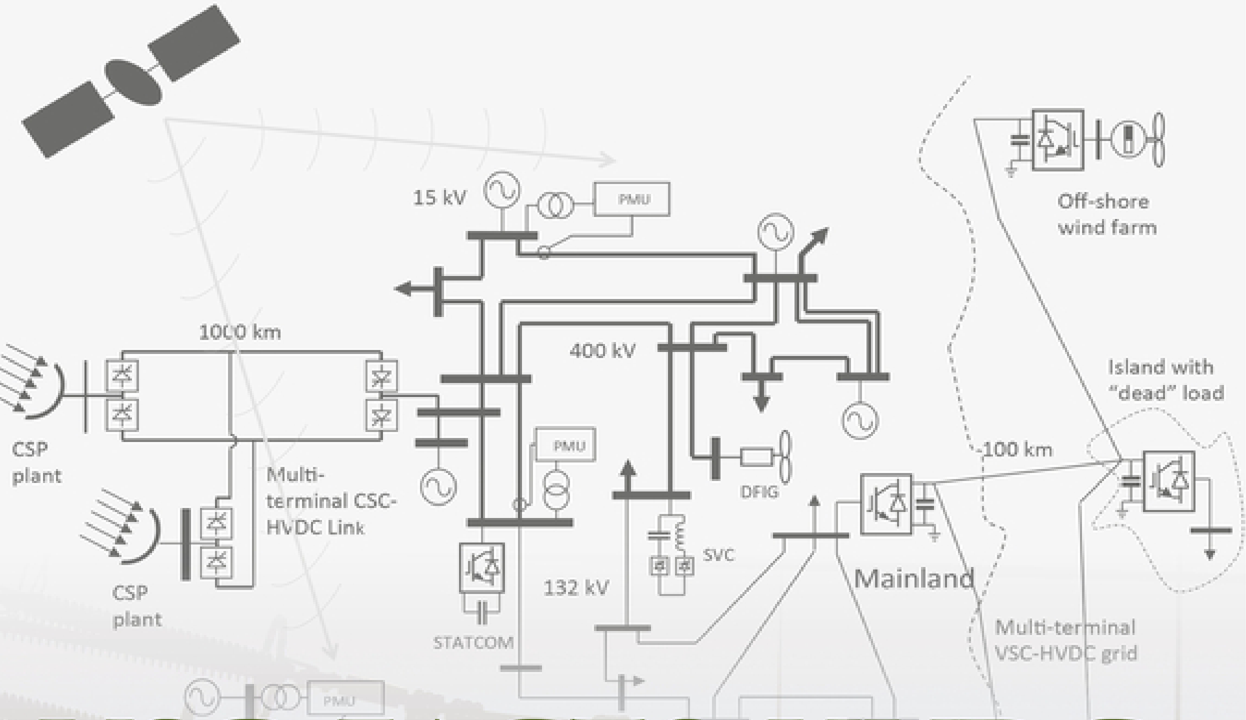

VSC-FACTS-HVDC

Analysis, Modelling and Simulation in Power Grids

Enrique Acha • Pedro Roncero-Sánchez
Antonio de la Villa-Jaén • Luis M. Castro • Behzad Kazemtabrizi

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To the memory of Jos Arrillaga, the one who wrote the most and best about HVDC transmission.

Contents

Preface

Electrical power transmission using high voltage direct current (HVDC) is a well-established practice. There is common agreement that the world's first commercial HVDC link was the Gotland link, built in 1954, designed to carry undersea power from the east coast of Sweden to the Island of Gotland, some 90 km away. The original design was rated at 20 MW, 100 kV and used mercury-arc valve converters. Its power and voltage ratings were increased in 1970 to 30 MW and 150 kV, respectively. Solid-state electronic valves were used for the first time in the upgrade, with the new type of valve, termed silicon-controlled rectifier (SCR) or thyristor, being connected in series with the mercury-arc valves. This kind of HVDC link, and ancillary technology, has been magnificently described in earlier treatises by Adamson and Hingorani, Kimbark, Uhlmann and Arrillaga.

By the turn of the second millennium, there had been 56 HVDC links of various topologies and capacities built around the world: 22 in North and South America, 14 in Europe, 2 in Africa and 18 in Australasia. They ranged from the small, 25 MW, Corsica tapping of the Sardinia–Italy HVDC link to the large, 6300 MW HVDC link, a part of the awesome Itaipu hydro-electric development on the Brazil–Paraguay border. At the time, three other large capacity HVDC links were at the planning/construction stage in China, to transport hydro-electric power from the Three Gorges to the east and southeast of the country, each spanning distances of around 1000 km, rated at 3000 MW – the Three Gorges is a gigantic hydro resource in central China, with an estimated power capacity of 22 MW. Heretofore all the HVDC links in the world had employed either mercury-arc rectifier or thyristor bridges and phase control to enable the rectification/inversion process. These converters are said to be line commutated and when applied to HVDC transmission are termed LCC-HVDC converters. The LCC-HVDC technology has continued its upward trend and five other high-power, high-voltage, long-distance DC links have been built in China since 2010. The most recent LCC-HVDC in operation was commissioned in 2012; it is the Jinping-Sunan link in East China, rated at 7200 MW and ±800 kV, spanning a distance of 2100 km.

In LCC-HVDC systems the current is unidirectional, flowing from the rectifier to the inverter stations. Such a fundamental physical constraint in thyristor-based converters limits applicability to the following HVDC system topologies: point-to-point, back-to-back and radial, multi-terminal links. In this context, the conventional, or classical, HVDC transmission technology is not a meshed grid maker; rather, its role has been to interconnect AC systems where an AC interconnection is deemed too expensive or technically infeasible.

However, one has to bear in mind that nowadays, in many situations, robust AC interconnections may be achieved more economically using one or more of the options afforded by the Flexible Alternating Current Transmission Systems (FACTS) technology, an array of power electronics-based equipment and control methods which became commercially available in around 1990. It is widely acknowledged that N.G. Hingorani and L. Gyugyi stand out prominently as the intellectual driving force behind the development of the FACTS technology.

The main aim of the FACTS technology is to enable almost instantaneous control of the nodal voltages and power flows in the vicinity of where the FACTS equipment has been installed. We should not forget that power flows over an AC line can be manipulated very effectively by controlling the line impedance, or the phase angles, or the voltages, or a combination of these parameters up to the thermal rating of the equipment. A key element of the FACTS technology is the so-called static compensator (STATCOM), which, in the parlance of a power electronics engineer, is a voltage source converter (VSC) and serves the purpose of injecting/absorbing reactive power to enable tight voltage magnitude regulation at its point of connection with the AC power grid. The advent of the STATCOM in the mid-1990s was made possible by the development of power semiconductor valves with forced turn-off capabilities, like the gate turn-off (GTO) first and the insulated gate bi-polar transistor (IGBT) soon afterwards. GTOs are like thyristors, which can be turned on by a positive gate pulse when the anode–cathode voltage is positive, and, unlike thyristors, can be turned off by a negative gate pulse. This turn-off feature led to new circuit concepts and methods such as self-commutated, pulse-width-modulated, soft-switching, voltage-driven and multi-level converters. These circuits may be made to operate at higher internal switching frequencies than the fundamental level, at several hundreds of hertz, which, in turn, reduces low-order harmonics and allows operation at unity and leading power factors. This contrasts sharply with what can be achieved with the normal thyristors.

Advances in the design of the power GTO and its applications in Japan and the USA continued apace by virtue of strategic collaborative R&D projects funded by utilities, manufacturers and governments. In Japan there was a target to develop 300 MW GTO converters for back-to-back HVDC interconnections, while in the USA a 100 MVAR GTO-STATCOM was commissioned in 1996 for the Tennessee Valley Authority. Meanwhile, similar efforts were conducted in Europe in the design of the power IGBT. It is reported that on 10 March 1997, power was first transmitted between Hellsjön and Grängesberg in central Sweden using an HVDC link employing IGBT converters driven by pulse-width-modulation (PWM) control. The link is 10 km long, rated at 3 MW, 10 kV and is used to test new components for HVDC.

In spite of the great many technical advantages and operational flexibility of the VSC compared with the thyristor bridge, the GTO-based converters did not make inroads into HVDC applications because of the much higher power losses and cost of GTOs compared with thyristors. A further reason is that the ratings of GTOs are low compared with those of thyristors. All this conspired to make VSC-HVDC installations expensive. The impasse was broken with the use of IGBT valves, which exhibit lower switching losses than GTO valves, and decreasing manufacturing costs. Three years after the commissioning of the Hellsjön-Grängesberg, four other VSC-HVDC links had been commissioned in very distant parts of the world: a 50 MVA DC link in the emblematic Island of Gotland to evacuate wind power, an 8 MVA DC link in West Denmark to link an offshore wind farm, the 180 MVA Directlink or Terranora project in Australia for power export from New South Wales into Southern Queensland, and a 36 MVA DC link for system interconnection on the Mexican–Texan border. The undersea Estlink 1, linking the Estonian and Finnish power grids, was commissioned in 2006, rated at 350 MW and using VSC stations. Intriguingly, the Estlink 2, rated at 650 MW and commissioned in 2014, uses the classical thyristor-converter technology.

It should be noted that all the VSC stations used in HVDC projects until 2010 had been of the so-called two- and three-level power converters. In around 2008, a new breed of VSCs was introduced into the market, the modular multilevel converters (MMCs), which switch at low frequencies, yield minimum harmonic production and have power losses just above those of the classical thyristor-based HVDC converters. Equally important is the fact that it has been possible to increase the capacity of VSC-HVDC links using MMC, by a very considerable margin, say 1000 MW per circuit, such as in the INELFE DC link between Baixas, France, and Santa Llogaia, Spain. Two identical circuits make up for a transmission capacity of 2000 MW. The link was commissioned at the end of 2013. Note that this application comes into the realm of bulk power transmission and is already eating into the niche area of classical thyristor-based HVDC technology, namely asynchronous bulk power transmission, an area until recently thought to be unassailable. The Trans Bay Cable link was the first MMC VSC-HVDC, commissioned in 2010, transmitting up to 400 MW of power from Pittsburg in the East Bay to Potrero Hill in the centre of San Francisco, California.

Furthermore, there are new application areas in which VSC-HVDC transmission does not seem to have a competitor in sight – the connection of wind sites lying more than 70 km away from the shore is one of the most obvious applications, but there are a few others. For instance, the connection of microgrids with insufficient local generation and little or no inertia (inertia-less power grids), the electricity supply of oil and gas rigs in deep waters, the infeed of densely populated urban centres with power grids already experiencing high short-circuit ratios. Moreover, the unassailable characteristic of the HVDC transmission using the VSC technology is that it is a natural enabler of meshed DC power grids, with such a high level of operational flexibility, reliability and efficiency that one day may surpass that of the meshed AC power grids. To get to this point, though, further technological breakthroughs are still awaited in the ancillary areas of DC circuit breaker technology and high-temperature superconductor cables and circuit breakers, as well as more affordable VSCs.

About the Book

The purpose of this book is to facilitate the study of technology that has emerged over the past 15 years in the area of flexible alternating current transmission systems (FACTS) and its technological convergence with the long-standing application of high voltage direct current (HVDC) but now using voltage source converters (VSC). This includes the back-to-back, point-to-point and multi-terminal VSC-HVDC applications. The subject is addressed from a modern perspective, including the latest development in the power systems industry that will extend the applicability of the VSC-FACTS-HVDC technology.

Contrary to *FACTS Modelling and Simulation of Power Networks*, published by the leading author and colleagues in 2004, which was limited to material on FACTS power flows and optimal power flows (OPFs), this book will address new FACTS power system application areas which have received much attention from industry over the past 12 years. These areas include FACTS state estimation, FACTS-constrained OPF, studies of FACTS dynamic performance and control, and the all-important topic of electromagnetic transients. These applications areas coincide with research areas, which the authors have developed over the past 15 years and have published widely in the top journals and presented in their research work at international forums.

The book is aimed at a very wide sector of the power engineering community, encompassing utility and equipment manufacturing engineers, researchers, university professors and PhD and MSc students, and undergraduate students in their final year. The reader is expected to have a sound knowledge of electrical and electronic circuits, algebra and numerical methods, and a working knowledge of electrical power and control engineering – an undergraduate student embarking on their final year in an electrical and electronics degree course should be well qualified to read the book. It goes without saying that utility engineers and managers with a background in electrical power would also take to the book like a 'duck to water'. Students conducting research in any of the topics covered in the book will find useful the modelling approach adopted by the authors which has resulted in flexible and comprehensive FACTS and HVDC-VSC models with which to carry out a wide range of power network-wide simulation studies, ranging from steady-state to dynamic and transient studies.

Chapter 1 gives an overview of the role that the VSC plays in the area of power systems VAR compensation. To qualify its prowess in this arena, a qualitative comparison is carried out against the long-enduring static var compensator. The VSC is a rather flexible piece of equipment which may be connected either in shunt or in series with the AC system, according to requirement. Two or more of them may be made to combine to give rise to compound equipment or systems, such as the UPFC and the various flavours of VSC-HVDC systems. Moreover, it is shown that the VSC combines well with the DC-DC converters and plays a pivotal role in enabling the grid connection of the renewable sources of electricity and energy storage systems. Equally important is the fact that the VSC technology is a builder of multi-terminal HVDC systems, with a DC network which may be a single node, a radial system or a meshed system. This is in stark contrast to the classical CSC-HVDC technology, whose flexibility is very limited as far as multi-terminal schemes is concerned. This chapter illustrates that a strategic feature of the VSC technology is to enable the conversion of AC transmission systems into DC transmission systems with an unassailable power transfer capacity and having, at least, an equal level of operational flexibility. Future developments in distribution systems seem to lie squarely in the incorporation of VSCs to enable greater operational flexibility, greater power throughputs and the incorporation of renewable electricity sources and storage.

Chapter 2 presents the theory of power electronics, which is essential to a good understanding of modern power converters topologies. The most popular semiconductor valves are presented first, followed by the classical two-level, single-phase and three-phase power converters. This forms the preamble of the study of multi-level converters, which is the technology used today by industrial vendors. The chapter presents a comparison between the HVDC systems based on voltage source converters and those that employ current source converters. A comprehensive list of current VSC-HVDC installations around the world is given at the end of the chapter.

Chapter 3 addresses the theory of power flows. The chapter may be seen as consisting of two parts: (i) the conventional power flow theory, including a Newton-Raphson power flow method in rectangular coordinates used to solve the set of nodal power equations describing the power grid during steady-state operation; and (ii) the power flow equations of the VSC model, which are derived from first principles and then extended to establish the power flow models of the STATCOM, VSC-HVDC links and generalized multi-terminal VSC-HVDC systems. The algebraic, non-linear equations describing the steady-state performance of the VSC, the STATCOM and VSC-HVDC systems are solved using the Newton-Raphson method in rectangular coordinates. The ensuing solutions fulfil the quadratic convergence characteristic which is the hallmark of the Newton-Raphson method. The VSC is the basic building block with which all the VSC-FACTS and VSC-HVDC equipment is assembled; hence, a Newton-Raphson power flow computer program written in Matlab, with the model of the VSC included, is available at www.wiley.com/go/acha_vsc_facts for the user to gain hands-on experience.

Chapter 4 introduces the topic of optimal power flow (OPF) used by transmission system operators for optimal economic and security assessments of their power grids. The chapter is divided into three main sections: (i) a general overview of the OPF problem and its applications in power systems operational planning; (ii) the introduction of the OPF problem as a non-linear optimization problem and possible solution methods; and (iii) an extension to the OPF formulation to incorporate hybrid AC-DC networks using VSC-HVDC systems. The OPF methodology introduced in this chapter uses the VSC model developed in Chapter 3 to formulate versatile models of hybrid AC-DC networks suitable for minimum-cost assessments of power systems subject to realistic operational constraints in both the AC and the DC grids. The overall solution algorithm adopted for solving the non-linear system of equations is the de facto industry's standard Newton's method. Concerning the introduction of models of VSC-based equipment, the chapter follows a similar line of development as in Chapter 3, starting with the VSC and progressing to develop models of the various kinds of VSC-HVDC systems. However, in this chapter the complex nodal voltages are represented in polar form as opposed to rectangular form because the former is widely employed in the OPF literature. The models are formulated and solved using a general-purpose mathematical solver package called AIMMS (Advanced Interactive Multidimensional Modelling System), employing its nonlinear augmented Lagrangian solver. However, the reader may implement these models using any equivalent general-purpose simulation platform. Alternatively, the more advanced readers may wish to write their own OPF computer program using MATLAB scripting. In any case, a free academic licence of AIMMS can be obtained for academic research purposes.

Chapter 5 presents the theory of power systems state estimation. The chapter is divided into two main parts, addressing the following issues: (i) the classical power systems state estimation theory using the weighted least squares method as the solution algorithm; and (ii) the state estimation models of the VSC, the STATCOM, UPFC, VSC-HVDC links and generalized multi-terminal VSC-HVDC systems. The timely topic of PMUs in power systems state estimation is addressed in this chapter. Each major topic in this chapter is accompanied by a set of well-designed numerical exercises using a MATLAB environment (WLS-SE) for the user to gain hands-on experience.

Chapter 6 is dedicated to the study of power systems dynamics in time domain. It uses a similar outline to the previous four chapters. In the first part, it introduces the theory of conventional power systems dynamics, where the synchronous generators and their controls are the only equipment that exhibit a dynamic behaviour following a disturbance in the power grid. The transmission lines, transformers and loads are taken to exhibit a static behaviour, although provisions are made for the models of these equipment to have a voltage and frequency dependency. In this chapter the interest is the study of power system dynamic phenomena which exhibit a relatively low variation in time. Hence, the dynamics of the power grid is described well by a set of algebraic-differential equations which are discretized and linearized in order to carry out the solution by iteration, which is valid for a single point in time. The solution algorithm used is an implicit simultaneous method employing the Newton-Raphson method. The resulting mathematical model is coded in software and applied to assess the dynamic behaviour of a test system, in order to illustrate the usefulness of the overall dynamic model. In the second part of the chapter, the dynamic model of the VSC-STATCOM, receives a similar treatment to the synchronous generator but having a detailed representation of the dynamics of its DC bus. This dynamic model is then suitably extended to encompass the dynamic models of the back-to-back, point-to-point and multi-terminal VSC-HVDC system. The VSC-HVDC model is applied to study the timely issues of frequency support in power grids with near-zero inertia and supplied by a VSC-HVDC link.

Chapter 7 is devoted to the simulation of the transient responses of various FACTS and HVDC systems using PSCAD/EMTDC, a commercial software package for electromagnetic transient analysis, which is widely used in industry and academia. Four different systems are simulated: (i) a STATCOM based on a conventional two-level voltage source converter; (ii) an extension of the STATCOM using a three-level flying capacitor converter as an example of a multilevel converter; (iii) a two-terminal

HVDC system based on a multilevel voltage source converter topology; and (iv) a multi-terminal HVDC system which also employs multilevel VSCs. Furthermore, the control schemes of the different power systems are comprehensively explained and control design specifications are provided.

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About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/acha_vsc_facts

The website includes software files associated to Chapters 3, 5 and 7:

- Matlab files corresponding to Chapters 3 and 5.
- Two PSCAD files of Cases 1 and 4 corresponding to Chapter 7.

Scan this QR code to visit the companion website.

1

Flexible Electrical Energy Systems

1.1 Introduction

Following a sustained programme of expansion of high-voltage power grids in the 1960s and their widespread interconnection in the 1970s, by the end of that decade the expansion programmes of many utilities had become thwarted by a variety of well-founded, environmental, land-use and regulatory pressures, preventing the licensing and building of new transmission lines and electricity generating plants. This was in the face of sustained global demand for electricity.

An in-depth analysis of the options available for increasing power throughputs with high levels of reliability and stability pointed towards the use of modern power electronics equipment, control techniques and methods [1]. Such a far-reaching work was carried out first at the Electric Power Research Institute (EPRI) in Palo Alto, CA, under the leadership of N.G. Hingorani. The result was an integrated philosophy for AC network reinforcement using electronics principles, endowing AC transmissions lines with a degree of operational flexibility and power-carrying capacity that had not been possible before. Flexible alternating current transmission systems (FACTS) was the name given to the family of power electronic-based equipment, control techniques and methods emanating from this initiative [2].

In the same time span, electricity distribution companies were experiencing a marked increase in the deployment of end-user equipment which was highly sensitive to poor-quality electricity supply. Several large industrial users reported experiencing significant financial losses as a result of even minor lapses in the quality of electricity supply. A great many efforts were made to remedy the situation, with solutions based on the use of the latest power electronic technology of the time [3].

A range of custom-made equipment and solution techniques was put to the fore, with the key ideas emanating from EPRI. This initiative, aimed at ameliorating adverse power quality phenomena at the interface between the low-voltage distribution power grid and the industrial user, was given the name 'custom power' by its creator, N.G. Hingorani. Indeed, custom power technology was announced as the low-voltage counterpart of the FACTS technology, aimed at high-voltage power transmission applications and emerging as a credible solution to many of the problems relating to continuity of supply at the end-user level [2].

It is fair to say that many of the ideas upon which the foundation of FACTS rests evolved over a period of several decades, building on the experience gained in the areas

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of high-voltage direct current (HVDC) transmission and reactive power compensation equipment, methods and operational experiences [4, 5]. Nevertheless, there is widespread agreement that FACTS, as an integrated philosophy, was a novel concept brought to fruition at EPRI in the 1980s. Since those early days of the FACTS technology, a great many breakthroughs have taken place in the area of power electronics, encompassing new valves, control methods and converter topologies [6]. To a greater or lesser extent, the recent technological developments have all been incorporated into the fields of FACTS and HVDC, giving rise to a new generation of power transmission equipment in either AC or DC, with unrivalled operational flexibility [7].

The original boundaries between HVDC and FACTS were drawn along the type of solid-state converters employed and their control [1], but these boundaries became blurred with the arrival of newer technology. For instance, the static compensator (STATCOM), which is essentially a voltage source converter (VSC), is a product of the FACTS technology used to provide reactive power support [8]. Two such devices connected in series on their DC sides results in the modern expression of an HVDC transmission system. This has been designated VSC-HVDC to distinguish it from the classical HVDC transmission using thyristor-based bridges and phase control [9]. The largest vendors of power electronics equipment, ABB, Siemens and Alstom, have proprietary equipment termed HVDC *Light*, HVDC *Plus* and *MaxSine* HVDC, respectively. It is documented that the use of a VSC in a utility-level application was in the form of a STATCOM, which falls squarely within the realm of the FACTS technology. The VSC application in HVDC transmission came next, which, it may be argued, is an application comprising two STATCOMs connected back-to-back or through a DC cable. Of course, such an argument is more difficult to sustain when we progress into the realm of multi-terminal VSC-HVDC [10].

From a traditional perspective, artificial lines have been drawn between the FACTS and the HVDC technologies. It is argued here that these lines be removed and that, instead, the focus should be on flexible transmission systems (FTS), a unifying concept bridging the FACTS and HVDC technologies – the aim being to enable the best-of-breed solutions underpinning the new power-carrying structures that the smart grids demand [11].

The breakthroughs in power electronics impacted not only the transmission and distribution sectors of the electrical energy industry but also the generation sector, particularly the renewable generation and energy storage technologies [12]. The use of advanced power electronic converters enabled the wind power equipment manufacturers to transit from the first generation of fixed-speed wind turbines to the second generation of variable-speed wind turbines, which are larger, more efficient and fully compliant with modern grid codes [13]. The use of advanced power electronic converters also led to the proliferation, on a global scale, of grid-connected photo-voltaic generators, with full compliance to modern grid codes [14]. More recently, with the widespread availability of affordable lithium-ion batteries suitable for power applications, battery energy storage systems (BESS) are becoming off-the-shelf products [15]. It is very likely that, once BESS prices decrease further, this equipment will become ubiquitous in the power grid since it has a potentially major role to play in electrical energy retailing.

In a more ample technological sense than FTS or flexible power generation, a wide range of enabling technologies has become cost-effective, such as extruded cables, smart meters, phasor measurement unit (PMU), advanced protection systems, accessible satellite communications and distributed energy resources such as EV charging stations [16]. Equally important is the fact that information and communication technologies (ICTs), the internet, the web and distributed computing, have become even more powerful and popular than, say, only one decade ago.

The widespread availability of all these technological developments has been seized on by the proponents of the smart grid philosophy, who argue that the coming together, in an all-encompassing manner, of these technologies should provide a solid foundation on which to build new, smarter energy grids, now that a large portion of the existing infrastructure in many countries is ageing and up for renewal [17, 18]. Key drivers of the smart grid technology are enhanced security of supply and self-healing properties, its market-oriented philosophy, progressive demand-side response (DSR) and demand-side management (DSM) policies [19].

The available technologies and drivers of the smart grid concept are voltage-level independent and network structure independent. Hence, it is argued here that it should be feasible to talk about smart grids at either the low-voltage distribution system level or the high-voltage transmission system level. Admittedly, each has its own peculiarities but with a great many common objectives and interrelated technology issues yet to be resolved.

The power network is expected to incorporate increasing amounts of wind and solar power, leading to new challenges in its operation owing to the intermittent nature of these two new forms of renewable power generation. Frequency oscillations, resulting from temporary power imbalances, may become more common. Also, voltage control may become a significant problem if no suitable FTS equipment is in place, such as static var compensators (SVCs) or VSCs in the form of STATCOMs, BESSs or as part of VSC-HVDC systems [7]. Moreover, the power-carrying structures of AC low-voltage smart grids are likely to use mainly underground cables – which is already happening in Denmark – and inductive reactive power compensation equipment may be required [20]. Alternatively, smart grids using AC and DC microgrids may reach the commercial stage, following on from the experience gained with current prototypes deployed by some of the distribution companies in Finland [21].

Indeed, structures based on multi-terminal VSC-HVDC systems are just the kind of transmission structures that are likely to be used by the next generation of smart grids, both at the transmission level and at the distribution level [7]. This may be a system within a larger AC system, as exemplified in the Figure 1.1. In this one-line diagram, an AC power system incorporating a fair amount of FACTS controllers and a multi-terminal VSC-HVDC system is also equipped with synchronized measurement systems at key points of the power grid using PMU and satellite communications. The deployment of such equipment would go a long way towards establishing a high-voltage smart grid, particularly if the FTS equipment is fitted with processor agents, sensors and a fibre optic network – or some other means of fast communications – linking all the FTS equipment, so that a coordinated action takes place at the system level as opposed to the local, individual level [22]. Such arguments would also apply to low-voltage, low-power microgrids where the core system could be a multi-terminal VSC-HVDC system interconnecting an arbitrary number of AC systems – this point is elaborated further in Section 1.3.

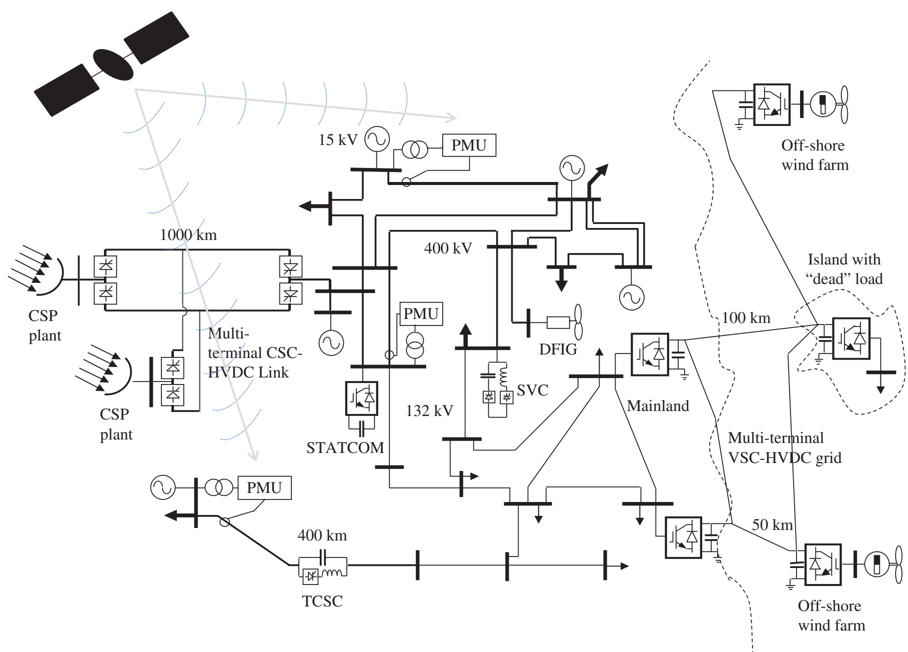

Figure 1.1 Flexible transmission system with renewable energy sources.

1.2 Classification of Flexible Transmission System Equipment

Many of the ideas upon which the foundation of FACTS rests evolved over a period of many decades. Chiefly among them is:

– experience gained with HVDC transmission technology [4]
– experience gained with SVC technology [5]
– experience gained with electric drives for motor control [23].

In a nutshell, FACTS and HVDC equipment uses power semiconductor devices and advanced power electronics control techniques and methods to fulfil its task in a matter of a few milliseconds [24].

The wide range of modern equipment available is bundled together in this book under the umbrella title of FTS equipment. The range of functions that this technology can fulfil is very wide but it is equipment-dependent. Table 1.1 lists the equipment comprising the FTS technology and the respective areas of power systems application.

Various classifications of the FTS equipment are possible. It can be classified in terms of the power systems application, as outlined in Table 1.1: (i) voltage control, (ii) reactive power control, (iii) active power control, (iv) frequency control, and (v) AC systems interconnection. This list is not exhaustive by any means and other applications exist, such as loop flow control.

Alternative classifications may be drawn according to the number of power converters used or the way in which the equipment connects to the AC power grid or grids,

Table 1.1 FTS equipment and the respective areas of power systems applications.

Equipment	Voltage control	Reactive power control	Active power control	Frequency control	AC systems interconnection
SVC	✓	✓			
STATCOM	✓	✓			
BESS	✓	✓		✓	
SSTC	✓				
TSSC			✓		
TCSC			✓		
SSPS			✓		
SSSC		✓	✓		
UPFC	✓	✓	✓		
IPFC		✓	✓	✓	
VFT			✓	✓	✓
CSC-HVDC			✓	✓	✓
VSC-HVDC	✓	✓	✓	✓	✓

SVC: static var compensator; **STATCOM**: static compensator; **BESS**: battery energy storage system; **SSTC**: solid-state tap changer; **TSSC**: thyristor switched series capacitor; **TCSC**: thyristor-controlled series compensator; **SSPS**: solid-state phase shifter; **SSSC**: solid-state series compensator; **UPFC**: unified power flow controller; **IPFC**: interphase power flow controller; **VFT**: variable frequency transformer; **CSC-HVDC**: current source converter high-voltage direct current; **VSC-HVDC**: voltage source converter high-voltage direct current.

Table 1.2 Classification of FTS equipment according to converter type.

Converter type	Equipment
Thyristor and phase control	SVC, SSTC, TSSC, TCSC, SSPS, CSC-HVDC
IGBT or GTO and PWM control	STATCOM, BESS, SSSC, UPFC, IPFC, VSC-HVDC, VFT

namely, shunt, series, cascade and multi-terminal. The equipment can also be classified according to the type of semiconductor valves and switching control that the converters use: (i) thyristor valves and phase control, and (ii) insulated gate bipolar transistor (IGBT) or gate turn-off (GTO) valves and pulse width modulation (PWM) control [2]. This classification is shown in Table 1.2.

For any practical purpose, an IGBT valve outperforms a GTO valve in terms of its speed of response, better power loss performance and improved reliability; they have become the standard forced commutated valves used in converters aimed at power systems applications. They are driven by PWM control of various kinds [24].

In this book, the application of IGBT-based converters driven by sinusoidal-PWM control is given priority. In particular, the ubiquitous STATCOM and the VSC-HVDC. Other equipment which uses the STATCOM as the basic building block also receives attention in this chapter, such as the BESS, the solid-state series compensator (SSSC), the unified power flow controller (UPFC) and the interphase power flow controller (IPFC). As a means of emphasizing the much-increased functionality that the STATCOM has brought into the arena of electrical power systems, in general, the SVC and the current source converter high-voltage direct current (CSC-HVDC) are also covered in sufficient detail.

1.2.1 SVC

The SVC appeared on the power systems scene at least two decades before the FACTS initiative was put forward [5]. In some respects, the SVC may be considered the forebear of some of the equipment developed under the auspices of the FACTS initiative [1]. It comprises a bank of thyristor-controlled reactors (TCRs) in parallel with a bank of thyristor switched capacitors (TSCs). The one-line schematic representation of the SVC is shown in Figure 1.2.

The SVC is connected in shunt with the AC system through a step-up transformer. Its main function is to supply/absorb reactive power to support a specified voltage magnitude at the high-voltage side of its connecting transformer.

At the construction level, a criticism levelled at the SVC is its rather large footprint [8]. The inductor, in Figure 1.2a, is a bulky air-core reactor, to prevent saturation; the capacitor banks are also quite sizable and so are the tuned filters. As suggested in Figure 1.2b, the SVC performs like a variable susceptance.

The TCR consumes variable reactive power up to its design limit, governed by firing angle control, α, in the range: $\pi/2 \leq \alpha \leq \pi$. It achieves its fundamental frequency operating point at the expense of generating harmonic currents, which is an undesirable side effect. Hence, the three-phase TCR is connected in delta to prevent the triple harmonics from reaching the power system. In addition, passive filtering is required

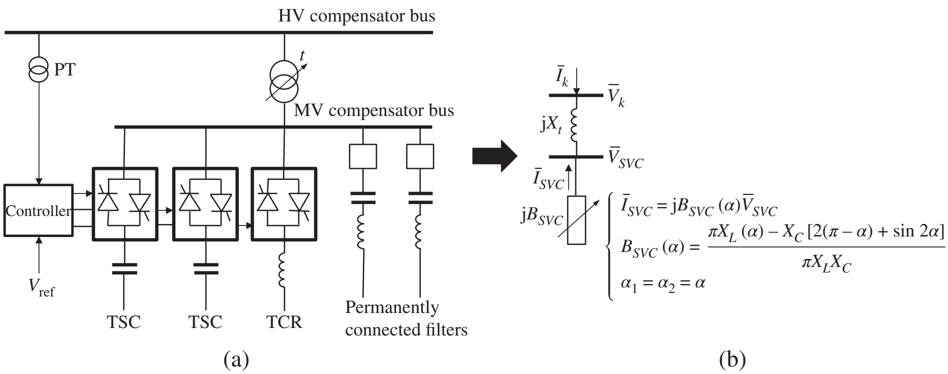

Figure 1.2 (a) An SVC (©MPCE, 2017) and (b) its equivalent circuit representation.

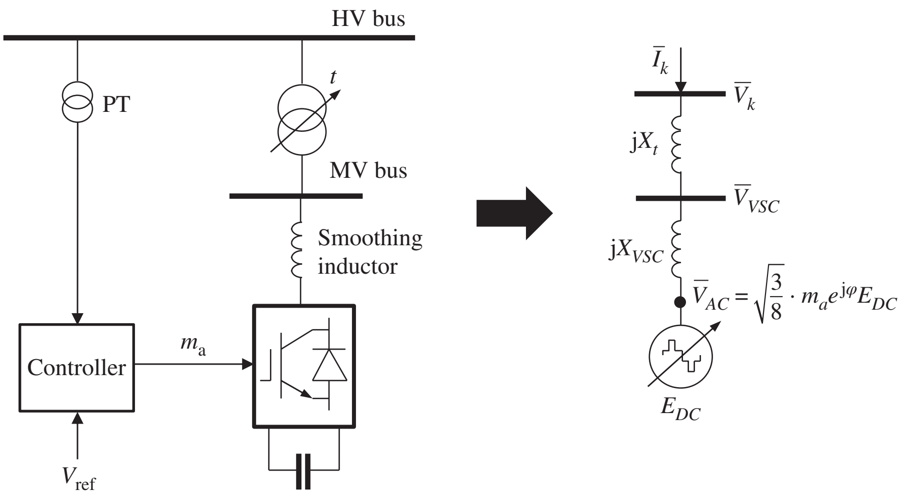

Figure 1.3 (a) A STATCOM (©MPCE, 2017) and (b) its equivalent circuit representation.

to mitigate the $6k \pm 1$ and $12k \pm 1$ harmonics generated by the 6-pulse and 12-pulse converter topologies, respectively, with $k = 1,2,3\ldots$ being the harmonic order. The TSC generates reactive power in a variable, discrete manner, with the thyristor pairs operating as switches (on/off); hence, during steady-state operation, no harmonic distortion is produced by the TSC [5].

1.2.2 STATCOM

The STATCOM is the modern counterpart of the SVC [8]. Coincidentally, its main operational task is to inject regulated volt-ampere reactives (VAR) to provide voltage support at the high-voltage side of its connecting transformer, but much more effectively. As illustrated in Figure 1.3, it connects in shunt with the AC power system. Its main elements are the VSC, the smoothing inductor, the interfacing transformer and the PWM control system.

Table 1.3 STATCOM operating modes.

Voltages	Operating mode	Functionality
$V_k > V_{AC}$	Consuming vars	Standard function
$V_k < V_{AC}$	Injecting vars	Standard function
$-\delta$	Consuming watts	Normal operation
$+\delta$	Injecting watts	Possible only with DC storage

Contrary to the SVC, the STATCOM does not use bulky inductors and banks of capacitors to absorb and to generate reactive power, respectively. This can be appreciated from Figure 1.3a. The reactive power production process is carried out entirely by the electronic processing of the voltage and current waveforms within the valves, to enable either leading or lagging VAR production to satisfy operational requirements [2]. The smoothing inductor laying between the VSC and the step-up transformer is used to eliminate the high-order harmonics produced by the action of the PWM control. The DC capacitor is an extruded capacitor of a small rating, employed only to support and stabilize the DC voltage to enable the converter operation – it does not play a significant part in the VAR generation process. The DC current in the capacitor in Figure 1.3a is taken to be zero during steady-state operation, as an indication that the capacitor is fully charged. During dynamic and transient operation, I_{DC} will differ from zero.

The STATCOM's operational behaviour is superior to that of the SVC because its operation mimics a variable voltage source as opposed to a variable susceptance [8]. This is illustrated in Figure 1.3b. In fact, the STATCOM's operational performance is closer to that of a rotating synchronous condenser but with a faster speed of response because it has no moving parts.

The basic operating principles of the STATCOM may be explained with reference to the complex voltages $\overline{V}_{AC} = V_{AC}\angle\delta$ and $\overline{V}_k = V_k\angle 0$ in Figure 1.3b, where the amplitude and the phase angle of the voltage drop across the reactances X_{SVC} and X_t can be controlled, to define the amount and direction of both active and reactive power flows.

For leading and lagging VARs, the STATCOM's active and reactive power flows are defined by the following fundamental expressions:

$$\left.\begin{aligned} P &= \frac{V_k V_{AC}}{X_{VSC} + X_t} \cdot \sin\delta \\ Q &= \frac{V_k^2}{X_{VSC} + X_t} - \frac{V_k V_{AC}}{X_{VSC} + X_t} \cdot \cos\delta \end{aligned}\right\} \qquad (1.1)$$

To a large extent, the equation set (1.1) defines the STATCOM operating modes, which are summarized in Table 1.3.

The static voltage–current characteristics shown in Figure 1.4 correspond to the SVC and the STATCOM. The thick line is for the SVC (capacitor and thyristor-controlled inductor) at rated values; only one value of capacitor has been considered and the broken lines on the inductor side would be for various firing angle values of the TCR. As seen

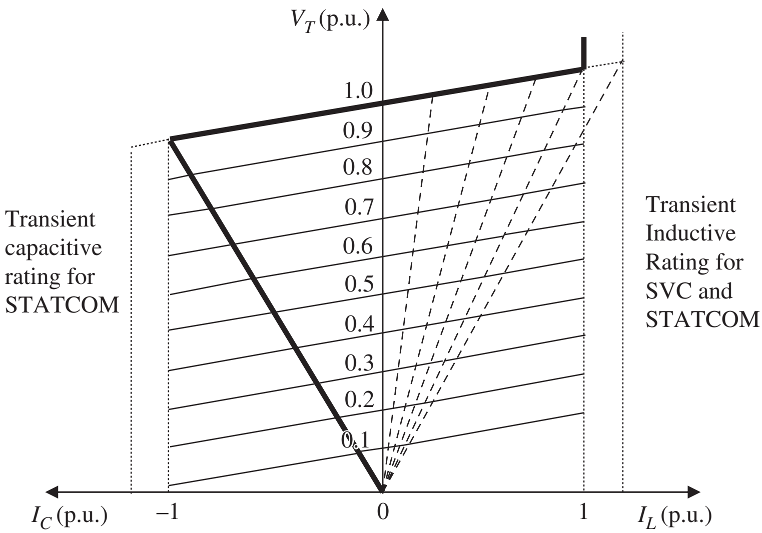

Figure 1.4 Static V-I characteristics of the VSC and the STATCOM.

from the figure, the characteristics of a STATCOM and a SVC of comparable ratings will coincide only at their rated values.

It can be seen from this characteristic that the SVC yields little capacitive current at low voltages. In contrast, the STATCOM is able to produce its full range of current, both inductive and capacitive, even when the voltage has dropped to about 10% of its nominal value. From the operational vantage, one of the main criticisms levelled at the SVC is that its ability to contribute reactive power becomes severely impaired in the presence of low system voltages in its vicinity, for instance in cases of voltage collapse. Conversely, the STATCOM's reactive power provision is system voltage-independent.

In spite of its superior technical performance, the STATCOM technology still carries a higher price tag than the SVC technology of comparable rating. Equipment manufacturer Alstom, Finland, has recently patented a new piece of VAR compensation equipment selecting the best attributes of the SVC and the STATCOM [25].

1.2.3 SSSC

This equipment may be seen as a series-connected STATCOM and serves the purpose of injecting a variable, controllable voltage to an incoming voltage to achieve a range of purposes, one of which is active power flow control through the power line and the injection of controlled reactive power at one of the two nodes [2].

An SSSC is normally a piece of equipment of small rating, with full control of the magnitude, phase and polarity of the injected series voltage. One may think of a small STATCOM which is connected to the secondary winding of an interfacing transformer whose primary winding is connected in series with the AC power grid, as illustrated schematically in Figure 1.5.

Note that the SSSC should be designed to carry the full line current, with the rated voltage being only a fraction of the rated line voltage.

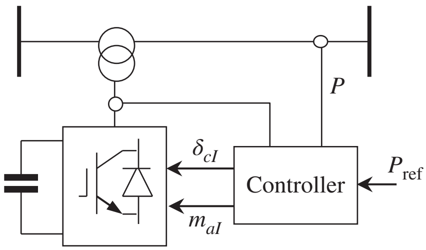

Figure 1.5 SSSC schematic representation (©MPCE, 2017).

1.2.4 Compound VSC Equipment for AC Applications

The VSC, which forms the kernel of the STATCOM and the SSSC, is a rather flexible device; not only does it connect easily in shunt or in series with the AC power system, it also combines rather well in any number and in any combination to suit a specific power systems application. This is illustrated in Figure 1.6.

The schematic diagrams of the four most popular compound FACTS devices – the UPFC, the IPFC, the back-to-back VSC-HVDC and the BESS – are shown in Figure 1.6. Their main salient characteristics are outlined below, according to the time at which they seem to have been conceptualized or emerged on the applications scene.

- The UPFC employs two VSCs, one connected in shunt and the other in series with the AC system. The two VSCs are connected back-to-back on their DC sides and have a unified control structure, giving rise to the UPFC, which has great operational functionality. Its schematic diagram is shown in Figure 1.6c. In this application, the shunt-connected VSC is rated at full capacity whereas the series-connected VSC is rated to carry only a fraction of the line current and have a fraction of the line voltage. Note that this contrasts with the SSSC, which is rated to carry the full line current [26].
- The UPFC combines the operational control capabilities of the STATCOM and the SSSC. It is capable of regulating, simultaneously, voltage magnitude at the high-voltage node of the shunt-connected VSC, active power flow arriving at the receiving node of the series-connected transformer – the opposite node to that where the shunt converter is connected – and the injection of reactive power at that node. Regulation of these parameters is limited by the ratings of the shunt and series converters. The UPFC plays the role, in any combination, of a STATCOM, a TCSC (thyristor-controlled series compensator), an SSSC, a phase-shifting transformer and a tap-changing transformer, simultaneously and in any combination. For all its operational flexibility and great expectations when it was conceptualized, the UPFC has not been a commercial success. Only two prototypes are known to exist in the world, in the USA [2] and Korea [27].
- If two or more transmission lines connecting to the same AC bus are fitted each with a SSSC then these can be made to share the same DC capacitor and to have a coordinated control system, giving rise to the IPFC [28]. Its schematic diagram is shown in Figure 1.6d. It has been designed to regulate active power flows between the various transmission lines by exchanging power through the common DC bus. No IPFC installation is known to exist at present but this is likely to change as more commercially-driven energy transactions take place between neighbouring transmission companies.

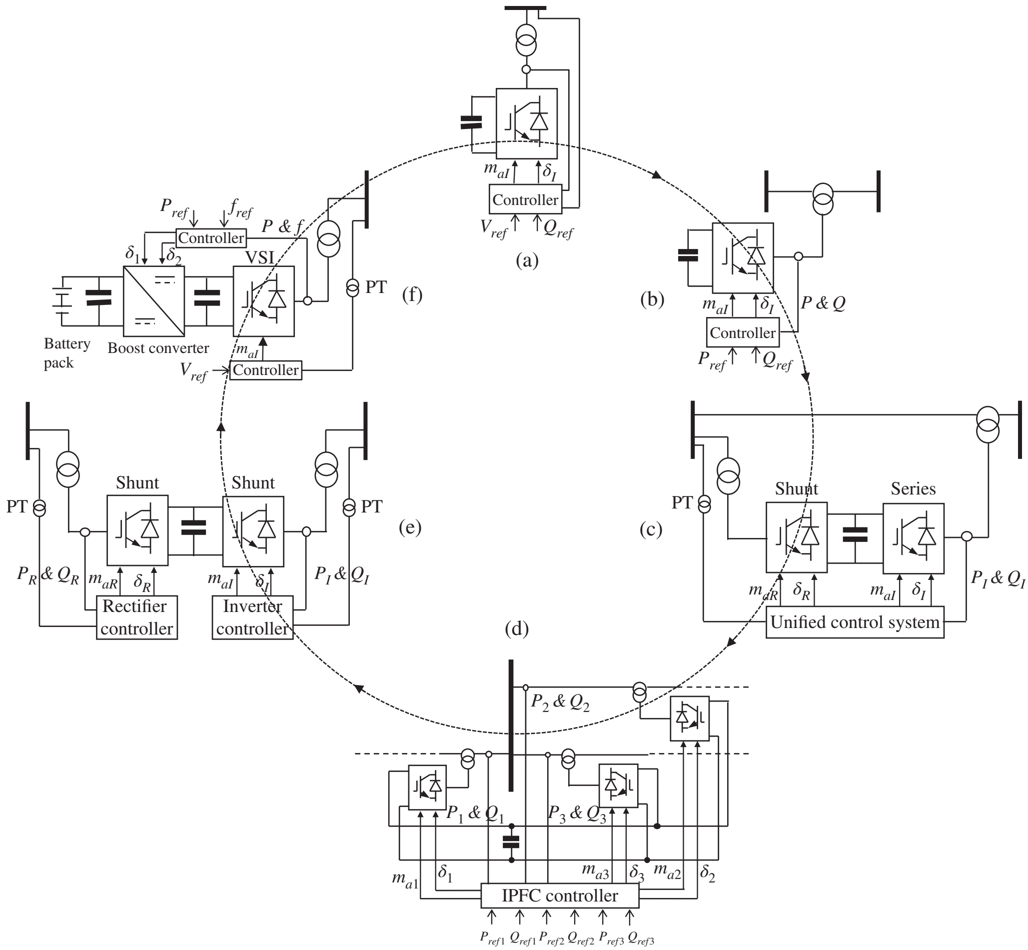

Figure 1.6 The most popular VSC-based equipment, placed, clockwise, in the order in which they appeared in the open literature: (a) STATCOM; (b) SSSC; (c) UPFC; (d) IPFC; (e) back-to-back VSC-HVDC: (f) BESS.

- Two VSCs connected in tandem form a back-to-back VSC-HVDC link, as shown in Figure 1.6e. The VSCs are connected in shunt at their respective AC systems and have a common DC bus [9]. There is some resemblance between the structures of the UPFC and the back-to-back VSC-HVDC. It may be argued that the operational functionality of the two controllers is comparable but the back-to-back VSC-HVDC achieves this at the expense of using two fully rated converters. Nevertheless, a key attribute of the VSC-HVDC link that the UPFC lacks is the ability to connect, in an asynchronous manner, two otherwise independent AC systems, which may have the same or different operating frequencies. Furthermore, the two VSCs of the HVDC link do not need to be connected back-to-back but instead may be linked by a cable and used to transport electrical power in DC form with less power loss than an AC transmission line of comparable rating and distance. Among all the VSC-based equipment, the VSC-HVDC link is the technology that has experienced the highest rate of growth since its introduction in 2000. Examples of VSC-HVDC installations in the world are given in Section 2.4 of Chapter 2.

- The VSC combines quite naturally with modern battery packs, such as lithium-ion batteries. The combined system is termed BESS, having the structure shown in Figure 1.6f. It should be noted that the battery pack connects to the VSC through a DC-DC converter to enable the smooth operation of the battery. Provided there is sufficient energy stored in the battery pack, the BESS is capable of injecting active power into the AC system, in a matter of milliseconds, to provide inertial and primary frequency support in the presence of synchronous generators frequency oscillations. Furthermore, the associated VSC acts as a source of VARs to enable effective voltage regulation at the AC bus. Indeed, not only can a modern BESS emulate the operation of a synchronous generator, it can also provide additional flexibility, such as adaptive time-varying behaviour during faults or perturbations. It is very likely that once BESS prices decrease further, this equipment will become ubiquitous in the power grid since it has a potentially major role to play in electrical energy retailing. BESSs commissioned in Chile and California [29, 30] in recent years are two good examples of where MW-size BESS have been installed.

1.2.5 CSC-HVDC Links

HVDC transmission using the classical six-pulse Graetz bridge, which uses thyristor valves and phase control, has been available, on a commercial basis, for more than half a century. Its main application has been in the area of bulk power transmission over long distances. The earliest schemes were point-to-point of the monopolar kind with ground return. The back-to-back and the point-to-point bipolar configurations were developed soon afterwards [4]. Today's classical HVDC transmission uses 12-pulse converters as opposed to 6-pulse converters. This type of HVDC technology is termed CSC-HVDC to distinguish it from the new HVDC technology which uses forced commutated valves and PWM control, namely VSC-HVDC [24].

The rectification and inversion processes are imperfect and the characteristic harmonics are produced in both the DC circuit and the AC circuits of the HVDC links. Hence, passive filtering is required to mitigate the $6k \pm 1$ and $12k \pm 1$ AC harmonic currents generated by the 6-pulse and 12-pulse converter topologies, respectively, with $k = 1,2,3\ldots$ being the harmonic order. On the DC side, filters may be required for the $6k$ order. The rectification process is achieved with thyristor firing angles in the range $0 \le \alpha < \pi/2$ and the inversion process in the range $\pi/2 < \alpha \le \pi$, although some margin would need to be left to avoid commutation failures. Moreover, the rectification/inversion process requires the provision of reactive power, which needs to be supplied locally to enable suitable operation of the link, with at least a part of this requirement being met by the passive harmonic filters in the installation. Contrary to the VSC, the Graetz bridge does not have VAR production capability and is unable to regulate AC voltage. Hence, connection to both AC grids is carried out through tap-changing transformers to enable AC voltage control.

Cases of a monopolar, back-to-back and bipolar, point-to-point HVDC schemes are exemplified in Figures 1.7a,b, respectively. For a full set of CSC-HVDC topologies, refer to [4].

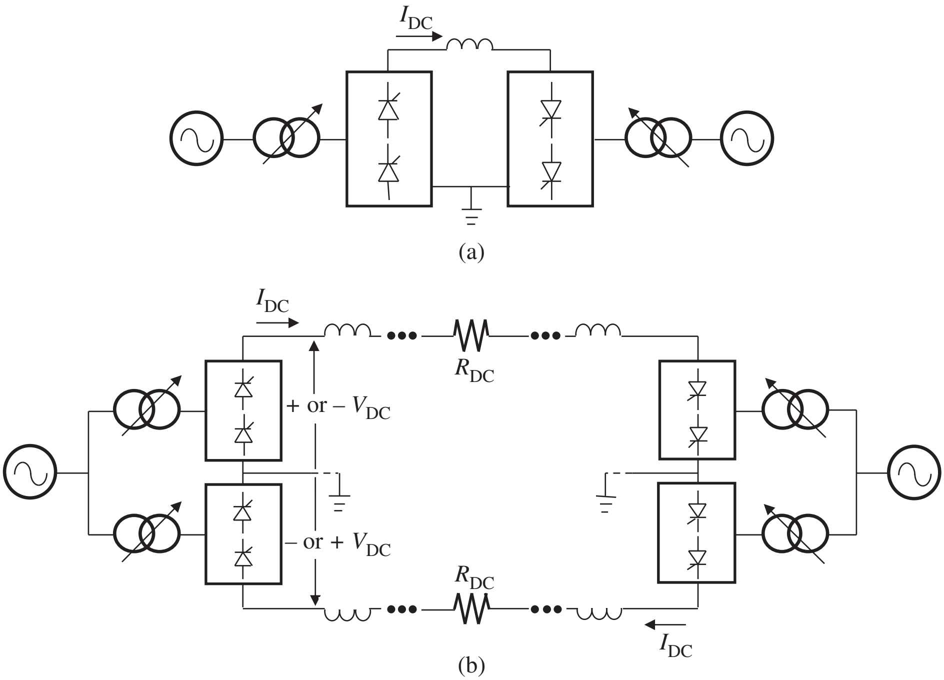

Figure 1.7 Two CSC-HVDC links: (a) back-to-back, monopolar HVDC; (b) point-to-point, bipolar HVDC.

Notice that the current flow is from the rectifier towards the inverter and so is the power flow when the voltage polarity is positive. Alternatively, the power follows an opposite direction to the current when the voltage polarity reverses, an operational characteristic achieved through firing angle control.

The two units of a back-to-back HVDC link have equal rating. They seem to be economical for voltage ratings as low as 50 kV. The bipolar link may be seen to comprise two monopolar links, one at positive and one at negative polarity with respect to ground. It is plausible to operate both monopolar links independently, each having its own ground return, but it is more effective to operate them together because their currents, being equal, cancel each other's ground return to zero. Indeed, the ground path is a valuable resource for cases when one pole is out of service due to a planned or an unplanned event [4].

This HVDC technology seems to have hit an intrinsic limitation when applied to multi-terminal HVDC systems because CSC-HVDC is based on current balances. Hence, only series, multi-terminal HVDC schemes seem to be realizable using this technology.

1.2.6 VSC-HVDC

In contrast to the UPFC, the two VSCs of an HVDC link are not constrained to be housed in the same substation [9]. They can be hundreds of kilometres apart and linked together by an overhead DC line or an underground or submarine DC cable, or a combination of these, to satisfy geographical, economical, technical and aesthetic requirements. Such

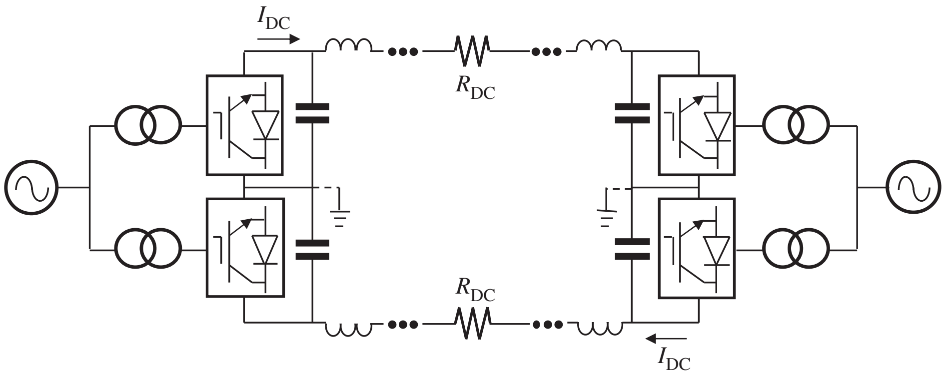

Figure 1.8 Point-to-point, bipolar VSC-HVDC system.

a VSC-HVDC link is termed point-to-point to differentiate it from the back-to-back VSC-HVDC link shown in Figure 1.6e. Since the point-to-point is aimed at bulk power transmission applications, it is normal to build it as a bipolar system as opposed to a monopolar one, as shown in Figure 1.8.

Note that the rectifier's AC system and the inverter's AC system do not necessarily need to have the same power frequency. The VSCs forming the bipole will be multi-level VSCs as opposed to the simpler two-level VSCs. Owing to the fast voltage-regulating capabilities afforded by the VSCs, it is likely that the connecting transformers will not need to have tap-changing facilities, saving on costs. Normally the rectifier is set to regulate power flow and the inverter is set to regulate DC voltage.

It is clear that the symmetrical bipole carries twice the rated power of a monopole HVDC link, with zero ground return. In the event of one of the poles being out of service because of maintenance or due to a contingency event, the link will remain in operation at 50% capacity. Tapping along the length of the DC line to pick up generation or to supply infeed points is carried out with ease. It requires only one extra converter station at each additional point. This is illustrated in the circuit diagram shown in Figure 1.9.

In some respects, the VSC-HVDC link in Figure 1.9 can be classified as a multi-terminal VSC-HVDC system [10], albeit of the radial type. As a matter of fact, the recent developments in VSC-HVDC technology are in the arena of multi-terminal VSC-HVDC systems; in particular, the kinds of multi-terminal systems which form meshed DC power grids. This is exemplified by the case of four VSCs interconnected in their DC sides through cables to make up a four-terminal VSC-HVDC system, as shown in Figure 1.10.

This is a generic concept that may be expanded to comprise n VSCs to link n AC systems of varying sizes, topologies and operational complexity. The DC cables may be overhead, underground or submarine, according to practical requirements.

The DC network may even comprise a single node – a common DC bus where the n VSCs would be sharing a DC capacitor, i.e. multi-terminal back-to-back configuration. Just as in meshed AC transmission systems there are transmission lines with non-regulated and regulated power flows, power flows sharing between neighbouring transmission lines, nodes with regulated and non-regulated voltages and so on, a meshed DC transmission system will have similar operational capabilities, as well as

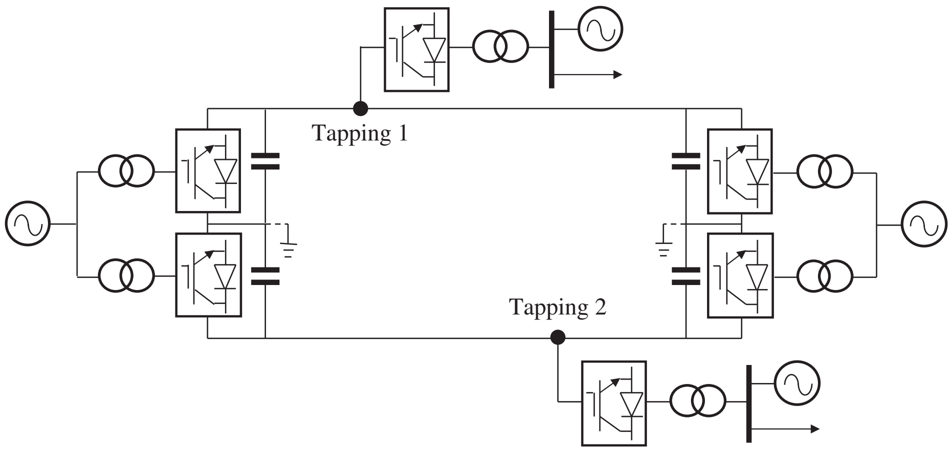

Figure 1.9 Radial, bipolar VSC-HVDC system with tappings.

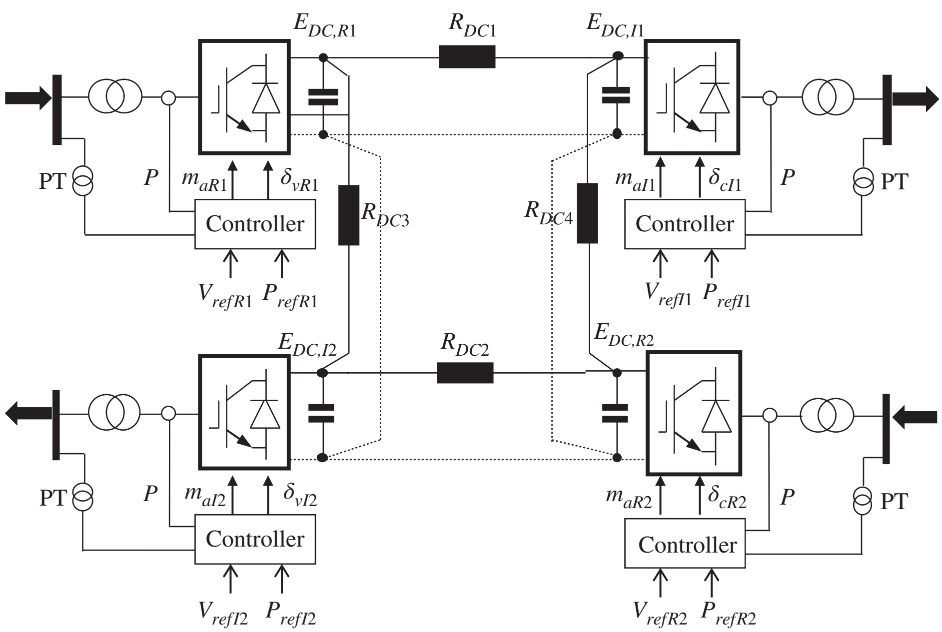

Figure 1.10 Four-terminal VSC-HVDC system.

suitable provisions for incorporating DC generation and DC loads directly. This will involve the use of DC-DC converters.

1.3 Flexible Systems Vs Conventional Systems

Conventional electrical energy systems have traditionally been divided into generation systems, transmission systems and distribution systems. The energy flows from the generation systems towards the distribution systems. It is assumed that generation exists neither in the transmission system nor in the distribution system. The three-phase voltage and currents waveforms are largely sinusoidal and symmetrical, with a current frequency of either 50 Hz or 60 Hz. In these AC systems, a transmission line is not normally loaded up to its thermal limit since angular stability limits take place at much lower values than the thermal limits. Furthermore, transmission lines longer than 300 km will normally require series and shunt VAR compensation to be able to operate in steady-state.

Power electronics valves, converter topologies switching techniques and control methods embedded in software have permeated all three sectors of the electricity supply industry, namely, generation, transmission and distribution. Power electronics has enabled the transformation of large, inflexible, inefficient, failure-prone and environmentally unfriendly power systems into flexible, efficient, reliable and environmentally benign power systems which may be large in size or a concatenation of microgrids.

1.3.1 Transmission

The large blocks of electrical energy which are moved from the large generating power plants to the cities and factories are transported at high voltages over long or extra-long distances. Three-phase AC transmission lines and HVDC transmission lines are employed to carry out this task. In particular, the latter option serves the purpose of transporting large amounts of electrical energy over extra-long distances, with lower power losses than a comparable high-voltage AC transmission line (HVAC) [4]. Further applications where HVDC outperforms the HVAC option, regardless of whether or not it uses FACTS upgrades, are submarine power transmission longer than 70 km and the interconnection of AC power grids exhibiting different operating frequencies or a substantial difference in network strength, i.e. connection of a weak network to a strong network [9].

It should be noted that the FACTS concept is based on the incorporation of power electronic devices and methods into the high-voltage side of the AC network to increase the control of power flows in the high-voltage side of the network during steady-state and transient conditions [31]. From the outset, the developers of the FACTS initiative emphasized that this was not intended to be a direct competitor to HVDC transmission but, rather, an initiative able to provide technical solutions to specific power transmission problems at a lower cost [1, 2], particularly when the AC transmission corridor already existed. In any case, the aim is to apply the FTS solution that carries the best technical performance and the best value for money for a specific power transmission problem [7]. By way of example, the following technical issues call for the application of FTS equipment and methods, either in AC form or in DC form:

- Higher power throughputs using the same right-of-way
- VAR compensation
- Frequency compensation/virtual inertia

1.3.1.1 HVAC Vs HVDC Power Transmission for Increased Power Throughputs

It is entirely feasible to have reinforced transmission systems using modern technology which perform their intended operating tasks in a rather smooth manner;