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Multiterminal HVDC Power Transmission Systems using VSC

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***Abstract*:**The ever increasing progress of high-voltage high-power fully controlled semiconductor technology continues to have a significant impact on the development of advanced power elec-tronic apparatus used to support optimized operations and efficient management of electrical grids, which, in many cases, are fully or partially deregulated networks. Developments advance both the HVdc power transmission and the flexible ac transmission system technologies. In this paper, an overview of the recent advances in the area of voltage-source converter (VSC) HVdc technology is pro-vided. Selected key multilevel converter topologies are presented. Control and modeling methods are discussed. A list of VSC-based HVdc installations worldwide is included. It is confirmed that the continuous development of power electronics presents cost-effective opportunities for the utilities to exploit, and HVdc re-mains a key technology. In particular, VSC-HVdc can address not only conventional network issues such as bulk power transmission, asynchronous network interconnections, back-to-back ac system linking, and voltage/stability support to mention a few, but also niche markets such as the integration of large-scale renewable en-ergy sources with the grid and most recently large onshore/offshore wind farms.

Index Terms—HVdc circuit breakers (CBs), HVdc converters, HVdc transmission, power electronics, power engineering educa-tion, power systems.

INTRODUCTION

HVDC POWER transmission systems and technologies associated with the flexible ac transmission system (FACTS) continue to advance as they make their way to com-mercial applications [1]–[30]. Both HVdc and FACTS systems underwent research and development for many years, and they were based initially on thyristor technology and more recently on fully controlled semiconductors and voltage-source converter (VSC) topologies [1]–[30]. The ever increasing penetration of the power electronics technologies into the power systems is mainly due to the continuous progress of the high-voltage high-power fully controlled semiconductors [31]–[36]. The fully controlled semiconductor devices available today for high-voltage high-power converters can be based on either thyristor or transistor technology (see Table I). These devices can be used for a VSC with pulsewidth modulation (PWM) operating at frequencies higher than the line frequency. These devices are all self -commuted via a gate pulse.

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TABLE I
SUMMARY OF FULLY CONTROLLED HIGH-POWER SEMICONDUCTORS

Acronym	Type	Full Name
IGBT	Transistor	Insulated Gate Bipolar Transistor
IEGT	Transistor	Injection Enhanced Gate Transistor
GTO	Thyristor	Gate Turn-off Thyristor
IGCT	Thyristor	Integrated Gate Commutated Thyristor
GCT	Thyristor	Gate Commutated Turn-off Thyristor

Typically, it is desirable that a VSC application generates PWM waveforms of higher frequency when compared to the thyristor-based systems. However, the operating frequency of these devices is also determined by the switching losses and the design of the heat sink, both of which are related to the power through the component. Switching losses, which are di-rectly linked to high-frequency PWM operation, are one of the most serious and challenging issues that need to be dealt with in VSC-based high-power applications. Other significant dis-advantages that occur by operating a VSC at high frequency are the electromagnetic compatibility/electromagnetic interfer-ence (EMC/EMI), transformer insulation stresses, and high-frequency oscillations, which require additional filters.

HVdc and FACTS systems are important technologies, sup-porting in their own way the modern power systems, which, in many cases, are fully or partially deregulated in several coun-tries [37]. In the near future, even higher integration of electrical grids and market-driven developments are expected, as for in-stance, countries in the Middle East, China, India, and South America require infrastructure to power their growth and inter-connection of “island” grids [38]–[43].

Today, there are approximately 100 HVdc installations world-wide (in operation or planned for the very near future) trans-mitting more th an 80 GW of power employing two distinct technologies as follows.

Line-commutated current-source converters (CSCs) that use thyristors (Fig. 1, CSC-HVdc): This technology is well established for high power, typically around 1000 MW, with the largest project being the Itaipu sys-tem in Brazil at 6300 MW power level. The longest power transmission in the world will transmit 6400 MW power from the Xiangjiaba hydropower plant to Shang-hai. The 2071 km line will use 800 kV HVdc and 1000 kV ultrahigh-voltage ac transmission technology [44].

Forced-commutated VSCs that use gate turn-off thyris-tors (GTOs) or in most industrial cases insulated gate bipolar transistors (IGBTs) (Fig. 2, VSC-HVdc): It is well-established technology for medium power levels, thus far, with recent projects ranging around 300 –400 MW power level (see Table II) [45]–[55].

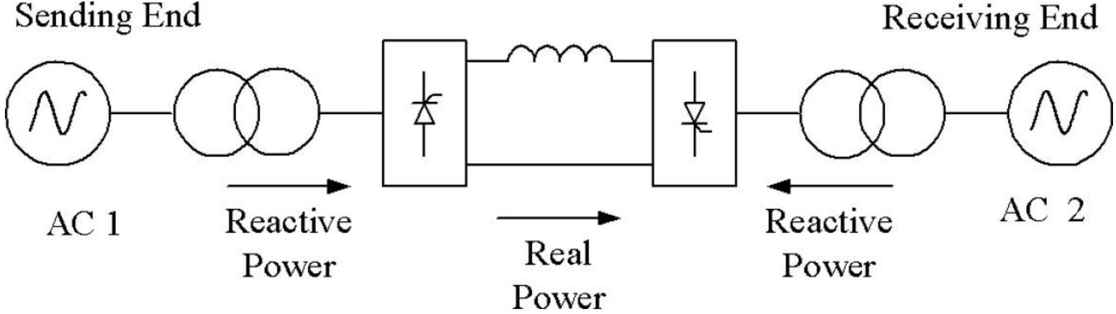

Fig. 1. HVDC system based on CSC technology with thyristors.

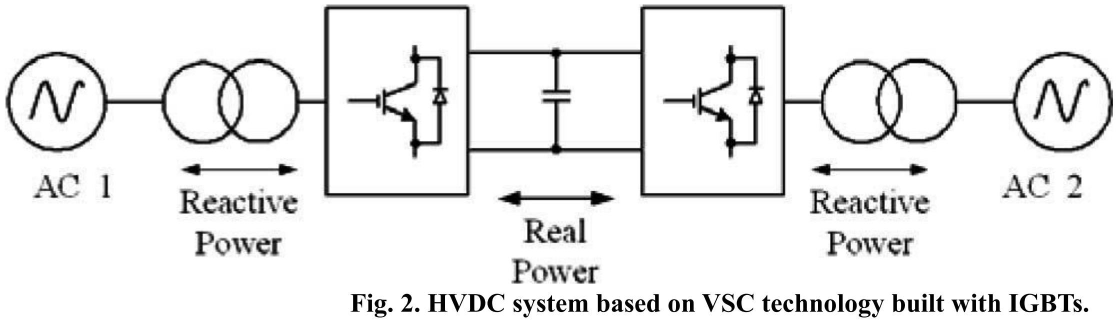

Fig. 2. HVDC system based on VSC technology built with IGBTs.

The CSC-HVdc systems represent mature technology today (i.e., also referred to as “classic” HVdc), and recently, there have been a number of significant advances [56]–[58]. It is beyond the scope of this paper to discuss developments associated with the CSC -HVdc that are well documented in [56]–[58].

On the other hand, VSC-HVdc systems represent recent developments in the area of dc power transmission technol-ogy [48]. The experience with VSC-HVdc at commercial level scatters over the last 12 years [45]–[47], [49]–[55]. The breakthrough was made when the world’s first VSC-based PWM-controlled HVdc system using IGBTs was installed in March 1997 (Hellsjon¨ project, Sweden, 3 MW, 10 km distance,

± 10 kV) [46], [47]. Since then, more VSC-HVdc systems have been installed worldwide (see Table II) [49]–[55].

The CSCs have the natural ability to withstand short cir-cuits as the dc inductors can assist the limiting of the currents during faulty operating conditions. The VSCs are more vulner-able to line faults, and therefore, cables are more attractive for VSC-HVdc applications.

It is worth mentioning relevant de-velopments that led to the success of VSC-HVdc such as the advanced extruded dc cable technologies [59]–[61]. Faults on the dc side of VSC-HVdc systems can also be addressed through the use of dc circuit breakers (CBs) [62]–[68]. In the event of the loss of a VSC in a multiterminal HVdc, the excess of power can be restricted by the advanced dc voltage controller [69].

The objective of this paper is to provide an overview of the HVdc technologies associated with VSC-based systems includ-ing converter topologies. Modeling and control are another area of importance, and recent contributions presented in the techni-cal literature are analyzed briefly. Finally, emerging applications of VSC-HVdc systems and multiterminal dc configurations that can be used to interconnect large -scale wind energy sources with the grid are discussed.

The paper is organized as follows. Section II provides a sum-mary of the CSC-HVdc system configurations, which also ap-ply, with some modifications, to the VSC-HVdc ones as well.Section III discusses in detail the fundamental concepts as-sociated with the VSC-HVdc system. The various multilevel converter topologies suitable for VSC-HVdc are presented in Section IV. Modeling and control issues are mentioned in Sec-tion V. Technical issues associated with dc faults, dc CBs, and isolation/reconnection of the dc network of multiterminal sys-tems are discussed in Section VI. Emerging applications in-volving the integration of large-scale wind energy systems are presented in Section VII. The various worldwide VSC-HVdc projects are summarized in Section VIII.

CSC-HVDC SYSTEM CONFIGURATIONS

Depending upon the function and location of the converter stations, various configurations of HVdc systems can be iden-tified. The ones presented in this section involve CSC-HVdc configurations but similar types of configurations exist for VSC-HVdc with or without transformers depending upon the project in question.

A. Back-to-Back CSC-HVDC System

In this case, the two converter stations are located at the same site and there is no transmission of power with a dc link over a long distance. A block diagram of a back-to-back CSC-HVdc system with 12-pulse converters is shown in Fig. 3. The two ac systems interconnected may have the same or different frequency (asynchronous interconnection).

B. Monopolar CSC-HVDC System

In this configuration, two converters are used that are sep-arated by a single pole line, and a positive or a negative dc voltage is used. Many of the cable transmissions with subma-rine connections use a monopolar system. The ground is used to return current. Fig. 4 shows a block diagram of a monopolar CSC-HVdc system with 12-pulse converters.

C. Bipolar CSC-HVDC System

This is the most commonly used configuration of a CSC-HVdc system in applications where overhead lines are used to transmit power. In fact, the bipolar system is two monopolar systems. The advantage of such system is that one pole can continue to transmit power in case the other one is out of service for whatever reason. In other words, each system can operate on its own as an independent system with the earth return. Since one is positive and one is negative, in case that both poles have equal currents, the ground current is zero theoretically, or, in practice, within a difference of 1%. The 12-pulse-based bipolar CSC-HVdc system is depicted in Fig. 5.

D. Multiterminal CSC-HVDC System

In this configuration, there are more than two sets of convert-ers. A multiterminal CSC-HVdc system with 12-pulse convert-ers per pole is shown in Fig. 6. In this case, converters 1 and 3 can operate as rectifiers while converter 2 operates as an inverter. Working in the other order, converter 2 can operate as a rectifier and converters 1 and 3 as inverters. By mechanically switching

TABLE II
Summary of Worldwide VSC-HVDC Projects and Their Basic Parameters

Project Name	Year of Commission	Power rating	Number of circuits	AC voltage	DC voltage	Length of DC cables	Comments and reasons for choosing VSC-HVDC	Topology	Semi-contactors
Hellsjön, Sweden	1997	3 MW ±3 MVAr	1	10 kV (both ends)	± 10 kV	10 km Overhead lines	Test transmission. Synchronous AC grid.	2-level	IGBTs (series connected)
Gotland HVDC Light, Sweden	1999	50 MW -55 to +50 MVAr	1	80 kV (both ends)	± 80 kV	2 × 70 km Submarine cables	Wind power (voltage support). Easy to get permission for underground cables.	2-level	IGBTs (series connected)
Eagle Pass, USA	2000	36MW ±36 MVAr	1	138 kV (both sides)	± 15.9 kV	Back-to-back HVDC Light station	Controlled asynchronous connection for trading. Voltage control. Power exchange.	3-level NPC	IGBTs (series connected)
Tjæreborg, Denmark	2000	8 MVA 7.2 MW -3 to +4 MVAr	1	10.5 kV (both sides)	± 9 kV	2 × 4.3 km Submarine	Wind power. Demonstration project. Normally synchronous AC grid with variable frequency control.	2-level	IGBTs (series connected)
Terrenora Interconnection (Directlink), Australia	2000	180 MW -165 to +90 MVAr	3	110 kV – Bungalora 132 kV – Mullumbimby	± 80 kV	6 × 59 km Underground cable	Energy trade. Asynchronous AC grid. Easy to get permission for underground cables.	2-level	IGBTs (series connected)
MurrayLink, Australia	2002	220 MW -150 to +140 MVAr	1	132 kV – Berri 220 kV – Red Cliffs	± 150 kV	2 × 180 km Underground cable	Controlled asynchronous connection for trading. Easy to get permission for underground cables.	3-level ANPC	IGBTs (series connected)
CrossSound, USA	2002	330 MW ±150 MVAr	1	345 kV – New-Heaven 138 kV – Shoreham	± 150 kV	2 × 40 km Submarine cables	Controlled synchronous connection for power exchange. Submarine cables.	3-level ANPC	IGBTs (series connected)
Troll A offshore, Norway	2005	84 MW -20 to +24 MVAr	2	132 kV – Kollsnes 56 kV - Troll	± 60 kV	4 × 70 km Submarine cables	Environment, CO_2 tax. Long submarine cable distance. Compactness of converter on platform electrification.	2-level	IGBTs (series connected)
Estlink, Estonia-Finland	2006	350 MW ±125 MVAr	1	330 kV – Estonia 400 kV – Finland	± 150 kV	2 × 31 km Underground 2 × 74 km Submarine	Length of land cable, sea crossing and non-synchronous AC systems.	2-level	IGBTs (series connected)
NORD E.ON 1, Germany	2009	400 MW	1	380 kV – Diele 170 kV – Borkum 2	± 150 kV	2 × 75 km Underground 2 × 128 km Submarine	Offshore wind farm to shore. Length of land and sea cables. Asynchronous system.	------	IGBTs (series connected)
Caprivi Link, Namibia	2009	300 MW	1	330 kV – Zambezi 400 kV – Gerus	350 kV	970 km Overhead lines	Synchronous AC grids. Long distance, weak networks	--------	IGBTs (series connected)
Valhall offshore, Norway	2009	78 MW	1	300 kV – Lista 11 kV – Valhall	150 kV	292 km Submarine coaxial cable	Reduce cost and improve operation efficiency of the field. Minimize emission of green house gases.	2-level	IGBTs (series connected)

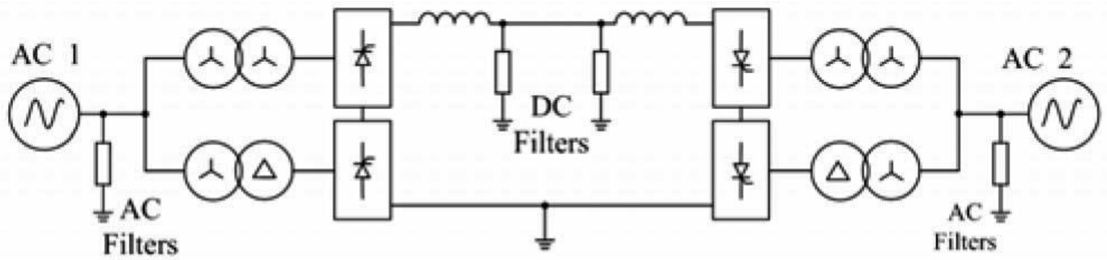

Fig. 3. Back-to-back CSC-HVDC system with 12-pulse converters.

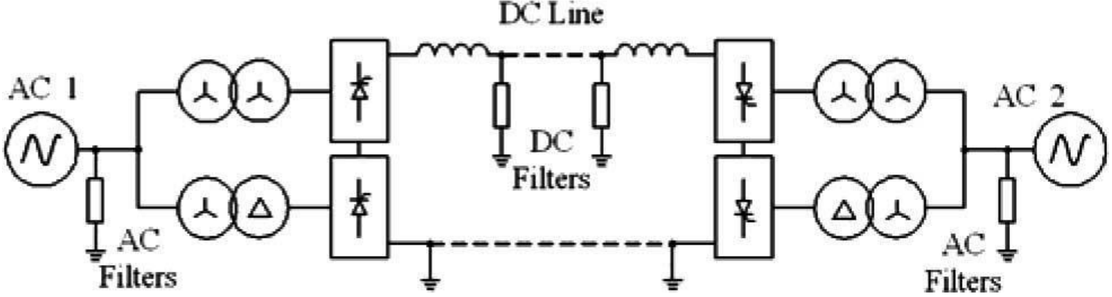

Fig. 4. Monopolar CSC-HVDC system with 12-pulse converters

the

connections of a given converter, other combinations can be achieved.

VSC-HVDC Fundamental Concepts

A basic VSC-HVdc system comprises of two converter sta-tions built with VSC topologies (see Fig. 2). The simplest VSC topology is the conventional two -level three-phase bridge shown in Fig. 7.

Typically, many series-connected IGBTs are used for each semiconductor shown (see Fig. 7) in order to deliver a higher blocking voltage capability for the converter, and therefore in-crease the dc bus voltage level of the HVdc system. It should be noted that an

antiparallel diode is also needed in order to ensure the four-quadrant operation of the converter. The dc bus capacitor provides the required storage of the energy so that the power flow can be controlled and offers filtering for the dc harmonics. The VSC-HVdc system can also be built with other VSC topologies. Key topologies are presented in Section IV.

The converter is typically controlled through sinusoidal PWM (SPWM), and the harmonics are directly associated with the switching frequency of each converter leg. Fig. 8 presents the basic waveforms associated with SPWM and the line-to-neutral voltage waveform of the two-level converter (see Fig. 7). Each phase leg of the converter is connected through a reactor to the

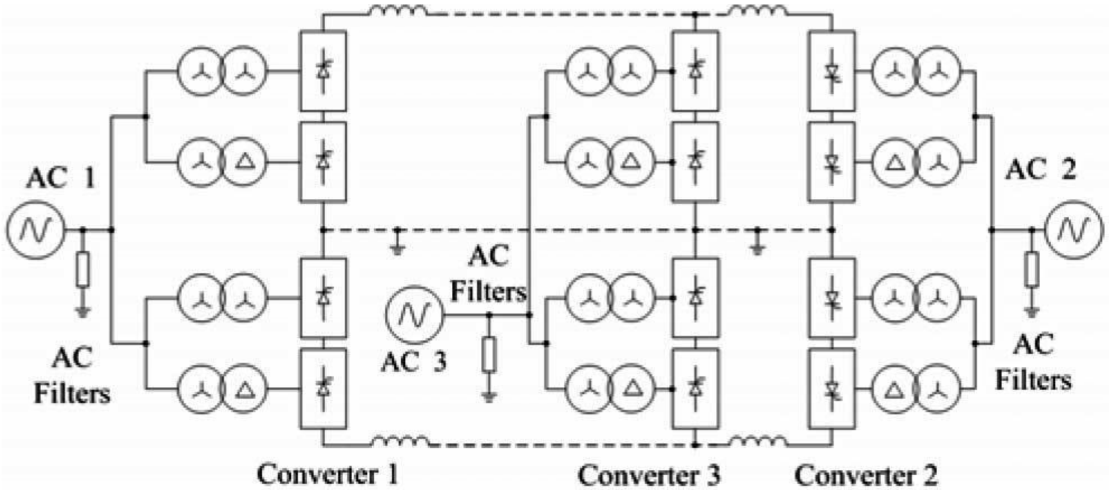

Fig. 6. Multiterminal CSC-HVDC system—parallel connected

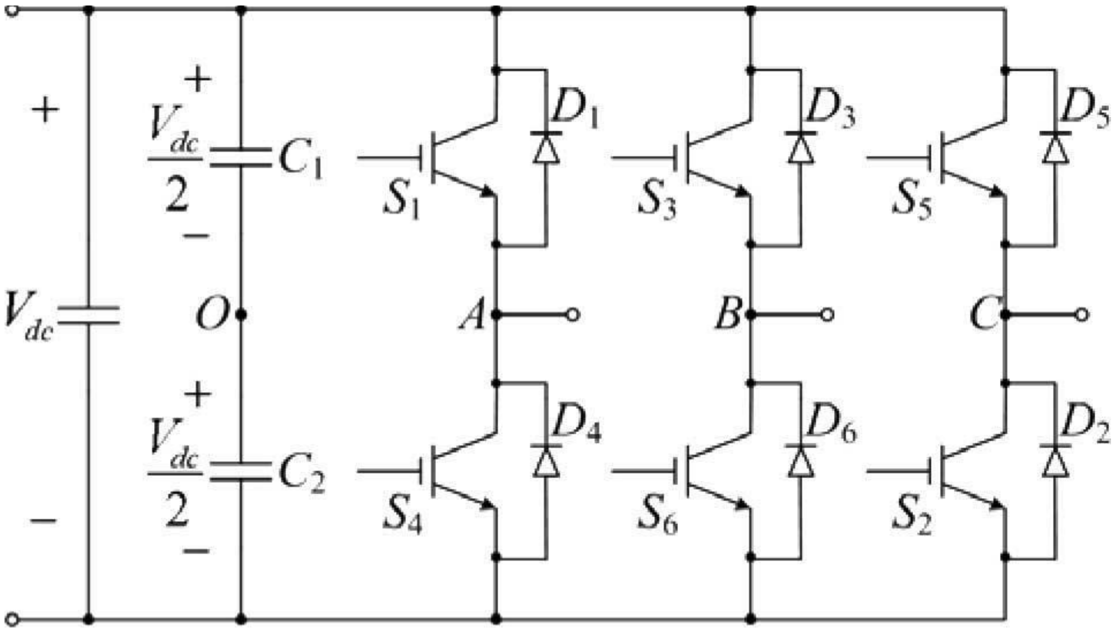

Fig. 7. Conventional three-phase two-level VSC topology

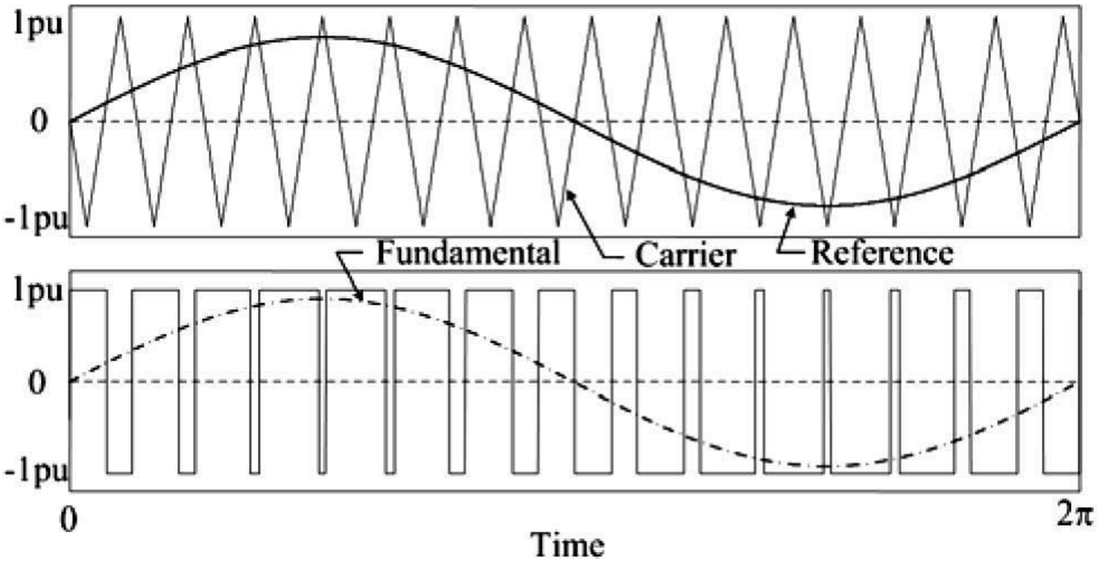

Fig. 8. Two-level sinusoidal PWM method: reference (sinusoidal) and carrier (triangular) signals and line-to-neutral voltage waveform

ac system. Filters are also included on the ac side to further reduce the harmonic content flowing into the ac system. Generalized two ac voltage sources connected via a reactor is shown in Fig. 9. Fig. 10 shows the relative location of the phasors of the two ac sinusoidal quantities and their relationship through nthe voltage drop across the line reactor (see Fig. 9). One voltage is generated by the VSC and the other one is the voltage of the ac system. At the fundamental frequency, the active and reactive powers are defined by the following relationships, assuming that the reactor between the converter and the ac system is ideal (i.e., lossless):

$$P = \frac{V_s \sin\delta}{X_L} V_r \qquad (1)$$

$$Q = \frac{V_s \cos\delta - V_r}{X_L} V_r \qquad (2)$$

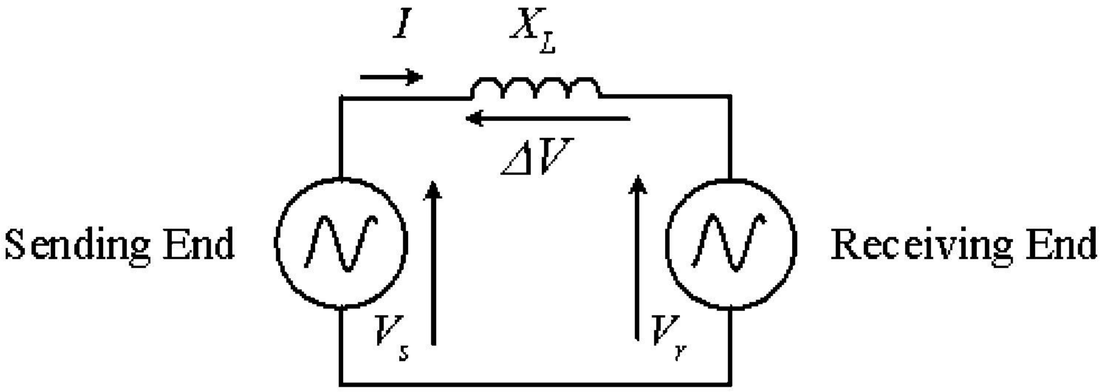

Fig. 9. Interconnection of two ac voltage sources through a lossless reactor

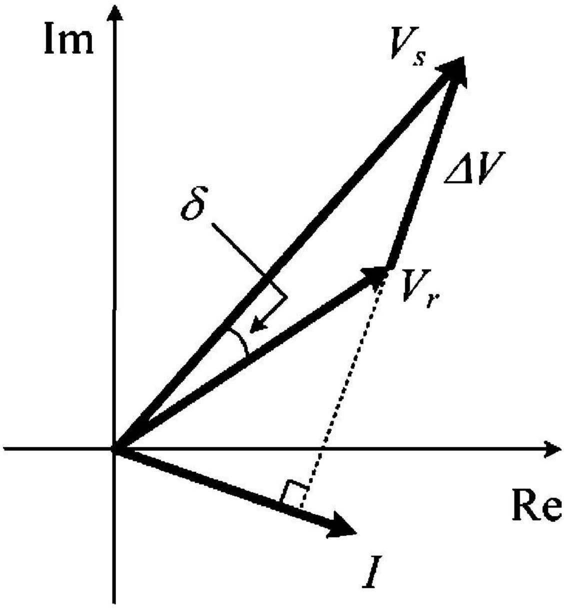

Fig. 10. Phasor diagram of two ac voltage sources interconnected through a lossless reactor.

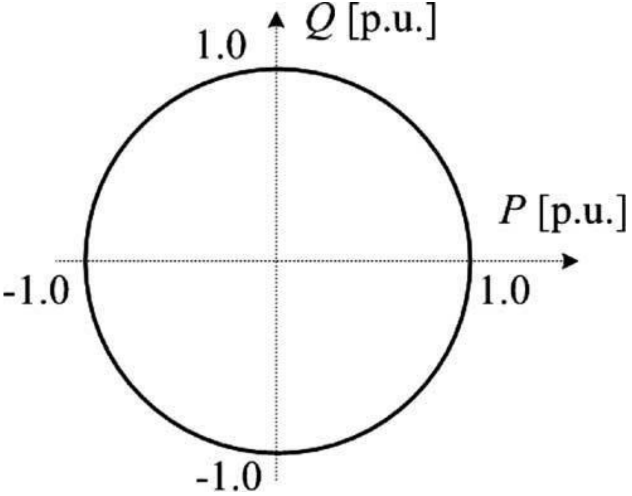

Fig. 11. Active–reactive locus diagram of VSC-based power transmission system.

where δ is the phase angle between the voltage phasors V_s and V_r at the fundamental frequency.

Fig. 11 shows the entire active–reactive power area where the VSC can be operated with 1.0 per unit (p.u.) value being the megavolt amperes rating of each converter (assuming that the HVdc operates in ideal conditions). The use of VSC as opposed to a line-commutated CSC offers the following advantages.

Avoidance of commutation failures due to disturbances in the ac network.

Independent control of the reactive and activ e power con-sumed or generated by the converter.

Possibility to connect the VSC-HVdc system to a "weak" ac network or even to one where no generation source is available, and naturally, the short-circuit level is very low.

L. Faster dynamic response due to higher PWM than the fundamental switching frequency (phase-controlled) op-eration, which further results in reduced need for filtering, and hence smaller filter size. No need of transformers to assist the commutation process

M. of the converter's fully controlled semiconductors.

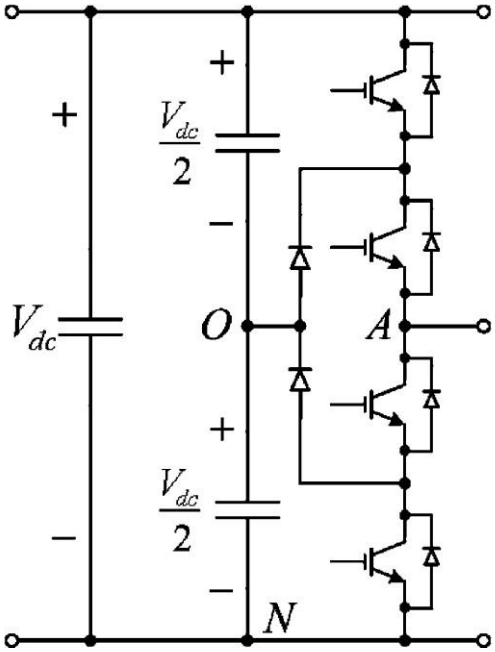

Fig. 12. NPC phase leg.

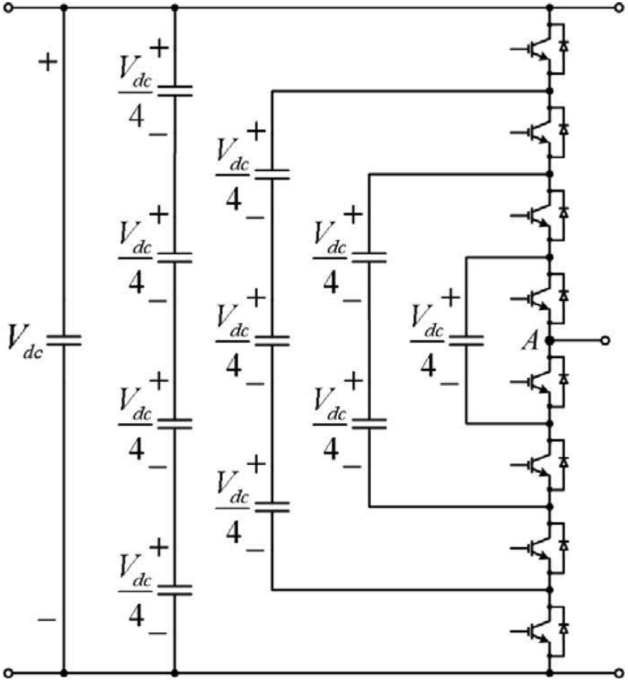

Fig. 13. Five-level FC VSC phase leg.

IV. VSC-HVDC MULTILEVEL TOPOLOGIES

In this section, different selected VSC topologies suitable for the implementation of a VSC-HVdc system are discussed. Multilevel converters extend the well-known advantages of low- and medium-power PWM converter technology into the high-power applications suitable for high-voltage high-power adjustable-speed drives and large converters for power sys-tems through VSC-based FACTS and HVdc power transmission [70] –[86].

There are numerous multilevel solid-state converter topolo-gies reported in the technical literature [74]. However, there are two distinct topologies, namely, the diode-clamped neutral-point-clamped (NPC) converter (see Fig. 12) [70] and the flying capacitor (FC) converter (see Fig. 13) [71], [72]. For clarity purposes, three-level and five-level PWM voltage waveforms on the line-to-neutral basis are shown in Figs. 14 and 15, respectively.

Contributions for selected topologies that can be used to build an HVdc system were made in numerous technical papers and are not limited to [78]–[102]. Specifically, PWM-controlled HVdc concepts based on the three-phase two-level converter were reported using GTOs in [87]. A similar system was developed and reported using IGBTs and DSP control in [93]. Using modular approach and phase-shifted SPWM concepts, a number of advantages can be gained as far as the harmonic performance of the overall VSC-HVdc system is concerned [88], [89], [91], [101]. The modular multilevel converter using half-bridge cascaded connections [see Fig. 16(a)] that seems to be more suitable for different number of voltage levels [see Fig. 16(b)] is presented in [81] and examined for HVdc applications [82], [83]. The diode-clamped NPC topology was studied in [90] for an HVdc system in its three-level version (see Fig. 12). The benefits of

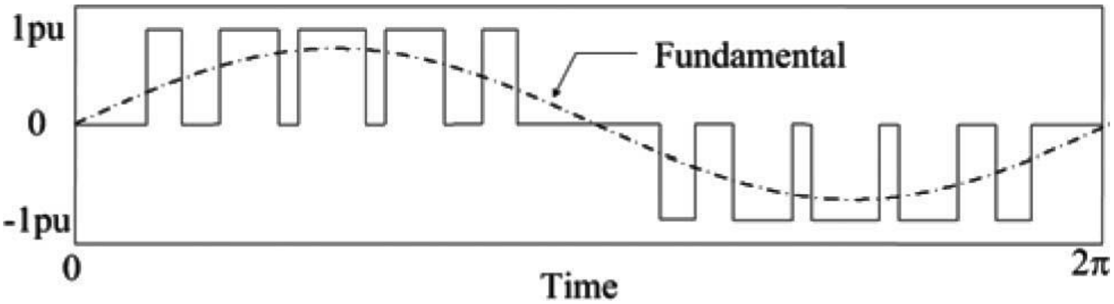

Fig. 14. Three-level PWM line-to-neutral voltage waveform.

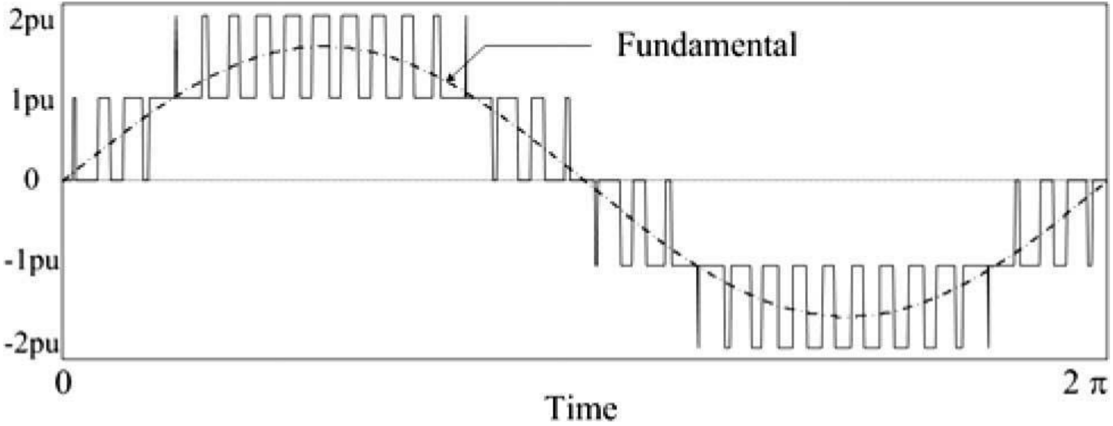

Fig. 15. Five-level PWM line-to-neutral voltage waveform

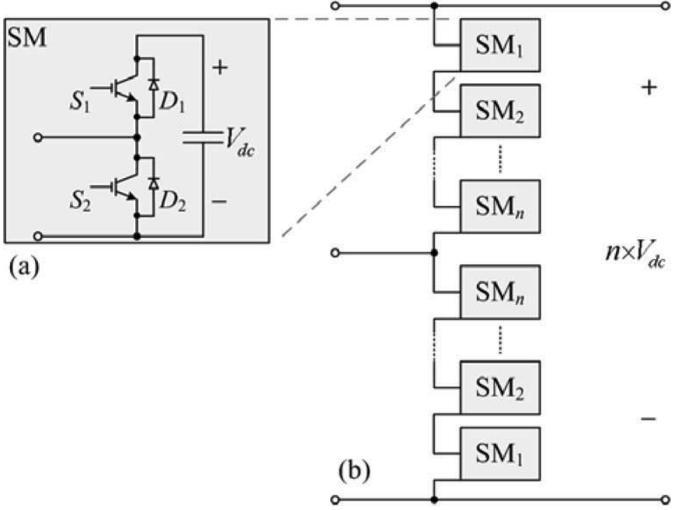

Fig. 16. Module-multilevel converter topology. (a) Structure of the submodule (SM). (b) Phase leg.

using such a system were brought out; however, the converter has significant challenges with voltage, balancing across the various dc bus capacitors, in addition to the uneven loss distribution between the devices. An actively clamped topology that is able to offer a solution to the loss distribution problem of the NPC was introduced in [78] and is called active NPC (ANPC) converter (see Fig. 17). This topology is an attractive solution for HVdc applications. A VSC-HVdc system based on the five-level PWM FC topology was studied in [92] (see Fig. 13). The three basic topologies, namely the two-level converter (see Fig. 7), the NPC converter (see Fig. 12), and the FC converter (see Fig. 13), were com-pared for the HVdc system in [84]. A hybrid system is proposed in [94] as a way to exploit the benefits of more than one technol-ogy, i.e., the advantages of CSC-based HVdc and VSC-based static synchronous compensator (STATCOM) used as a static compensator for the connection of two ac systems when there is no synchronous generation to a main grid. The proposed system is shown in Fig. 18. The system studied through simulations combines the robust performance and relatively lower capital cost due to the low frequency switching with the fast dynamic response of a PWM-controlled VSC STATCOM. The power level of the STATCOM is not as high as the power level of the CSC-based HVdc. The multilevel FC topology and its opera-tion under fault ac conditions were discussed in [96] and [97]. The control of the FC VSC-based HVdc system by selective har-monic elimination (SHE) PWM, hybrid SHE-PWM, and SPWM strategies was presented in [95] and [102]. Advances of SHE-PWM techniques that result in a reduced switching frequency were discussed in [103] and [104]. Space vector modulation (SVM) methods are also investigated to minimize the switching losses [91], [101]. Recently, VSC transmission topologies based on the multilevel current/voltage reinjection concept have been reported in [79], [80], and [98]–[100]. The configuration in [85] generates multilevel voltage waveforms with about 5% of total harmonic distortion under the fundamental switching frequency for the main bridges and six times the fundamental switching

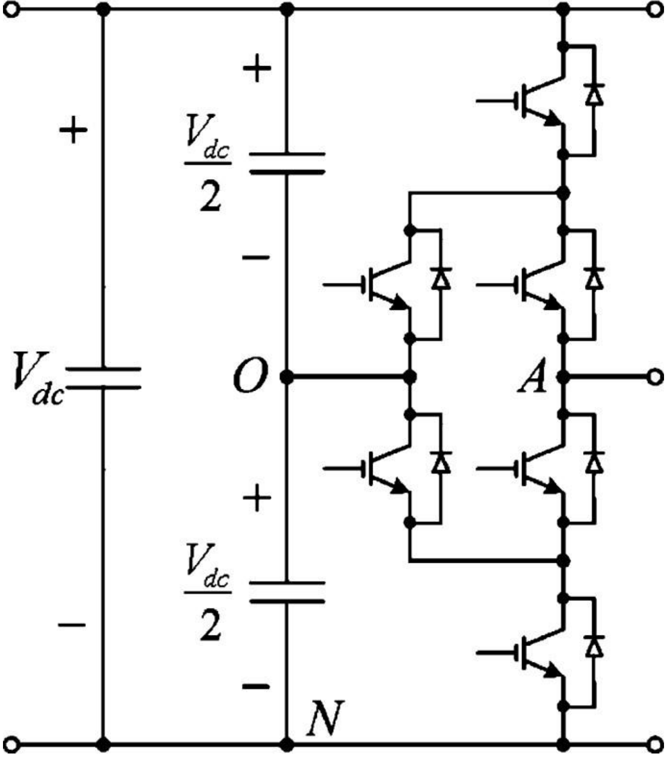

Fig. 17. ANPC phase leg.

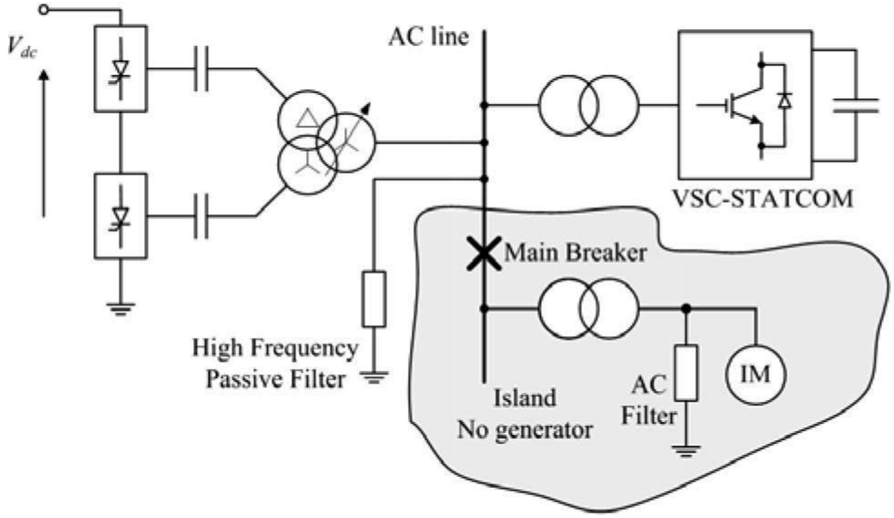

Fig. 18. Hybrid CSC-based HVDC combined with VSC-based STATCOM [94].

frequency for the reinjection bridge without the assistance of filters or PWM. Another multilevel configuration that is suited for high-voltage ratings is proposed in [79] and [80].

I. Modeling and Control

The large number of technical papers associated with VSC-HVdc systems, in the area of modeling and control, is not limited to [105]–[111]. A dc bus voltage control system using equivalent continuous-time state-space average modeling was presented in [105]. It is shown in [106] that including a back-to-back VSC-HVdc system at the midpoint of a transmission line can increase the transmissibility of the line by a factor of 1.68. It is shown in [107] that the VSC-HVdc system can be operated as a static synchronous series compensator (SSSC). Recently, a control system for the VSC-HVdc during island operation and under three-phase balanced faults was investigated in [108], and it has been found that the current limit of the converters has a significant influence on the dynamic response of the system. Finally, a dynamic model for a back-to-back HVdc system based on the three-level NPC topology was presented in [109].

VI. HVDC CBS

The availability of dc CBs is limited. DC CBs are commonly used in traction applications [62]–[67] but the voltage and cur-rent ratings of these devices are considerably lower than what would be required in HVdc and multiterminal applications. The use of the dc CBs is feasible if a number of breakers are con-nected in series. Series connection of the dc breakers implies that all breakers should commutate simultaneously. Any time delays or breaker mismatching will result in breaker failure.

A plethora of publications exists in the literature concern-ing mechanical, solid-state, and hybrid ac CBs. On the other hand, only a few scientific publications are available studying the feasibility of different solutions concerning dc CBs. The different dc CBs topologies can be divided into three categories as follows. 1) A configuration employing a conventional ac CB and: a) a charged capacitor in parallel with the breaker;

b) a resonance circuit is connected in parallel with the breaker. 2)

A solid-state CB that can consist of:

a) a controllable device such as IGBT, integrated gate commutated thyristor (IGCT), GTO, with an an-tiparallel diode;

b) a bidirectional switch that consists of controllable devices and diodes.

3) A hybrid dc CB where a solid-state breaker, uni- or bidi-rectional configuration, is connected in parallel with a conventional ac CB.

During a dc fault, the antiparallel diodes of the three legs of the converter conduct as a rectifier to feed the fault. The fault can be cleared either by ac CBs without protecting the VSC or by breakers at the dc side. Two IGBT CBs (IGBT-CBs) are required for each converter of a two-terminal VSC-based HVdc system. For a multiterminal system, the IGBT-CBs can

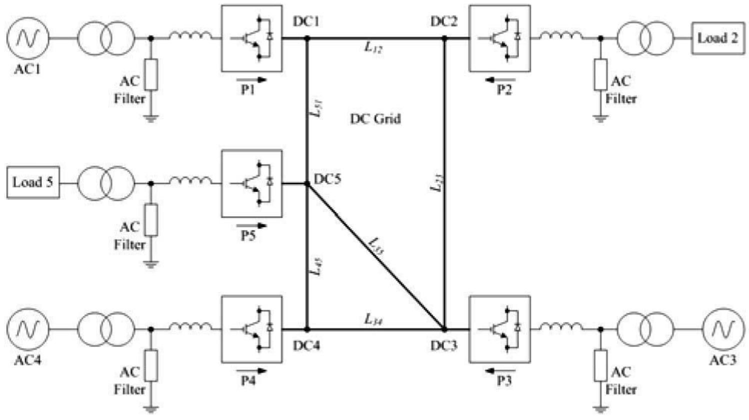

Fig. 19. Five-terminal VSC-HVDC system [112].

be placed between each VSC and the dc network or at each end of a dc branch line [68].

When IGBT-CBs are placed between each VSC and the dc network, mechanical switches are placed at each end of a dc branch line. During dc fault, the VSCs are isolated from the dc network by blocking of IGBT-CBs and give sufficient time for the arc to deionize. For a temporary fault, the system can be restored by unblocking of IGBT-CBs. If there is a permanent fault, the mechanical switches can be opened to isolate the fault, and then unblock the breakers to resume operation [68].

An alternative method that may imply higher cost is to place the IGBT-CBs at each end of a dc branch line. Therefore, the dc fault can be isolated from the VSCs directly, without the need of extinguishing of the fault current.

VII. EMERGING APPLICATIONS

VSC-HVdc can be effectively used in a number of key areas as follows [45]–[55]: small, isolated remote loads; power supply to islands; infeed to city centers; remote small-scale generation; offshore generation and deep-sea crossings; multiterminal systems.

As a way of example, a five-terminal VSC-HVdc [112] and a multiterminal configuration [113] are shown in Figs. 19 and 20, respectively.

From the technology point of view, wind farms and offshore wind farms in particular are well suited for VSC-HVdc applica-tion [114], [115]. The discussion continues as to whether the dc is more cost-effective to the ac counterpart as a means to connect wind farms with the main grid [116]. Evaluation of grid connect-ing offshore wind farms through a dc link and their technical and economic analyses are recently presented in [117]. The oppor-tunity to use dc systems based on permanent-magnet generators and medium-frequency transformers, as opposed to 50/60 Hz generators and transformers, has b een presented offering more compact and light solution for offshore wind farms [128].

Multiterminal dc systems have been studied for wind farms and work is reported in [112], [118], and [119].

Fig. 21 presents a scenario of three wind generators connected through dc into a multiterminal grid through a VSC connection,

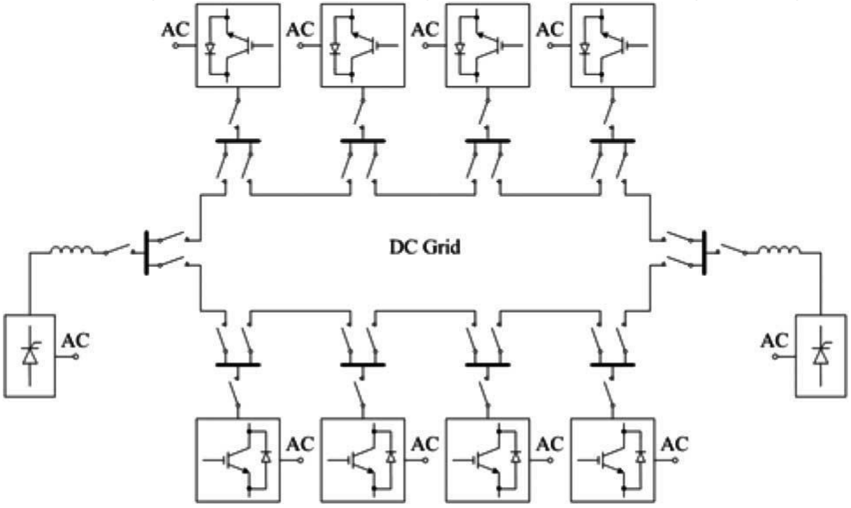

Fig. 20. Single-line multiterminal VSC-HVDC system [113].

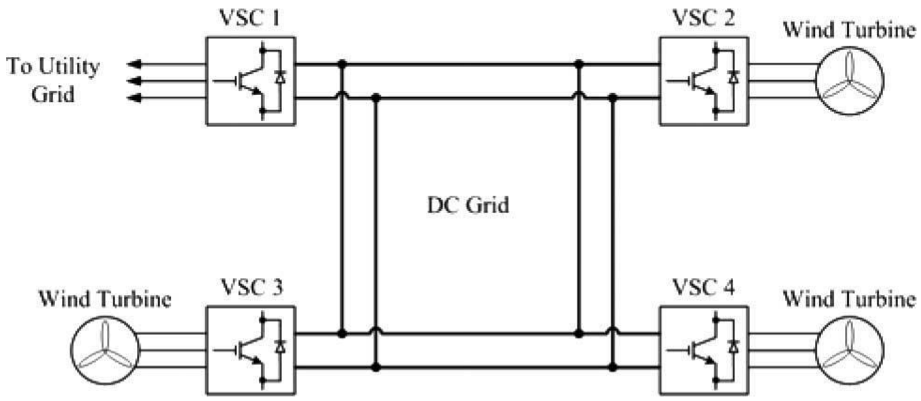

Fig. 21. Four-terminal PWM VSC-based HVDC system for wind turbines/ wind parks [118].