In multi-terminal configurations, voltage source converter HVDC technology is preferred, because it allows power reversal with a change of DC current direction (as opposed to voltage reversal). This simplifies the HVDC transmission control system and improves the chances of the system to recover from AC and DC faults.
- On the grounds of cost, the DC cable used with VSC-HVDC is much cheaper and lighter in weight than that used in current source converter HVDC transmission systems.
- Except for IGBT current handling capability (power level) restrictions, VSC-HVDC transmission systems have much to offer compare to LCC-HVDC or CCC-HVDC transmission systems.

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Appendices

Appendix A

Examples of Installed FACTS devices and HVDC schemes.

A1. Data and illustrations of installed FACTS devices

Table A1: Examples of the projects or substations that utilise FACTS device to improve system performance (Sources: ABB, Siemens and Areva websites)

Project (or substation)	Type and rating	Commissioning year	Manufacturers	remarks
EDM Mozambique (Macuba substation)	±35MVAr SVC-Plus, connected to 33kV	2010	Siemens	Utility application
Thanet offshore wind farm (UK)	2×180MVAr SVC-Plus Connected at 33kV side	Expected to be commissioned in 2010	Siemens	Grid code compliance
Greater Gabbart offshore wind farm (UK)	3×180MVAr SVC-Plus, connected at 33kV side	Expected to be commissioned in 2011	Siemens	Grid code compliance
Calvisano project (Italy)	135MVAr SVC connected at 33kV	2010	ABB	Power quality
Hydro-Quebec, Chenier (Canada	2×600MVAr SVC connected to 735kV	2009	ABB	Utility application
Danieli - UNI Steel (Kuwait)	164MVAr SVC-Light, connected to 33kV	2009	ABB	Industry application (to damp low oscillation in active and reactive power caused by electric arc furnace, EAF). Also known as flicker mitigation
CFE - Escarcega (PID-1200), Mexico	2×600MVAr	2009	ABB	Utility application
Greenbank Pine (Australia)	SVC consists of TSC and TCR with 250MVAr(capacitive) and 100MVAr(inductive) capability, connected to 275kV	2008	Siemens	Utility application
Born Jesus da lapa (Brazil)	±250MVAr SVC (TCR plus TSC), connected to 500kV	2002	Siemens	Utility application
Lucknow, Bareilly, and Unnao substations (India)	2×189MVAr Fixed series capacitor (FSC), 2×187MVAr (FSC) and 1×311MVAr(FSC), all connected to 400kV	2008	Siemens	Utility application (to increase transmission capacity)
Fengjie substation (China)	2×610MVAr (FSC), connected to 500kV	2006	Siemens	Utility application (to increase power transfer capacity of the existing lines)
Serra da messa (Brazil)	107.48MVAr Thyristor controlled series capacitor (TCSC), connected to 500kV	1999	Siemens	Utility application (to increase power transfer capacity of the existing lines)
RTE, France	4×80MVAr and 8MVAr mechanically	Expected to be commissioned in	Siemens	Utility application (to stabilized the

	switched capacitor damping network (MSCDN), connected to 225kV and 63kV	2011		voltage fluctuation caused by heavy load variation and network conditions)

Project (or substation)	Type and rating	Commissioning year	Manufacturers	remarks
North-South 500kV interconnector (Brazil)	1100MVAr series compensator comprises of 107MVAr of TCSC and the remaining are 5 units of FC, all connected to 500kV	1999	ABB	Utility application (increase steady-state and dynamic stability of the intertie, and damping the inter-area oscillations between two region)
Evron (France)	±24MVAr, SVC-Light load balancer (This dynamic voltage restorer is slight different than known configuration of standard DVR), connected to 90kV	-	ABB	Utility application (balancing of the power flow among the three phases and filtering of the existing low order harmonics). ***In other words (combined functionalities of DVR and active power filter APF)***
Channel Tunnel Rail Link (between France and UK) border)	2x-5MVAr/+40MVAr Thyristor based SVC (configured as DVR plus APF)-	-	ABB	Utility application (active power filtering and balancing, dynamic voltage support)

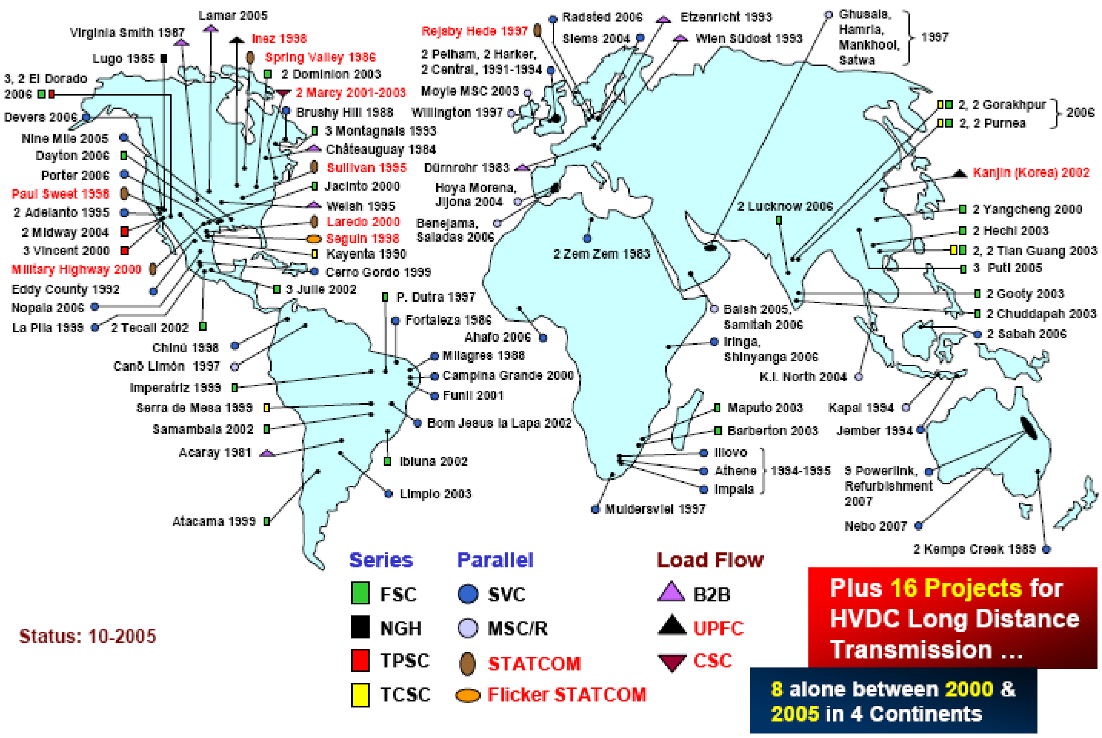


Fig. A1: Worldwide Installation of FACTS and HVDC until 2006 [104]

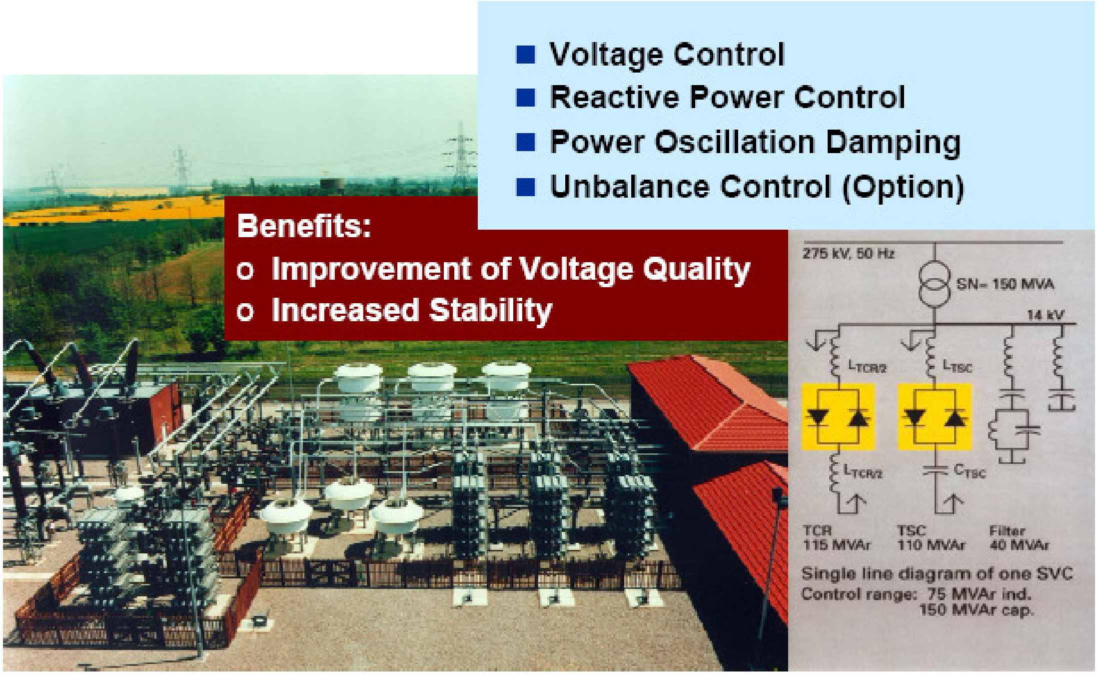


Fig. A2: SVC Pleham, NGC-UK, 400kV/14kV, -75/+150MVAr reactive power capability [78,104]
(Source: Siemens website)

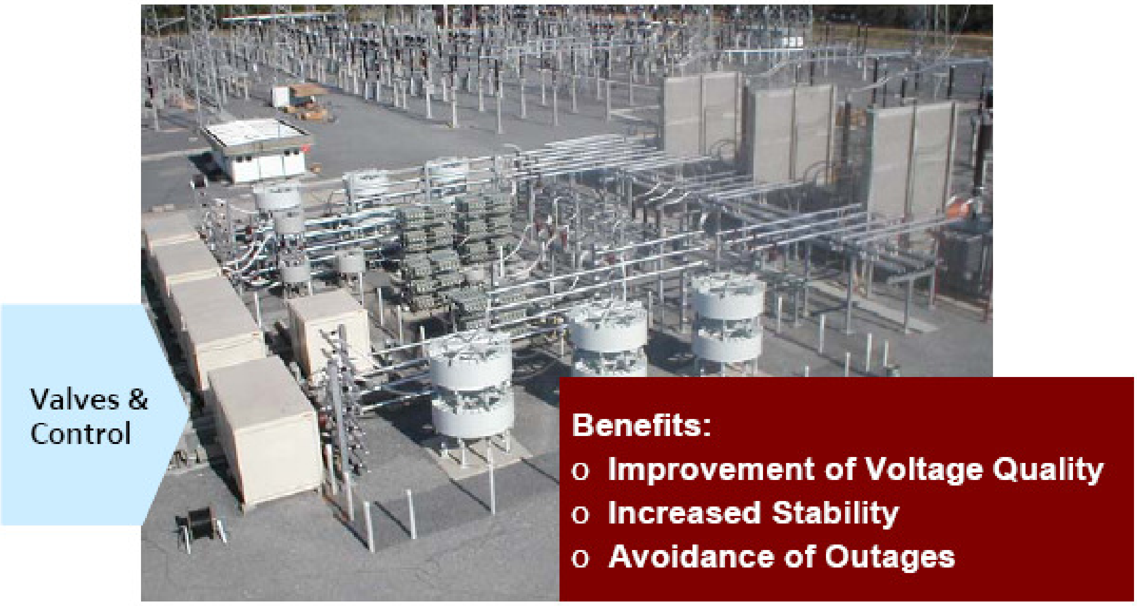


Fig. A3: SVC Bom Jesus da Lapa, Enepower, Brazil-500kV, ±250MVAr reactive power capability [78,104]
(Source: Siemens website)

Table A2: Availability of power electronic recorded from Natal SVC Republic of South Africa (SVC, TCR and 3 filters) [78,104]

Illovo SVC	1995	1996	1997	1998
Availability (%)	99.9	99.45	100	100
Forced and deferred Outages	2	5	2	1
Off-line Maintenance	0h	80h00	102h26	162h00
On-line Maintenance	10h15	2h00	3h00	0
MDT in hrs	2h13	9h40	36h40	1h00

Athene SVC	1995	1996	1997	1998
Availability (%)	99.78	99.71	99.92	99.77
Forced and deferred Outages	4	9	1	2
Off-line Maintenance	4h00	81h00	62h00	60h15
On-line Maintenance	1h00	0	0	0
MDT in hrs	4h40	3h20	4h40	10h30

A2. Data and illustrations of installed HVDC transmission systems

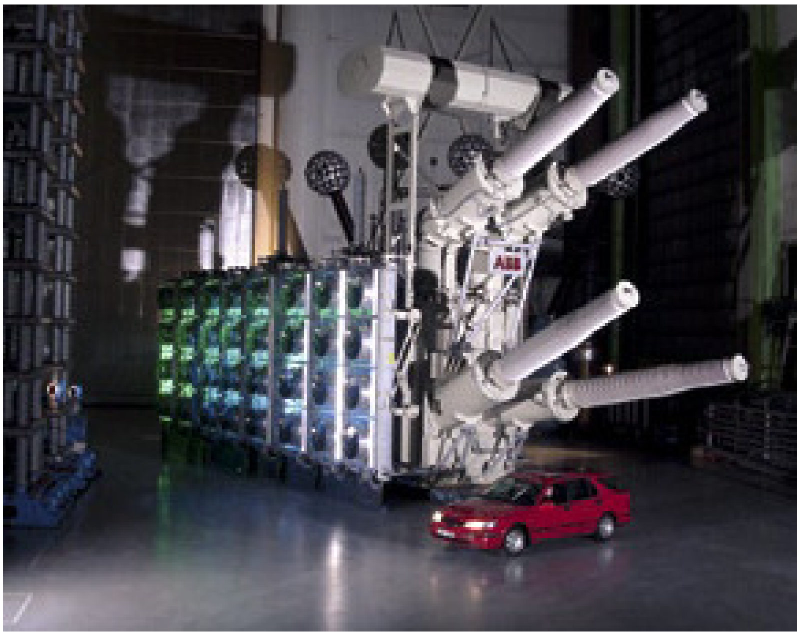


Fig. A4: 621MVA converter transformer with 30° phase shift to eliminate 5th and 7th harmonics, 355 tons weight, type single-phase 3-windings used in the converter station of the Pacific Intertie project HVDC transmission system (converter type is line commutated converter) (Source: Siemens website)

Fig. A5: Thyristor valves of the 12-pulse converter, quadruple suspended (Source: Siemens website)

Fig. A6: AC filters at converter station (Longquan) of the three Gorges-Changzhou HVDC transmission system (China)
AC filter at Longquan, Three Gorges - Changzhou, China (Source: ABB web site: www.abb.com)

Fig. A7: Smoothing reactor
(source: ABB website www.abb.com)

Fig. A8: Converter station, 200MW Rapid City based on CCC-HVDC transmission system with ±13kV DC link voltage
(source: ABB website www.abb.com)

Fig. A9: Converter station of the 500MW Vizag II LCC-HVDC system connected in back-to-back configuration with ±88kV DC link voltage (source: ABB website www.abb.com)

Fig. 10: HellsJÖn test installation in Sweden. The world's first HVDC Light transmission link rated at 3MW with bipolar DC link voltage of ±10kV, using 10km decommissioned AC line (for demonstration purpose).
(Source: ABB website www.abb.com)

1. AC filter
2. Converter reactors
3. Valves and DC equipments
4. Control equipment
5. Cooling system

Fig. A11: Converter station of 350MW, ±150kV Estlink VSC-HVDC transmission system based on two-level converter approach
(Source: ABB website www.abb.com)

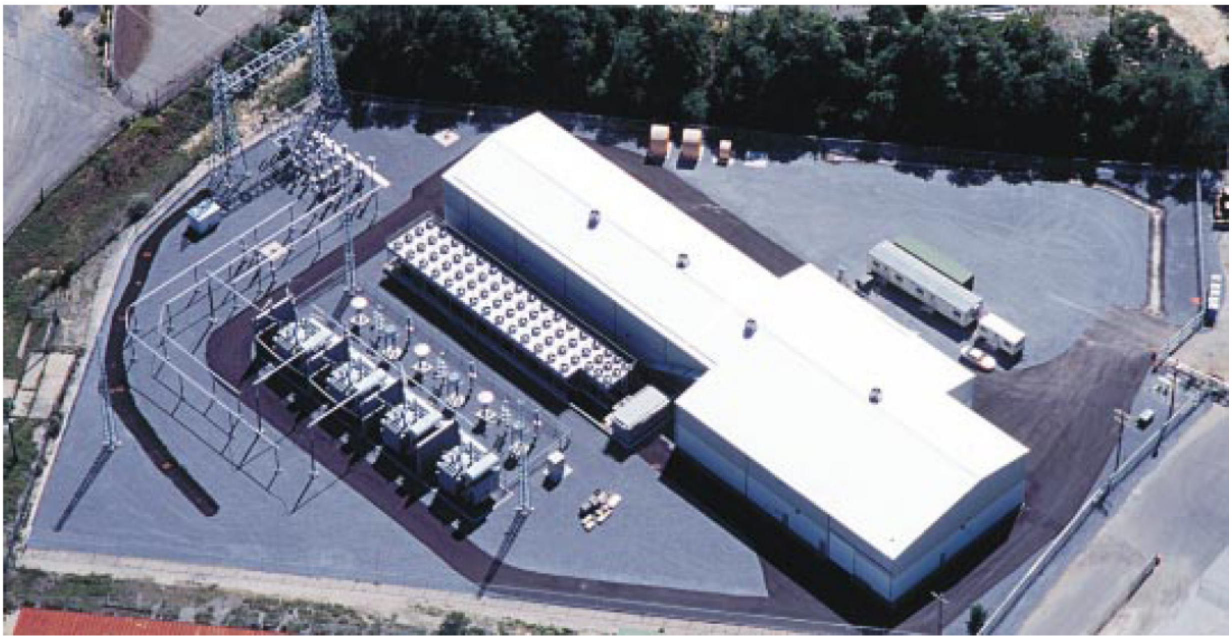


Fig. A12: Typical converter station, 350MW, ±150kV DC link voltage
(Cross Sound VSC-HVDC based on NPC converter)
(Source: ABB website www.abb.com)

Fig. A13: Converter station at offshore wind farm, NordE.ON 2 Project where 400MW of wind power will be transmitted to Northern Germany, over 200km (Source: ABB website www.abb.com)

Submarine and land cables for VSC-HVDC Transmission

Fig. A14: Cables with copper conductor for submarine applications and aluminium conductors for land.

(Source: ABB website www.abb.com)

Table A3: Examples of converters for high HVDC light (Source: ABB website www.abb.com)

80 kV modules			150 kV modules			300 kV modules		
Converter	DC current	Sending power	Converter	DC current	Sending power	Converter	DC current	Sending power
Type	**A**	**MW**	**Type**	**A**	**MW**	**Type**	**A**	**MW**
M1	627	102.0	M4	627	191.3	M7	627	382.6
M2	1233	200.5	M5	1233	376.0	M8	1233	752.1
M3	1881	306.1	M6	1881	573.9	M9	1881	1147.9

Table A4: Cable ratings for bipolar VSC-HVDC (DC cable for VSC-HVDC is oil free; lighter than that for classic HVDC, because it is not required to withstanding the higher voltage stresses during power reversal;
and cheap and easy to lay)
(Source: ABB website www.abb.com)

Appendix B

Power Semiconductor Devices for Transmission and Distribution Applications

B1: General Background

Power semiconductor device technology is a key factor in the design of high-voltage DC (HVDC) and Flexible AC Transmission Systems (FACTS). Until recently these applications were dominated by line commutated thyristor systems. Although thyristor technology can provide robust low loss solutions; the use of line-commutated techniques has disadvantages in terms of reduced harmonic signatures and passive component sizes. Continued improvements in power device technology have allowed the extension of self-commutated, pulse-width-modulated (PWM) converters from machine drives applications to utility power/voltage levels. This approach can realise gains in terms of output harmonics, dynamic response time, and installation size.

For PWM systems there is a choice between two power electronic device families, the Insulated Gate Bipolar Transistor (IGBT or IEGT) and Gate Commutated Thyristor technology (IGCT, GCT or SGCT). Although IGBTs and IGCTs are available with broadly similar voltage rating, they represent significantly different device technologies. IGBTs are voltage controlled devices characterised by fast switching times and simple gate drive requirements. Individual semiconductor chip size for IGBTs is limited with the result that high power modules require parallel connection. IGCT devices comprise an improved Gate Turn-Off Thyristor with an integral gate drive board. Single chip solutions for the main power device are available to high current ranges. For a given rating, IGCTs achieve lower conduction loss than IGBTs at the expense of a complex gate drive, and slower switching times. An enhanced IGBT, termed the IEGT, is manufactured by Toshiba. This device is claimed to deliver improved performance in medium voltage applications, however data for the IEGT is limited. IGBT and IGCT devices are reported with maximum blocking voltages to the region of 6.5 kV, with recommended DC operating voltages between 50%-70% of this value. Medium voltage IGBT devices, in the 3.3 kV- 6.5 kV range, have a significantly lower current rating than that of the IGCT devices. For example, the rated current of the commercially available 6.5 kV IGBT is only 600 A.

To achieve the AC voltages required for transmission applications, converter systems must operate at voltages above the rating of a single power semiconductor device. Line-commutated systems achieve this though series connection of thyristor devices. For PWM systems, two basic approaches exist: series connection of power devices or multi-level inverters.

Series connection of devices allows the extension of two level techniques to satisfy the required voltage level. Voltage sharing networks and the need for closely matched devices restrict this approach, which faces problems of switching loss and high impressed *dv/dt*.

Multi-level inverters provide a mechanism for achieving higher output voltages given the available ratings of power semiconductor devices. Multi-level converters also offer the additional benefit of providing an output waveform with finer discrete steps when compared with the traditional two-level converter. This feature results in improved output power quality spectrum for a given switching frequency.

B2. Line Commutated Devices

B2.1. Thyristor Technology

The thyristor (Silicon Controlled Rectifier, SCR) was one of the earliest power semiconductor devices. The device is capable of forward and reverse voltage blocking behaviour. In the presence of forward voltage, the thyristor may be turned on by the injection of a relatively small gate current pulse, thereafter internal regenerative action latches the device in the conducting state. Conduction will continue until the forward current has reduced to near zero (holding current); following the current zero and charge recovery, the thyristor may again support forward voltage. The safe switching characteristic of thyristors requires that the rate of rise of current (*di/dt*) at turn-on and rate of rise of voltage (*dv/dt*) at turn-off are limited, which impose a requirement for external limiting circuits (snubbers).

Thyristor devices are available with high voltage and current ratings and robust current surge capability (10ms withstand current approximately 30 times rated current) Conventional thyristor devices are reported as commercially available with ratings up to 7.5kV and 2.6kA average current.

Fig. B1: 63mm, 6.5KV, 1350A Diode Module Source http://www.westcode.com

B2.2. Light Triggered Thyristors

Direct light triggered thyristors were developed in the 1990's. This technology replaces the electrical gate drive with a light-sensitive semiconductor region. Illumination of this region generates charge carriers in the thyristor leading to turn-on. Light triggering eliminates the need for isolated gate drive electronics, resulting in simplified series connection of devices. Light triggered devices with integrated protection have also been reported. [Advantages in Application-Design by using Direct-Light-Triggered Thyristors J.Przybilla et al. http://www.infineon.com/].

Commercial light triggered thyristors are reported with single device ratings of 7.5kV and 2.5kA average current. *(Infineon is the only source of commercial light triggered thyristors).*

B2.3. Thyristor Switching

Thyristors are turned on by the action of the gate firing pulse. Turn-off is achieved by the action of the external circuit which imposes the necessary current zero. In general this switching is achieved by a commutation process in which current is removed from one thyristor by the firing of another. The time required for this process is determined by the impedance of the switching path and the voltage at the instant of commutation.

In order to re-establish voltage blocking capability, the thyristor requires removal of the internal stored charge produced during forward conduction which imposes a delay before the device can support a forward blocking voltage.

Thyristor circuits must therefore restrict switching to ensure a minimum interval (extinction angle) between a thyristor turning off and the application of a

forward voltage. If forward voltage is reapplied before this time, thryristor conduction may restart; this is known as commutation failure.
The turn-off characteristic limits the switching frequency of thyristor based systems to that of the power system. Control of these systems is achieved by varying the commutation instant relative to the supply voltage (firing angle control). This imposes constraints on system performance.

- Restricted switching frequency may give rise to the injection of low order harmonic current and results in increased power filtering requirements.
- Harmonic filters may be large, complex and act as a sink for network harmonics generated by other equipment.
- Converters switching at the line frequency require large passive components, sized for their impedance at the fundamental. These are physically large and electrical settling times can limit response times.
- Thyristor based systems have limited control functionality. (Notably line commutated HVDC systems have a high reactive power consumption and no independent control of P and Q components.)
- Because turn-off is determined by external voltage conditions, thyristor circuits can malfunction (commutation failure) in the event of network voltage transients. This may limit fault ride-through capability.

Despite these limitations, the high power capability, robust transient ratings, and low conduction loss make thyristors an attractive option for transmission applications.

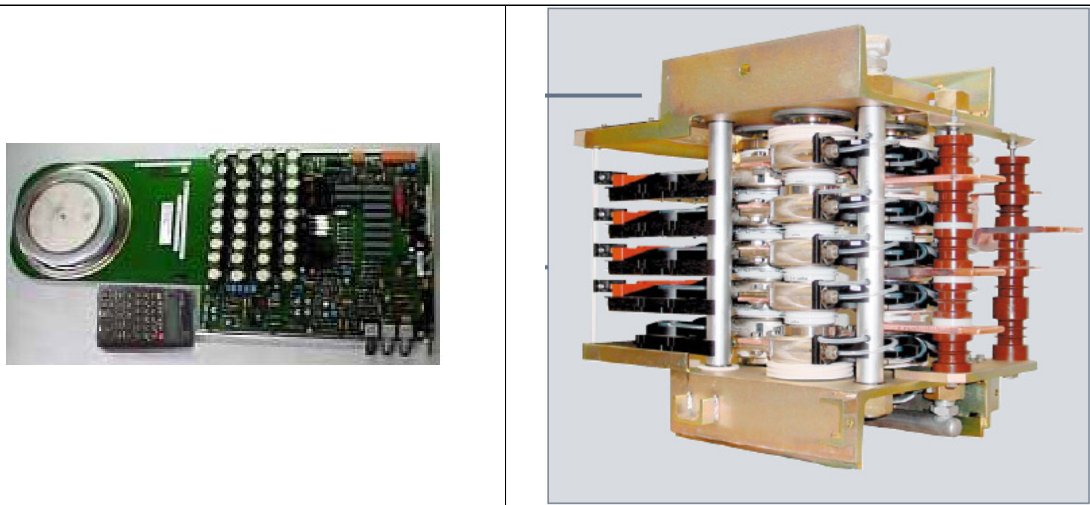
B3. Self-Commutating Devices

B3.1. IGCT/GCT Device Technology

IGCTs (and GCTs) are an evolution of GTO technology both in terms of device structure and packaging. Typically IGCTs achieve lower on-state voltages and turn-off times when compared with older Gate Turn-off Thyristors (GTO). Integrated Gate-Commutated Thyristors (IGCTs) display some important advantages over Insulated-Gate Bipolar Transistors (IGBTs). They have a much higher peak current carrying capability and a lower on-state voltage compared with IGBTs. An IGCT integrates an enhanced GTO with an appropriate turn-on and turn-off gate drive circuit for the device, Fig. B2(a). The gate turn-off thyristor is inherently robust and utilises one silicon device, unlike an IGBT module that will typically integrate many separate silicon wafers, interconnected, for example in plastic packages, using bond wires. Power device reliability is excellent at the expense of a complex, high current gate drive circuit, Fig. 1(a). During the switching transient the IGCT gate drive must source/sink a current in the order of kA; this gate current requires a large array of driver FETs and energy storage capacitors. The 4.5 kV, 4 kA IGCT gate drive shown in Fig. B2(a) requires 36 electrolytic capacitors and 21 FETs. The impact of IGCT gate drive complexity on reliability is a matter of debate between manufacturers. Snubber requirements are reduced to a single *di/dt* snubber compared with older GTO technology which additionally requires capacitive turn-off snubbering.

The turn-off requirements of IGCTs give rise to relatively high gate drive power requirements. For utility applications voltage levels are such that series connection techniques are required.
Supplying the necessary gate drive power to the many isolated stages of a high voltage converter system will result in increased system complexity relative to an IGBT based system. ***This may prove to be a key limitation to the use of IGCTs in transmission applications***.

Unlike IGBTs, IGCTs do not display a current limiting characteristic, therefore active protection circuits must be provided. Such circuits require current sensing, *di/dt* limitation and additional switching devices. These protection circuits are normally integrated into the turn-on snubber circuit where series inductance is used to manage switching current and the rate of rise of fault current. IGCTs are typically available in press packs.
Fig. B2(b) shows a 9 MVA power electronic building block using IGCT technology.



(a) (b)

Fig. B2: (a) ABB IGCT with associated gate drive circuitry and
(b) a compact 9 MVA IGCT-based power electronic building block.

B3.2 Emitter Turn-off Thyristor (ETO)

The ETO was developed to address the high gate current requirements of the IGCT. This approach aims to combine the low gate power of the IGBTs with the robust, low loss characteristic of the GTO. The ETO is in fact a hybrid device in which an additional MOSFET array is connected in series with the principal GTO device. Multiple parallel MOSFETs are required in order to achieve the high current rating and to limit the on-state voltage drop; this feature may compromise reliability compared to a single high current GTO device. Experimental ETO devices have been reported with ratings of 6kV and 1.5kA. Data on commercially available devices is scarce.

Although the ETO has been the subject of significant US government research projects, current information indicates that it is an emerging rather that commercially viable device. Fig. B3 shows an example of a 4.5kV ETO.

Fig. B3: 4.5kV ETO module with 4kA snubberless switching capacity.
MOSFET arrays in the emitter and gate connections of the basic GTO building block.
Source: ‘Performance of New Generation Emitter Turn-Off Thyristor’, Bin Zhang, Alex Huang et al. 2002

B3.3. IGBT Technology

IGBTs combine the on-state voltage characteristics of bipolar transistors with the low power gate characteristics of MOSFET devices. Fast switching speeds and a near rectangular safe operating area allow the use of IGBTs without external snubber circuits. IGBTs are currently the dominant power device for low voltage (<1kV) drive systems. IGBTs with blocking voltages up to 6.5 kV are available, however these devices show significant increases in both conduction loss and switching energy. In general, medium voltage IGBTs exhibit lower switching loss and increased conduction loss relative to IGCTs/GCTs.

Unlike IGCTs, IGBTs display self limiting over current behaviour. This allows a measure of short circuit protection through the use of intelligent gate drives without the need for additional power circuits.

IGBTs are available in press-pack and single-sided plastic modules.

a) IGBT Press pack Technology

IGBT press pack technology, fig. B4, provides the opportunity to cool the IGBT device(s) on both sides thereby improving cooling capability and reducing junction temperatures. Press pack IGBTs use multiple devices in parallel to achieve high current ratings. IGBT technology requires significantly more Silicon surface area for a given current rating compared to IGCT technology. One advantage is that there is more surface area available for cooling though this has to be balanced against the increased conduction loss that IGBT technology displays compared with the IGCT.

Press pack IGBTs can be designed to fail to short circuit. The design requires a paste, foil or component that melts and fuses with the silicon wafer and the pressure plate contact, under fault current conditions, creating a low-resistance conducting path (a short circuit) between the external collector and emitter terminals of the device. In a plastic package, the fault current fuses the bond wires, and the device will fail to an open circuit. Therefore, press-pack IGBTs are particularly useful where series-connected IGBTs are required for N+1 redundancy. When a device fails, the stack is still able to commutate on and off without remedial action on the part of the controller. The failed device can then be replaced at the next scheduled maintenance period.

Fig. B4: Example of press-pack IGBT modules.(Source TMGE website).

b) IGBT Plastic pack technology

Plastic pack technology is low-cost where external connections are made to the individual IGBT devices using bond wires, Fig. B5. Typically, the device is then encapsulated in silicon gel. Plastic packages often rupture under fault conditions as their I^2t rating is much lower than the equivalent press pack. The post-failure state of the package is likely to be open-circuit, though this is not guaranteed.

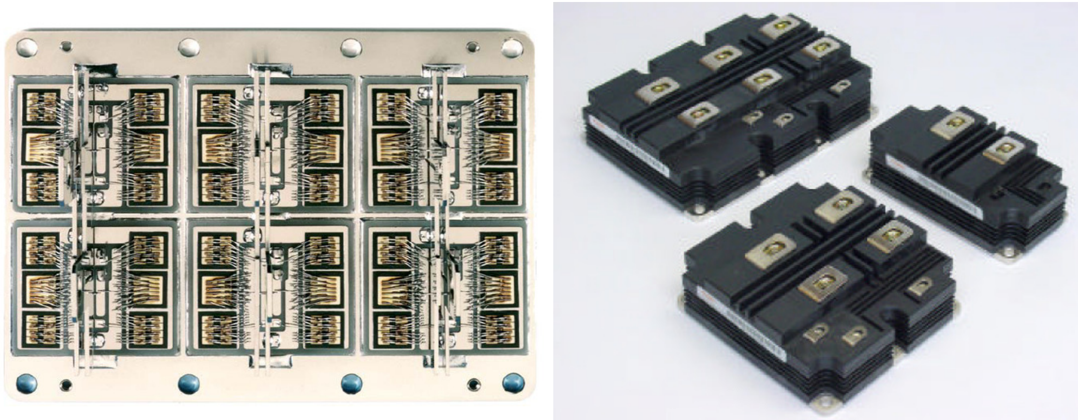


Fig. B5: IGBT devices mounted on base plate with bond wires making connections from individual devices to external connectors. (Source Infineon Website)

c) IEGT Technology

The Injection-Enhanced Gate Transistor (IEGT) is manufactured by Toshiba. It represents improved IGBT technology for medium voltage applications. By optimizing the gate structure it is claimed that the IEGT achieves a reduction in both on-state voltage and switching loss. A 42 chip, 4.5 kV, 5.5 kA press pack IEGT has been reported. The IEGT is manufactured in both press-pack and single-sided plastic pack versions.

B4. Fast Recovery Diodes

In addition to the principle power switch, all self commutating converter systems (based on voltage source inverter principles) require an anti-parallel diode to provide a conduction path for reverse current. These devices differ from rectifier diodes in that they must be compatible with the operating frequency (in the order of kHz) and switching speed of the converter.

In particular, these devices must have well controlled turn-off behaviour (reverse recovery characteristic); this determines the proportion of reverse current that is passed by the diode during voltage reversal and also the transient overvoltage seen by the main switching device when the diode enters the off-state.

Fast recovery diodes display significantly higher conduction loss and reduced transient overload capability when compared to rectifier diodes. ***For many utility applications, transient diode ratings may prove a limiting factor, for instance DC side faults in HVDC systems***.

There have recently been significant advances in silicon carbide diodes which are now commercially available with voltage ratings up to 1.7kV, 10A. Although these devices offer some superior characteristics to silicon devices they have yet to achieve the ratings required for transmission and distribution applications.

B5. Performance of Line Commutated and Self-Commutated Power Converters

Converter systems using self-commutating power devices can achieve a high level of control over the voltage and current waveforms that they inject to the system. The control capability being determined by the effective switching frequency 1 to 2 kHz for transmission and distribution applications and the associated ac harmonic filters. The development of multi-level techniques may achieve improvements in response characteristics. In general, self-commutating systems may give superior response to network transients than systems based around thyristor technology.

The use of self-commutating devices facilitates pulse width modulation and multi level techniques. These techniques may result in superior performance of thyristor based systems which are limited to line frequency switching. Passive filter requirements may be significantly reduced, leading to reduced size, improved dynamics and better rejection of harmonic/transient events. Energy smoothing components will operate at the switching frequency (in the order of 1kHz) and may be reduced relative to LCC based systems.

The benefits of self-commutated devices are achieved at the expense of increased on-state voltage and lower power capability relative to thyristors. The increased functionality is achieved at the expense of increased losses and complexity of systems. Overload capability is less than that of thyristor devices making protection more difficult.

Table B1. Example of Available Device Ratings (representative device ratings for high-voltage, high-current modules)

Device	Rated Voltage	Rated Current	On-State Voltage
Thyristor (Infineon T2871N)	7.5kV	2.6kA	2.7V
IGBT- MG1200FXF1US53 (Toshiba))	3.3kV	1200A	3.7V
Light Triggered Thyristor (Infineon T 2871N)	7.5kV	2500A	2.5V
IGCT (ABB 5SHX 26L4510)	4.5kV	1010A	2.95V
IGBT (Infineon FZ600R65KF2)	6.5kV	600A	5.3V

Appendix C

Current state of the art for
Wide Band-Gap Power Semiconductor Devices

C1. Introduction

For high-voltage, power applications, the voltage limits of silicon technology have been reached, for over twenty years in the case of thyristor and diode technology and five years for the more recent IGBT device. Although extensive die and package parallel connection can be used to increase power capability, voltage limits of 8.5kV for diodes/thyristors and 6.5kV for IGBTs hamper higher power use of silicon based devices. These limits are exasperated by slower switching speed, hence increased power losses, as voltage rating is increased.

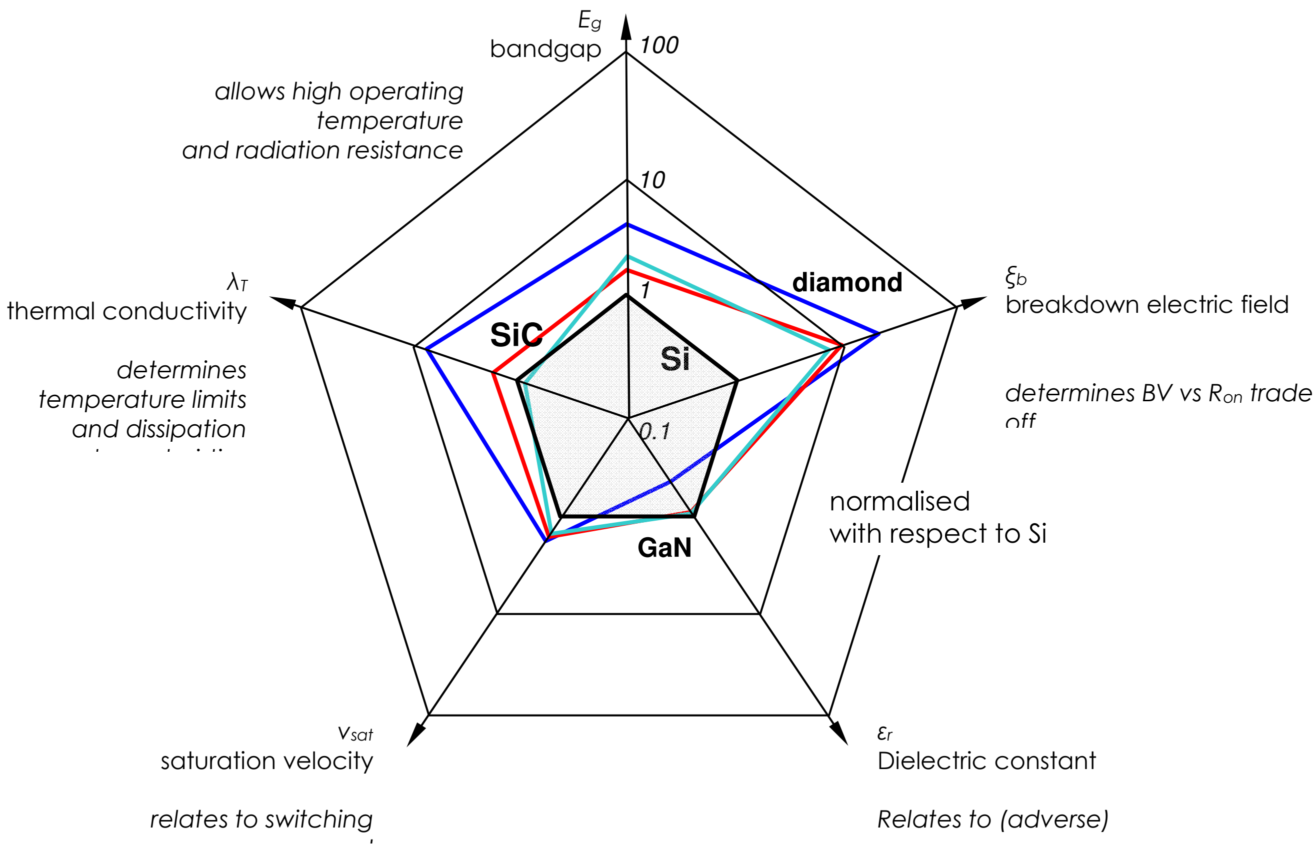


Figure 1: *Key electrical, physical, and thermal characteristics of group IV monocrystalline silicon, gallium nitride, diamond, and 3 polytypes of silicon carbide, at room temperature.*

It is an established fact that wide band gap materials like those present in tableC1, offer potential for high-speed, high-voltage, high-current, power switching devices. The higher the breakdown electric field strength, the higher the possible device voltage rating, while a higher saturated velocity results in a faster switching device. Higher thermal conductivity increases the power dissipation and operating temperature limits.

Table C1: *Key electrical, physical, and thermal characteristics of group IV monocrystalline silicon, gallium nitride, diamond, and 3 polytypes of silicon carbide, at room temperature.*

material	Bandgap energy	Dielectric constant	Electron mobility	Breakdown electric field	Saturated electron drift velocity	Thermal conductivity	Figure of merit w.r.t Si	coefficient of linear thermal expansion
	E_g	ε_r	μ_n	ξ_b	v_{sat}	λ_T	**FoM**	α
	eV	pu	cm^2/Vs	MV/cm	10^7 cm/s	W/mK	$\lambda_T \times (\xi_b \times v_{sat})^2$	$\times 10^{-6} K^{-1}$
Si	1.12	11.9	1400	0.3	1.0	130	1	2.6
GaN	3.44	9.5	900	3.0	2.5	110	407	5.6
3C-SiC	2.36	9.7	800	1.3	2.7	700	2381	7.7
4H-SiC	3.25	9.7	700	1.8	2.7	700	3241	5.2
6H-SiC	2.86	9.7	400	2.4.0	2.0	700	1307	5.2
diamond	5.5	5.8	2200	5.7	2.7	1000	54000	0.8

C2. Silicon Carbide

In the area of high-voltage (>600V) power switching based on wide bandgap materials, only SiC devices have progressed to the commercialisation stage. The devices available, based on 4H-SiC, are Schottky barrier diodes - SBD (multi-sources – Cree, Infineon, ST-M, etc.), mosfets (virtually single source - Cree), and the JFET (Semisouth). These available device types are currently limited to 1200V/1700V breakdown voltage limits.

Device development is hampered more by processing and metallisation issues than by defects in the SiC 100mm diameter substrate material.

C2.1. SBD

The Schottky barrier diode is rated at 1200V, 50A, based on an 8mm by 4mm die. (1700V, 25A die are currently being released by Cree) Being a wide bandgap device, the onstate voltage is about twice than with traditional Si based SBDs, and similar to the convention fast recovery Si diode. Being a majority carrier device, it does not suffer from reverse recovery effects, but has a large barrier junction capacitance. Advantageously, the device has a positive temperature coefficient, meaning device parallel connection is possible.
Cree have developed a 10kV, 20A SBD.

C2.2. Trench normally-off JFET

Available normally-off trench JFETs are rated at 1700V, but the on-state resistance is ½Ω (Semisouth). At the 1200V level, 63mΩ devices are available from Semisouth, and coupled with a positive temperature coefficient offer parallel connection possibilities. Switching speeds are ultrafast, typically 20ns at turn-on and turn-off. A normally on JFET is also available from Semisouth. (The SiCed SiC JFET is undesirably a normally-on device and is used in conjunction with a Si mosfet.)

C2.3. MOSFET

The n-channel mosfet from Cree is rated at 1200V, 20A, with an on-state resistance of 75 mΩ. Switching times are of the order of 20ns and a positive temperature coefficient offers parallel connection possibilities.
Cree have developed a 10kV, 20A, 70ns SiC MOSFET and a 12kV IGBT, and predict devices can be rated to between 15kV and 20kV.

C2.4. BJT

BJT development is still considered experimental since devices have operating stabilisation problems, with degradation caused by crystal defects, called Basal surface transition, in the epitaxial layer. Both Honda/Shindengen and Transic have developed 1200V, 100A devices with a gain of 135 at room temperature with a die area of 7mm by 8mm. The BJT is considered viable because it is simpler to manufacture than other power switch types. As with the Si power BJT, in the longer term, this processing advantage will dissipate.

C2.5. Modules

Because of high die costs, SiC modules are a specialty item, with reported 400A and 800A, 1200V dual switch modules produced for military applications (US Army, ManTech). Die measuring 8mm by 7mm have been used in 1200V, 1200A single switch modules. The Sandia (APEI Inc) half bridge modules (both JFET 1200V, 15mOhms and MOSFET 600V, 13mOhms) operate with junction temperatures over 300°C, but cost $2,500 in volume. Very high efficiencies are associated with higher SiC junction temperatures.
Cree has demonstrated a 1200V, 1400A SiC MOSFET based half-bridge module.
A Honda-ROHM module is rated at 1,200V, 230A with SiC Schottky barrier diodes (5.14mm^2) and SiC MOSFETs (4.8x2.4mm).
Powerex offers two SiC MOSFET modules (QJD1210006 and QJD1210007) rated at 100A, 1,200V that operate over a temperature range of -40° to 200°C.

C2.6. Conclusion about SiC

In the 1200V range, SiC devices and modules are available, at a cost. This voltage rating is suitable for three phase mains based inverter applications. The modules are based on the experience gained from the last twenty years of progress in IGBT based power modules, which is directly translatable to SiC. Devices rated at 1700V have been reported, but are not in production. The availability step from 1200V to 1700V devices, then modules, can be expected within the near future. A key factor limiting commercialisation of 1700V technology is the lack of a high volume market.

Switches and diodes rated at 10kV have been made (Cree), but are still experimental (Cree have demonstrated 10kV, 120A MOSFET half-bridge modules). Such SiC modules are applicable to HVDC and FACTS applications. Research at this voltage level is somewhat restricted by the lack of a high volume market.

C3. Gallium Nitride

In additional to the intrinsic cost of SiC-based technology, it is not highly scalable in substrate size, epitaxial deposition equipment throughput, material supply, and device-fabrication manufacturing platforms.

GaN-on-silicon epitaxial processes offer a combination of high electron mobility and higher bandgap, and provides GaN-based devices with a reduction in device-specific on-resistance $R_{DS(on)}$ for a given reverse voltage capability compared with both SiC and silicon devices.

It is difficult to achieve higher voltages for GaN hetero-epitaxy on silicon substrates. Thick GaN hetero-epitaxial films are easier to process on sapphire substrates, since the mismatch in thermal coefficient of expansion is small, but insulating substrates restrict the power-handling capability of the device, due to self heating constraints. It is therefore expected that SiC will remain an attractive choice for high voltage switches (above 1,500V) in the future.

Companies active in GaN power device R&D include Fujitsu Laboratories, Ltd., International Rectifier Corp., Sanken Electric Co., Ltd., NEC Electronics Corp., and Panasonic Corp.

C3.1. Gallium nitride on silicon (devices rated < 1700V)

(a) Diode

Sanken Electric Co., Ltd has developed a high-breakdown-voltage (800V) GaN-on Si SBD. Forward voltage is 0.5V lower than previous devices, achieved with the use of a new barrier metal and a two-dimensional electron gas are brought into direct contact in excavations made in the substrate.

(b) MOSFET

Sanken Electric Co., Ltd has developed a normally-off GaN 800V FET using the company's proprietary epitaxial technology for high-quality GaN crystals on a silicon substrate, and adopting a new device structure. The device has a normally-off design.

Efficient Power Conversion Corp (EPC) of El Segundo, CA, USA has introduced a family of enhancement-mode power transistors, based on its proprietary gallium nitride on silicon (GaN-on-Si) technology, for power management device applications. The specification range is 40–200V and 4–100 milliohms.

International Rectifier have proprietary GaN-on-silicon epitaxial technology that improves application-specific figures of merit (FOM) of up to a factor of 10 compared to state-of-the-art silicon-based 150mm technologies. iP2010/2011 dc to dc orientated GaN devices are rated at 13.5V, 30A.

The Panasonic chip (six devices on one chip) measures 2.7mm x 2.5mm in area, and is an inverter IC integrating six 700V GaN FETs. Normally-off operation is realized through a p-type AlGaN gate above the AlGaN/GaN heterostructure.

NEC transistors are fabricated with a source-to-gate separation and a gate length of 1µm, and a gate-to-drain distance of 15µm. At a threshold voltage of +1.5V, the MISFET produced normally-off characteristics, with a maximum drain current of 240mA/mm, and an on-resistance of 20 Ohm-mm. The three-terminal off-state breakdown voltage is more than 1000 V.

HRL have developed a GaN HEMTs fabricated with a fluorine-based process, resulting in a breakdown voltage in excess of 1100V, and a leakage current of less than 10µA/mm at voltages below 550V.

Many other companies are investigating GaN MOSFET devices rated at less than 1kV, including Furukawa, Toyota, etc.

C3.2. Gallium nitride on sapphire/SiC (for devices rated at >1700V)

Diode

The Panasonic GaN-based diode has a breakdown voltage of 9400 V with an on-state resistance of 52 $m\Omega cm^2$. The electrodes are over a recessed structure which reduces the contact resistance between the electrodes and the current channels, thereby reducing the on-state resistances.

MOSFET

Panasonic has a gallium nitride power transistor with a breakdown voltage over 10,000V. A novel device structure and a high quality GaN film on a highly resistive sapphire substrate realize the 10,400V breakdown voltage with an on-state resistance of $186\Omega cm^2$. Overlap of the electrodes via insulating film on the surface side is eliminated by use of a back-side electrode with through-holes in the sapphire, which results in the high breakdown voltage. The through-hole in chemically stable sapphire is formed by laser drilling with a high power pico-second laser.

C.3.3. Conclusion about GaN

No high-voltage GaN devices are commercially available. Devices rated below 1700V appear viable because they are based on GaN on Si technology. All research above 1700V is based on GaN on sapphire or SiC, which suffer from problems associated with processing such structures.

C4. DIAMOND

Diamond is a high-quality material that offers hardness, thermal conductivity, optical transparency over a wide wavelength range, and chemical stability. As a semiconducting material, it has excellent dielectric breakdown and mobility. In particular, if adopted in semiconductor power-switching devices, high performance can be realized in the form of high-temperature non-cooled devices associated with high-voltage and high-current density.

The Diamond Research Center and the National Institute of Advanced Industrial Science and Technology (Japan), have developed 200V SBD rectifying diodes for power devices using ruthenium and diamond. They can operate at temperatures exceeding 400°C.

Diamond based FETs are restricted mainly to low-voltage rf applications. Generally diamond exploitation for high-voltage power switching devices is at an immature research stage.

C5. Conclusion on wide band gap power switching devices

Generally SiC power devices (SBD, PIN diodes, MOSFETs, and IGBTs) are available with voltage ratings up to 1700V. These SiC devices have been demonstrated in practical applications, with device packages rated at 10kV, 100A, 200℃.

GaN, although theoretically more promising than SiC, has technological problems at voltages above 1700V, while diamond devices > 1700V (given the availability of SiC devices) are too immature to be viable possibilities for the next decade.

The www address below summaries SiC device and module development as of 2010, with devices rated at below 1700V and predicted devices rated to 15kV.
http://arpa-e.energy.gov/LinkClick.aspx?fileticket=RaTsvSs0acE%3D&tabid=116

The following reference also reports SiC developments and additionally reports a 4.5kV, 180A SiC pin diode and a 5kV 300A SiC thyristor
http://www.nist.gov/eeel/high_megawatt/upload/2007_Grider.pdf

A status summary of SiC and GaN, mainly at ratings below 1700V, may be found at:
http://www.power-mag.com/pdf/issuearchive/37.pdf

Appendix D

Other Network Capacity Enhancement Technologies

D1. Introduction

This appendix discusses two network technologies that are not new and are already in use on the transmission system in Britain, but for which there is currently debate about how much their use can be extended to facilitate additional renewable generation in a cost-effective manner. (Because they are not new technologies and their operational characteristics are well understood in broad terms, they are not the subject to detailed simulation studies in the ETI Network Capacity project).

The technologies are:

- special protection schemes, in particular system-to-generator inter-trips, and
- phase shifting transformers.

D2. Special protection schemes

The requirement for secure operation of transmission systems, i.e. that no one of a particular set of fault outages or 'secured events', were it to occur, would cause violation of system limits, often dictates that power transfers should be restricted before the event takes place. This may require the restriction of operation of generation by limiting the output of units in critical exporting areas or constraining on units in importing areas. However, because fault outages are relatively rare whereas preventive actions must be effective at all times, there has also been attention by system operators to corrective actions, i.e. actions taken only after the occurrence of an unplanned event. Depending on the nature of the violation of system limits that the event would cause, the action may be instructed manually by the system operator (for example if a high loading is still within 20 minute ratings but above post-fault continuous ratings) or automatically by, for example, a 'system to generator inter-trip', more generally known as a 'special protection scheme' (SPS) or 'system integrity protection scheme' (SIPS) [1,2]. These approaches are already used in many places including Britain.

In terms of economics, the balance of costs between preventive and corrective measures might be expressed as in Figure D.1. On the preventive side, the costs are definitely incurred while, on the corrective side, a cost-benefit analysis might use the expected cost of action, i.e. one that is dependent on the probability of the action being required. However, it should also be noted that the scope for adequate corrective actions should be established in advance. For example, the post-fault tripping of generation should be accompanied by a balancing increase in power generated elsewhere. This will require scheduling of sufficient response and reserve. Moreover, in Britain, the 'arming' of system to generator inter-trips generally has a price set by the owner of the affected generator.

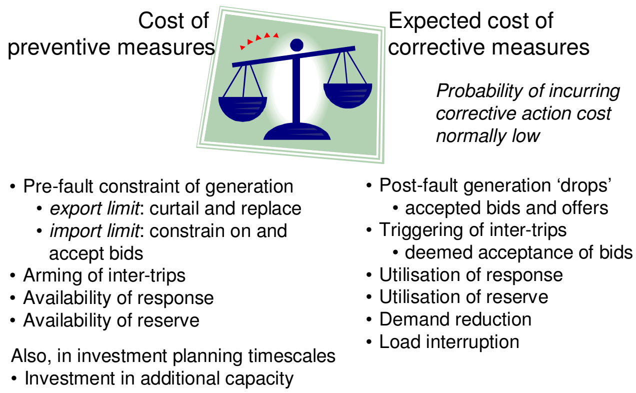


Fig. D.1: Balancing of costs of preventive and corrective actions

The use of inter-trips for management of the impact of limited transmission capacity has received renewed attention in Britain in the last few years. In particular, it has been suggested by some as having the potential to dramatically reduce the amount of transmission reinforcement needed to export power, especially that from new wind farms, out of Scotland.

Where the main actions concern re-dispatch of generation, the rewards for use of corrective actions instead of preventive are clear. However, in the context of import constraints, the only corrective action that is available may be reduction or shedding of load. Furthermore, an operator may view dependency on corrective actions as risky – will the corrective action succeed when it is needed? If the consequences of an action's failure might be a cascade of outages or a voltage or frequency instability, an operator is likely to prefer preventive actions. This is particularly true when the weather is forecasted to be bad and there is an increased likelihood of one or more fault outages in quick succession that prevent re-securing of the system after each event.

In recent consultation, the three GB transmission licensees (TLs) noted that the cost of an inter-trip 'service' with a generator depends on its context [3]. For example, where there would seem to be some choice in terms of which generators would be tripped, the service is regarded as 'commercial' with no regulation of the prices of 'arming' or utilisation of an inter-trip. In such circumstances the TLs argue that, in the longer term, use of an inter-trip in place of reinforcement of the network is unlikely to be economic. The TLs noted the increased system risk associated with the arming of multiple inter-trips in an area, particularly in adverse weather. They also noted that use of an inter-trip might allow a relatively limited amount of generation capacity to connect and operate, but that further generation would need further inter-trips, increasing operational risks. The alternative of reinforcing the network's capacity was argued to provide greater flexibility without increasing operational risk.

For connections of, for example, single wind farms on spurs of the network where that spur has limited capacity and there is no significant interaction with other connections, inter-trips remain a valuable tool. The approval in 2010 by the Department for Energy and Climate Change of a 'connect and manage' approach to accommodation of wind generation on the GB transmission system [4] has given a very immediate motivation to the use of inter-trips in such a context, largely as the cost of constraining the output of wind farms pre-fault would normally be very much larger than the expected cost of post-fault re-dispatch. Moreover, if an inter-trip is part of a connection agreement, the cost of arming and utilising it can be controlled as the corollary of enabling earlier connection. This is currently being actively pursued by National Grid.

The attractiveness of an inter-trip on a network spur is increased if the amount of reduction of generation output can be adapted to the circumstances, i.e. the concept of 'soft' inter-tripping is used. The difference between that and the conventional inter-tripping currently used is that rather than a hard 'on' or 'off' action that physically trips an entire generating unit when the trigger event occurs, output is maintained where possible albeit at a lower level determined according to the net export level and the post-event export capacity. This varies with the level of demand within the exporting area at the time of the event. Such an idea is already used in the 'active network management' scheme in the distribution network in Orkney [5] and is analogous to the automatic regulation of area control error in, for example, parts of the US [6]. It might also be noted that the export capacity varies with ambient conditions near the limiting circuit – with higher wind speeds and/or lower ambient temperature, the current rating of an overhead line will be higher. In other words, a 'soft' inter-trip might be linked to a 'dynamic rating' scheme that calculates the current carrying capability of a line in real time.

Actions, whether preventive or corrective, that do not involve re-dispatch of generation and the costs associated with it are understandably attractive. The ability to reduce or increase the power flowing on branches of a network by means of changing the tap positions on phase shifting transformers is one example that is discussed below. (Back-to-back power electronic converters or thyristor controlled series compensation will have similar capabilities but significantly higher costs).

D3. Phase shifting transformers

Phase shifting transformers (PSTs) or quadrature boosters (QBs) can be a useful option for controlling the flow of power under different operational circumstances. In particular, they offer the possibility of flexibly increasing utilisation of the thermal capacity of the network under a variety of different conditions. A number of QBs or PSTs are already installed in GB [7] and in the interconnected electricity network of continental Europe [8]. However, practical experience suggests that there is room for improvement in the way these units are operated both for day-to-day operation and in the assumptions that may be made about them for long term planning purposes.

This mainly concerns the degree to which the settings on multiple PSTs could be coordinated to maximise the network's power transfer capability without making it unduly vulnerable to differences between the planned operating state of the system and the actual one.

A phase shifting transformer's principle of operation is that it manipulates the voltage angle different between the two ends of a network branch by inserting a phase shift angle α that can increase or decrease the original angle δ and consequently the flow of active power on the branch. The flow of reactive power is also influenced but to a lesser extent. The phase shift angle can be acquired either by the appropriate connection (Y-Δ or Δ-Y) of the windings of a single three-phase transformer [9] or by using two separate transformers.

In the latter case, the transformer consists of a parallel (shunt) branch and a series branch. Power is extracted from the network through the parallel branch and injected back into the transmission line by injection of a voltage through the series branch. One can distinguish between two different design options. In the first – the Phase Angle Regulator (PAR) – the injected voltage is of the same magnitude as the line's voltage but is out of phase with it. This has the effect of introducing a controllable phase shift angle into the line. In the second design option – the Quadrature Booster transformer (QB) – the injected voltage is always shifted by 90° with respect to the line voltage. The magnitude of the injected voltage is the controlled variable [9]. (All the PSTs installed on the transmission network of GB belong to the second category).

Quadrature boosters and phase angle regulators have some differences in their operational characteristics. The most important one is that a QB has a greater effect on the reactive power flow on the line and the nodal voltage than that of PARs. While the location of a PAR on either end of a line will make no difference to the transmission characteristics or to the voltage profile of the network, this is not the case with the location of a QB [9].

Other important design characteristics of a phase shifting transformer are the through MVA ratings (nominal and short term), the phase shift angle range at no load and at rated load operation and the physical footprint (a PAR being generally larger but often having a greater control range) [10].

Although optimisation software was used at the investment planning stage to identify the potential benefits of PSTs in terms of maximization of boundary transfer capability [11], there is currently no overall coordination of the operation of the PSTs on the GB transmission network [12]. In steady state, pre-fault conditions, the PSTs are generally operated close to their nominal tap settings. After a fault has occurred, the PSTs may participate in post-fault corrective actions based on scenarios studied off-line in advance that take into account a credible set of contingencies. Usually the scenarios anticipate that only PSTs located at one particular site will be used as part of the corrective action. There is no automation of the control actions that involve the PSTs; instead, they are operated manually from the control centre.

The main reasons for restriction of PST tap changes in GB are understood to be that:

- pre-fault settings and changes to settings post-fault must be considered. Pre-fault continuous line ratings are pertinent to the former but a large set of possible contingencies influence the latter with short-term ratings needing to be checked for the immediate post-fault state before there is any chance to change tap settings; there are sometimes conflicts between these constraints.
- a co-ordinated set of tap positions, both pre- and post-fault, might maximise pre-fault power transfers but leave the system very close to a limit post-fault, especially if there is a failure to communication or actuation of one or more tap changes after occurrence of a network fault or the actual state of the system is different from that which was anticipated at the operational planning stage.

The restriction in GB of changes to PST tap settings to just one transformer at a time means that, in many instances, pre-fault constraint of generation or post-fault re-dispatch of generation will be necessary. The coordination of PSTs in future system operation promises a fuller utilisation of the available thermal capacity of the network but raises concerns among operators. One of the key challenges is the interaction between the control actions at one PST device and other parts of the network.

Any action taken on one part of an interconnected network has an effect, albeit sometimes small, on every other part of it. This is particularly true of actions that, in effect, change the series reactance characteristics of the network and shift large amounts of power onto other branches. For instance, reference [13] describes how, during pre-commissioning tests of the phase shifters installed at the Meeden substation close to the Dutch/German border, it was realised that changing the tap settings of the devices at Meeden has a significant effect on the power flow on the interconnectors between Netherlands and Belgium as well as those between Belgium and France. It may also be noted that, although phase shifting transformers are able to influence the flow of power on a transmission line, they are not able to determine it completely. The flow of power on a transmission line is determined by the circuit parameters of all the transmission lines of the network as well as the disposition of generation and demand across the network.

For coordinated control to be fully trusted by system operators, optimisation algorithms and techniques have to be developed that will determine both the optimal combination of settings that takes into account uncertainty about the future state of the system and a secure way to reach them. This means taking into account the dynamics of the system while it is being shifted from one intermediate state to the next one. In addition, the possibility of secondary failures should be considered either in the design of a coordinated control system or in the determination of settings. These possible failures include the failure of individual tap change actions or failure of communication.

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