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Course handout

High Voltage Direct Current Light

Course and Applications

Level: PhD and Master Students

Specialty: Electrical Networks

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Preface:

This course material is intended for Master and PhD students specializing in electrical networks.

This document consists of giving an overview of the fundamental notions of the HVDC (High voltage direct current) light connection based on the IGBT element. The components of a DC transmission system are cited and also the fundamental principle of operation of a DC transmission system is well detailed and the control systems are given and finally the application of this type of transmission energy for the connection of offshore wind farms to electrical networks is given to fully understand the concepts presented in the course.

Dr. L. MAZOUZ

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Introduction

In 50 years, HVDC technology has reached maturity and is a reliable means of transporting high power over long distances with minimal losses. The question now is what direction development work will take in the next few years. It was thought that they would follow, once again, the evolution of industrial drives. Here, thyristors were replaced long ago by voltage source converters with both blockable and bootable semiconductors. The latter offered many advantages for the control of industrial drive systems, which it was thought could be transposed to electrical energy transmission systems. Adapting voltage source converter technology to HVDC is not easy, however. It's all the technology that needs to be reviewed, not just the valves.

The development of power semiconductors, in particular IGBTs, has made it possible to produce HVDC installations equipped with voltage source converters (VSC) which can also interrupt the current, and not only switch it, as in the case of switching converters. phase (based on thyristors). These latter conventional converters still have some weaknesses, the elimination of which is relatively costly and involves certain operating limits in the application of HVDC links. The most significant weak point is the need for rotating machinery in the receiving network and the corresponding risk of switching fails, during which no power is transmitted for several periods.

VSC-HVDC connections are marketed under the name "HVDC Light" by the company ABB, or "HVDC Plus" by the company SIEMENS. It is a new DC power transmission technology that lowers the economical range of HVDC transmissions to a few megawatts of power. This system not only represents a competitive alternative to conventional alternating current transport and local electricity production, for example in remote areas and on small islands. It also offers new possibilities to improve the quality of the power supply of AC power networks.

An advantage of VSC-HVDC technology is that it improves the stability and regulation of reactive power at each end of the network. In addition, it can operate at very low short circuit power levels and even offers fault start functionality. The cable of the VSC-HVDC solution is made of polymer material, which makes it particularly resistant and robust. It is thus possible to lay HVDC cables in aggressive environments without risk of deterioration. Extruded cable also enables the economic viability of long terrestrial HVDC cable transmission lines.

Electricity is mainly produced by fossil or nuclear power plants, transmission and distribution system operators traditionally based on the nature of this production to compensate inelasticity and fluctuations of the demand. The rise of renewable energies, such as wind power, is changing the situation: in fact, they have the disadvantage of being more difficult to control and anticipate. The networks must then be able to react quickly, under optimal conditions of reliability and economy, to the great variability and unpredictability of the delivered power. HVDC technology, especially its version HVDC-VSC allows quick and precise adjustment of voltages and power flow. It is reliable and economical and it can enhance the flexibility of existing AC networks. HVDC-VSC is also used to connect large offshore wind farms to onshore AC networks.

The large wind farms connected to the electric network can potentially bring a significant contribution to the operation of the AC transport networks, for example by regulating the frequency or stabilizing the network. The ability of HVDC-VSC technology to provide independent active and reactive power control can be used to support the AC transport network, resulting in significant technical and economic benefits for network operators.

Essentially, due to the increase in the size of the wind power plant, noise, and visual pollution and also due to high wind speed values, offshore winds are gaining more and more compared to onshore ones. But the placement of wind farms at the sea is done with many challenges related to the construction, installation and transmission of energy. The latter requires a great effort to make the offshore wind farms reliable, especially for long distances between them and the coast.

The solution that can solve the above problem is the use of a transmission system based on VSC (Voltage Source Converter) technology. The main advantages of these transmission systems are related to transmission losses as well as costs.

Chapter 01: High voltage direct current Links

1.1 Introduction

At the end of the 19th century, the dawn of the Electrical Power Industry, a passionate debate developed over the generation of electricity and its distribution. The outcome determined the structure of the power grid as we know it nowadays[01]. The most representative players of the dispute, so fierce that is also known as the “Battle of the currents”, were Nikola Tesla and Thomas Edison, the former a supporter of the electric distribution in Alternate Current (AC) and the latter a supporter of the Direct Current (DC). In spite of the well-known result of the “battle”, nowadays we are seeing a revival of DC, not only at the transmission level. In fact, the DC solutions include, among others, renewable energy integration (e.g. solar energy systems), charging of electric vehicles, data center supply and, of course, long HVDC interconnections [02].

The first modern HVDC interconnections were the Moscow-Kashira system and the connection Gotland-Sweden mainland in 1954. Since then, big steps has been done in the development of HVDC converters whose employment is driven by several technical and economic factors, to mention a few [03]:

- Lower overall investment;
- Lower losses, due to only active power flow;
- Increased stability and improvements in power quality;
- Less expensive circuit breakers in the AC side and simpler bus-bar arrangements in switch-yard due to lower short-circuit currents;

VSC-HVDC links are marketed under the name "HVDC Light" by ABB, where many "HVDC Plus" by SIEMENS. It is a new technology of power transmission in DC current that lowers economic range of HVDC transport to a power of a few megawatts. This system represents not only a competitive alternative to conventional AC transport and local production of electricity, for example in remote areas and small islands. It also offers new possibilities to improve the power quality of AC power networks.

An advantage of the VSC-HVDC technology is that it improves the stability and the control of reactive power at each end of the network. Moreover, it can operate at short circuit power levels very low and provides same functionalities of starting on fault. The cable of the VSC-HVDC solution is of polymer material, which makes it particularly resistant and robust. It is thus possible pose HVDC cables in aggressive environments without risk of deterioration. The extruded cable also allows the economic viability of long terrestrial lines of HVDC transmission by cables. As an example, VSC-HVDC interconnection of Murraylink in Australia which is 180 km long [04].

1.2 Historical Overview

The first transmission of power using HVDC systems was marketed in 1954.This was an interconnection between the island of Gotland and the Swedish main land. It was made through a submarine cable of 96km long, providing a transport capacity of 20 MW with a rated voltage of100kV.Thereare currently more than 50 HVDC systems operating around the world and many others are under construction [05].

The success of these initial projects aroused considerable interest around the world. In the 60s, several HVDC links were built: Konti-Skan link between Sweden and Denmark, Sakuma in Japan (with frequency converters 50/60 Hz), the New Zealand link between the islands of the south and north, the Italy-Sardinia link and the link with the island of Vancouver in Canada [06].

In 1965, the laboratories of General Electric realize a semiconductor device capable of achieving the static switch function with controlled closure: The thyristor.

In 1970, a first thyristor valve is experimented on the link of Gotland and in 1972; the first converter station back-to-back is commissioned by General Electric Eel River, Canada. [05].

The largest HVDC transport project ever built to date, the Itaipu link in Brazil (6300 MW), was launched in 1979. This connection, is made and put into operation in several steps between 1984 and 1987, played a key role in the supply of electrical energy in Brazil.

The significant decrease in the cost of converters, facilitated by this new technology, has allowed to greatly enhance the growth of DC links. After Itaipu, the most ambitious project was undoubtedly interconnection Quebec-New England (2000 MW, ± 450 kV), the first major multi-terminal HVDC link was built on 1992.

In 1999, the first transport system HVDC converters, voltage source based IGBT, called HVDC Light began to carry electricity between Hellsjon and Granges berg in Sweden [06, 07].

1.3 High voltage alternating current transmission (HVAC)

AC Systems are the most common mode for transmitting electrical power, and they are used worldwide. But this technology has many disadvantages for transmitting power from renewable energy sources like wind power. These disadvantages can be summarized as follows:

• Submarine cables produce huge amounts of reactive power that must be consumed at the ends of the cables.

• It is not possible to use HVAC transmission over long distances due to dielectric losses and also due to the previous drawback;

• It is always necessary to use many cables in parallel when the amount of power transmitted is enormous;

• Load losses increase considerably due to the increase in the size of wind farms and the distance traveled between these farms and the coast.

1.4 The benefits of HVDC

HVDC systems can transmit more electrical power over longer distances than an similar AC transmission system, which means fewer transmission lines are needed, saving both money and land. In addition to significantly lowering electrical losses over long distances, HVDC technology is also very stable and easily controlled, and can stabilize and interconnect AC power networks that are otherwise incompatible.

The HVDC market is growing rapidly and has become an important part of many transmission networks, not least because it can connect remote sources of electrical power – often emissions-free renewable sources like hydro or wind generation – to load centers where it is needed, hundreds or even thousands of kilometers away. Once installed, HVDC transmission systems often form the backbone of an electric power system, combining high reliability with a long, useful life. Their core component is the power converter, which serves as the interface with the AC transmission system. The conversion from AC to DC, and vice versa, is achieved by controllable electronic switches (called valves).

1.5 The development of HVDC technology

Today there are two main technologies. HVDC Classic, the first developed technology, is used primarily for bulk electrical transmission over long distances, overland or subsea, and for interconnecting separate power grids where conventional AC methods cannot be used. Today there are more than 100 HVDC installations in all parts of the world. A classic HVDC transmission typically has a power rating of more than 100 megawatts (MW) and many are in the 100 – 10,000 MW range. They use overhead lines, or undersea/underground cables, or a combination of cables and lines.

HVDC Light® , developed by ABB and launched in 1997, is an adaptation of HVDC classic used to transmit electricity in power ranges (from 50 – 2,500 MW) transmitted using overhead lines or invisibly, using environmentally friendly underground and subsea cables. It is used for grid interconnections and offshore links to wind farms and oil and gas platforms. In both HVDC Classic and HVDC Light®, it is possible to transmit power in both directions and to support existing AC grids in order to increase robustness, stability and controllability.

1.6 VSC-HVDC System Description

VSC HVDC link uses IGBT valves instead of thyristors valves, which HVDC Classic is using. A major difference between VSC HVDC and HVDC Classic is that the Classic works as a current source while the VSC works as a voltage source. In other words, the power transmission for HVDC Classic is determined from current while for VSC HVDC it determined from voltage.

In Figure 1.1the description of VSC-HVDC transmission is shown. At the end of the DC cable an exact same type of terminal can be found. The terminal consists of a power transformer, which transform up the voltage to the transmission level. The voltage is rectified with help from the voltage source converter. The VSC works both as a rectifier and inverter, depending of the active power flow direction. The VSC consists of six valves and it will later be discussed in the next chapter. After that the voltage has been rectified it is connected to the DC cable. At terminal B the voltage is inverted and transformed down to the grid voltage level.

VSC HVDC needs filter to work as thought. There is a Harmonic filter and its purpose is to limit the amount of harmonics that can reach the grid. There is one phase reactor per phase, between the power transformer and the VSC. The phase reactor works as a series filter. The phase reactor reduces the amount of current harmonics that reach the utility grid. By using the phase reactor an almost perfect sinusoidal current reaches the grid. At the DC side there is also a filter and it consist of capacitors. They keep the voltage at the DC cable as constant as possible [08].

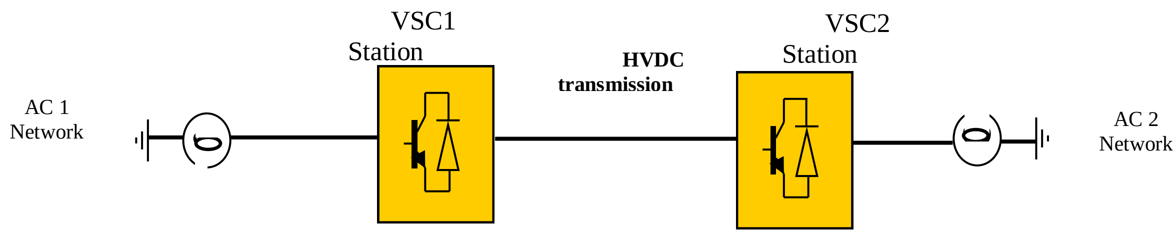


Fig.1.1: The description of VSC-HVDC transmission

1.7 Comparison of VSC HVDC and Classic HVDC

From a power system point of view a VSC can be seen as a voltage source which operates with the same frequency as the AC system to which it is connected, controlling active and reactive power independently of each other. Classical HVDC consumes reactive power and needs a present AC voltage source for commutations, which is not the case for VSC-HVDC. This makes VSC-HVDC suitable for restoration scenarios and it is claimed to possess a "black start capability". If a power reversal is desired, the VSC changes the direction of the current, in contrast to Classic HVDC which changes the polarity of the DC voltage [09].This makes Classic HVDC unsuitable for MTDC configurations as changing the polarity of the voltage at one converter would invert the polarity of all converters connected to the same DC grid, which may not lead to the desired power flow [09].VSC does not have this problem as the power flow can be reversed at a single VSC without inverting the DC voltage polarity of the whole system. Also, reversal of the power flow for Classic HVDC involves time consuming mechanical maneuvers but with VSC it can be achieved almost instantaneously. Furthermore, Classic HVDC needs to be connected to a strong AC grid as fluctuations in voltage or frequency may result in errors in the commutation which can interrupt the power flow. With VSC, the power flow will only be reduced in case of a voltage drop; depending on how large the reduction of the AC voltage is [09].The main disadvantage for VSC-HVDC is the switching losses, which are higher compared to Classic HVDC. Since the introduction of VSC in the 1990s the conversion losses have been reduced from around 3% to 1%, for Classic HVDC the conversion losses is around 0.5%. For point to point links, where large amounts of power need to be transferred, Classic HVDC is still preferable. There are projects commissioned with a DC voltage of ±800kV and rated power of7200 MW For VSC-HVDC, projects commissioned have voltage ratings up to ±350kV and rated power up to approximately 900 MW [10].

1.8 Areas of application VSC- HVDC links

The HVDC transmissions are basically used in one of the following applications [01]:

1.8.1 Underground/submarine cable transmissions

In the case of underground or submarine HVDC cables there is no physical restriction concerning the distance, the power level and also there are considerable savings in installed cable costs. Furthermore, in the case of the underground cables, these ones can be used on shared Right-of-Way with other utilities [11, 12].

Some examples in this type of application are: Gotland project (1954), Sardinia (1967)and more recent the 180 MW Direct link connection in Australia (2000).

1.8.2 Long distance bulk power transmissions

The HVDC transmission systems provide an economical alternative to AC transmission systems regarding the bulk power delivery from remote locations such as hydroelectric developments or large scale wind farms whenever the breakeven distance is exceeded [11]. As presented above, a higher power transfer is possible over long distances using fewer lines with HVDC technology than with the AC technology.

1.8.3 Asynchronous connections of AC power systems

The HVDC transmissions systems offer a reliable and economical way of interconnection between two AC asynchronous networks. Usually, these interconnections are realized using back-to-back converters with no transmission line [11, 12].Many examples of asynchronous interconnections can be found in North America, as in the case of Electric Reliability Council of Texas (ERCOT) and its neighbors [11].

1.8.4 Stabilization of power flows in integrated power systems

Due to the fast controllability of DC power, strategically placed DC lines can solve issues like power flow in AC ties which can be uncontrollable and can lead to overloads and stability problems. One example of using HVDC transmission systems in such application is the IPP link in USA.

1.8.5 Offshore transmission

Due to their advantages, such as: self-commutation, black-start capability and dynamic voltage control, VSC-based HVDC transmissions can be used to serve isolated loads on islands or offshore platforms over [11]. Moreover, VSC-based HVDC transmission systems can provide reactive power support to wind farms as well as interconnection point.

The VSC-based HVDC technology represents a very suitable way of transmitting power from wind farms to the main AC grid. The ability of controlling reactive power as well as the AC voltage and its contribution to the grid stability makes the VSC-HVDC technology very popular for such applications. Moreover, the technology is flexible and new units can be easily added if the expand of the WF is desired.

The VSC-HVDC transmission is a compact transmission and can feed production or transportation loads on offshore oil or gas platforms from shore [12].

1.8.6 Power supply to insular loads

Due to some of its advantages such as: dynamic voltage control, black start capability or forced-commutation the VSC-HVDC transmission is capable to supply remote locations(i.e. islands) using submarine cables and without any need of running expensive local generation [12]. An example of this application is the Gotland Island System.

1.9 Advantages links VSC- HVDC

The main operation difference between classic HVDC and VSC-HVDC is the higher controllability of the latter. This leads to a number of potential advantages and applications, where some are given below:

- Independent control of active and reactive power without extra compensating equipment. With the use of PWM, the VSC-HVDC can control both active and reactive power independently. While the transmitted active power is kept constant the AC voltage controller can control the voltage in the AC network. Reactive power generation and consumption of a VSC-HVDC converter can be used for voltage control to compensate the needs of the connected network within the rating of a converter.

- Mitigation of power quality disturbances. The reactive power capabilities of the VSC-HVDC can be used to control the AC network voltage and thereby contribute to an enhanced power quality. Furthermore, the faster response, due to increased switching frequency (PWM), offers new levels of performance regarding power quality control such as flickers and harmonics. Power quality problems are issues of priority for owners of industrial plants, grid operators and for the public .

- Reduced risk of commutation failures. Disturbances in the AC system may lead to commutation failures in a classic HVDC system. As the VSC-HVDC uses self commutating semiconductor devices, it is no longer necessary to present a sufficiently high AC voltage. This significantly reduces the risk of commutation failures and extends the application of the VSC-HVDC for stability control.

- Communication not needed. As the control systems on the rectifier and inverter sides operate independently, they do not depend on a telecommunication connection, which in turn improves the speed and the reliability of the controller.

- Feeding islands and passive AC networks. The VSC converter is able to create its own AC voltage at any predetermined frequency without the presence of rotating machines. Therefore, it may be used to supply industrial installations or to connect large wind farms.

- Multi-terminal DC grid. The VSC converters are suitable for creating a DC grid with a number of converters since little coordination is needed between the VSC-HVDC Converters. One potential application of multi-terminal DC grids is to provide power Supply to city centers.

1.10 VSC- HVDC and Environment

An HVDC transmission system is basically environment-friendly because improved energy transmission possibilities contribute to a more efficient utilization of existing power plants.

1.10.1 Electromagnetic Fields

The magnetic field produced by a DC line is stationary while in the AC case it is alternating, which can cause inducing body currents. This results in fewer restrictions for the magnetic field in the HVDC line. The electric field is less severe in DC lines compared to AC ones since there is no steady state displacement current in the DC case. VSC-HVDC cables' magnetic fields are almost eliminated with the bipolar system. However, an undersea HVDC line can cause disturbances to magnetic compass systems on vessels crossing the cable.

1.10.2 Audible Noise

An underground DC cable naturally has no audible noise emission. Audible noise from transmission line corona is most noticeable when OHL conductors are wet in foggy weather conditions. Consequently, buildings construction close to OHLs might be restricted. Audible noise mostly depends on line's voltage and its design specifications.

Furthermore, underground HVDC cables have better environmental problem than overhead HVAC lines in favor of these additional reasons:

- Right-of-way as a loss of CO_2 sink: growing forests are considered CO_2 sinks because trees convert carbon dioxide from the atmosphere into carbon stored in the form of wood and organic soil matter. A forest can absorb 9.2 tons of CO_2 per hectare per year. For example, building a 400 km, 400 kV OHL through an area that is 75 percent forest represents a loss of a carbon sink of 16,780 tons of CO_2 per year ;

- Material use: AC OHL's material weight is higher than for a DC cable. The material used in a DC cable has only 17.6 percent the environmental impact of AC OHL.

1.10.3 Space

AVSC-HVDC link requires much less space. A high voltage line 380 kV conventional link requires a minimum width of 60 meters. This band must be free of tall trees or buildings.

AVSC-HVDC link requires only an installation road of 4meters wide. For comparison: for an air link with a length of 100 km, it needs aground area of 600 hectares (1hectare =10,000m^2).An HVDC link requires for its 40 hectares, less than 6% of the space required for high voltage airline [04].

1.10.4 Danger for bird

Various studies show that in the Netherlands, airlines are approximately a million victims per year, on average, about 300 birds per kilometer each year. Underground lines provide a definitive solution to this problem [04].

1.10.5 Security

As the VSC-HVDC technology based entirely on underground cable, the security is optimal. This is not the case of high voltage air links that pose a risk of electric shock or for workers at height, boat masts, fishing lines or intervention of the fire service. With VSC-HVDC technology, it also eludes the risk of damages or electric shock due to the fall lines due to snow or storm [04].

1.11 VSC HVDC Technology - BORWIN (Borkum 2) Offshore Wind Farm

The BORWIN (Borkum 2) offshore wind farm is situated 128 km off the North Sea Cost and is the largest and most remote offshore wind farm in the world. Furthermore, for the case of BORWIN it is for the first time when wind power generated at such a distance is connected to the AC grid through high voltage direct current transmission. The connection with the grid is realized through a 400 MW HVDC Light transmission system, developed by ABB.

The VSC HVDC Cable technology has a series of advantages (over the HVAC technology) for connecting the offshore wind power plants to the onshore grid, such as: their reduced weight and dimensions, resulting in a higher power density. Moreover, the HVDC Light cables operate at higher electric field stress and in comparison with the traditional HVAC cables, they have to be dimensioned only for their ohmic conductor losses. In Figure 1.2, the Borkum 2 wind farm and its grid connection through HVDC transmission is presented [01].

Fig. 1.2: The Borkum 2 wind farm cluster situated 128 km from shore

1.12 VSC-HVDC Recent Installations

Table 1.1 shows various projects worldwide where VSC-HVDC systems have been successfully exploited. For each project, the reasons of choosing VSC-HVDC are clearly summarized. VSC technology has been selected as the basis of these recent projects in favor of its controllability, compact modular design, ease of system interference and low environmental impact. VSC-HVDC transmission systems can practically transmit power underground and underwater over long distances. It offers numerous environmental benefits, including "invisible" power lines, neutral electromagnetic fields, oil-free cables and compact converter stations. Therefore, the experiences gained from the projects so far ensure that VSC-HVDC technology remains competitive and assists utilities worldwide in order to deliver economic energy to customers no matter how challenging the applications are.

Table 1.1: various projects worldwide for VSC HVDC system

	Year	P (MW)	VAC (kV)	VDC (kV)	DC link (km)	Comments and Reasons for VSC-HVDC Choice
Gotland, Sweden	1999	50	80	+ /- 80	(2×70)*	Wind power voltage support.
Eagle Pass, USA	2000	36	132	+ /- 15:9	B2B	Controlled asynchronous connection for trading. Voltage

						control.
Tjaereborg, Denmark	2000	7.2	10.5	+ /- 9	(4×4.3) *	Wind power (Demonstration project).
DirectLink, Australia	2000	180	110 (Bungalora) 132 (Mullumbimby)	+ /- 80	(6×59) *	Controlled asynchronous connection for trading.
MurrayLink, Australia	2002	220	132 (Berri) 220 (RedCliffs)	+ /- 150	(2×180) +	Controlled asynchronous connection for trading.
Cross Sound, USA	2002	330	345 (NewHeaven) 138 (Shoreham)	+ /- 150	(2×40) *	Controlled connections for power enhancement.
Troll offshore, Norway	2005	84	132 (Kollsnes) 56 (Troll)	+ /- 60	(4×70) *	Environmental merit; Compactness of converter on platform.
Estlink, Estonia-Finland	2006	350	330 (Estonia) 400 (Finland)	+ /- 150	(2 ×31) * (2×74) *	Connection of asynchronous AC systems.
Valhall offshore, Norway	2010	78	300 (Lista) 11 (V alhall)	+ /- 150	292 *	Cost reduction; Efficiency improvement; GHG emission Minimization.

***** Submarine Cable **+** Underground Cable

1.13 Conclusion

HVDC today is a very mature technology that is still developing rapidly into higher voltages and higher power and more exibility. The world faces tremendous challenges on energy supply to growing population.

If this energy should be supplied without damage to the environment; new type of generation will be required such as distant hydro, wind at sea and solar generation in the deserts. All this require transmission of huge electric energy amounts over long distances. HVDC is the most suitable technology for this task. Thus, HVDC will have a great and considerable role in the future to create a more sustainable world.

Furthermore, VSC-HVDC technology is now emerging as a robust and economical alternative for future transmission grid expansion. Thus, well-controlled VSC-HVDC applications could significantly improve overall system performance, enabling smart operation of transmission grids with improved security and efficiency.

In addition, VSC-HVDC transmission also offers a superior solution for many challenging technical issues associated with integration of large-scale RE sources such as offshore wind power.

Chapter 02: Modeling and operation VSC-HVDC links

2.1 Introduction

A VSC-HVDC link is a new direct current power transmission technology. This technology is based on voltage source converters, where the valves are made up of IGBTs. a VSC converter connected to an AC network behaves like an alternator without inertia. It exchanges active and reactive power with the AC network depending on the phase and amplitude of the AC voltage it generates. Any active power exchange of the converter with the AC network will result in an equivalent exchange of the converter with the DC network.

The synthesis of the AC voltage by the converter requires forced switching at high frequency (1 to 2 kHz), which generates more losses than the AC/DC conversion in a thyristor converter.

Control of the reactive power exchanged with the network makes it possible not only to dispense with capacitor banks but also to support the network voltage at the connection point.

In this chapter, the topology of VSC-HVDC links is discussed. The design and modeling aspects are given.

2.2 Voltage Source Converters (VSC)

The use of voltage source converters is very interesting in offshore platforms (offshore station) and this due to the fact that VSC converters produce less harmonics making it possible to reduce the number of passive filters necessary, which results in a gain the cost of installation. The three commercially available topologies are: two-level, three-level and multi-level converters.

Two-level converters are the simplest variant of VSC. They take up the fundamentals of LCC technology, i.e. thyristors, replacing them with IGBTs, to which anti-parallel diodes are added for the reversibility of the current. For the LCC converter, the smoothing coil used to smooth the current is replaced by voltage filtering capacitors. To recreate an "AC" voltage with only two voltage levels, pulse width modulation is used.

When the switch on the upper side of the converter is closed, the AC line is connected to the positive DC line, the line voltage then becomes equal to +Vdc. In the same way, when the switch on the low side of the converter is closed, the AC line is connected to the line DC negative, the line voltage then becomes -Vdc. The two switches (valves) of the same phase must never be closed simultaneously. Figure 2.1 shows a two-level HVDC converter.

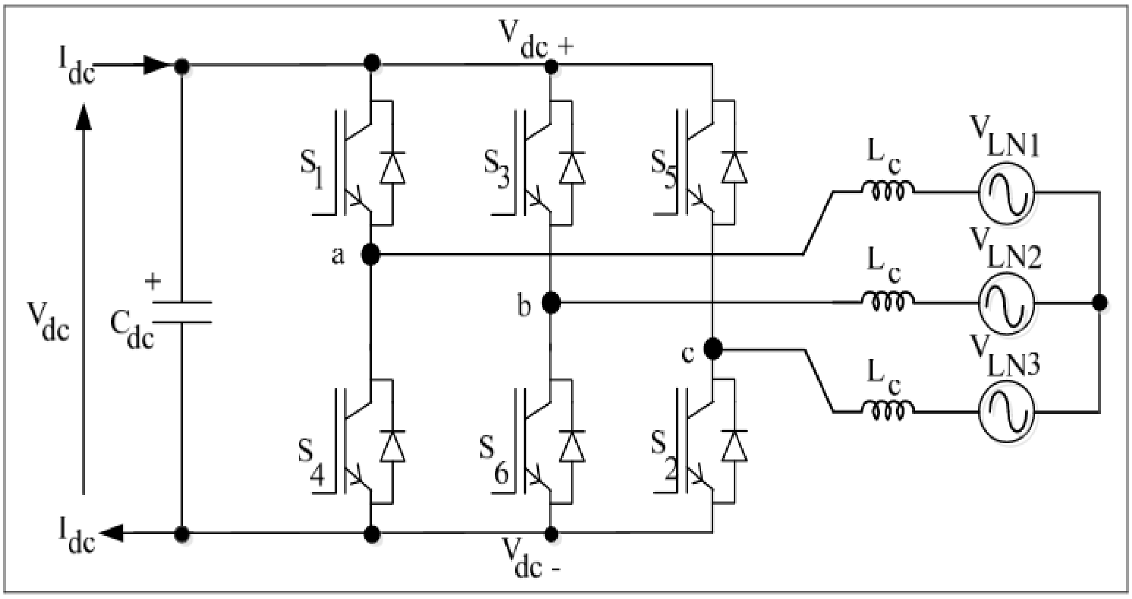


Fig 2.1: two-level HVDC converter

In order to improve the harmonic content of the voltage delivered by two-level converters, three-level systems have been built, there are levels +½ Vdc, 0, - ½ Vdc. Figure 2.2 shows a three-level HVDC converter based on a configuration using three-level clamping diodes.

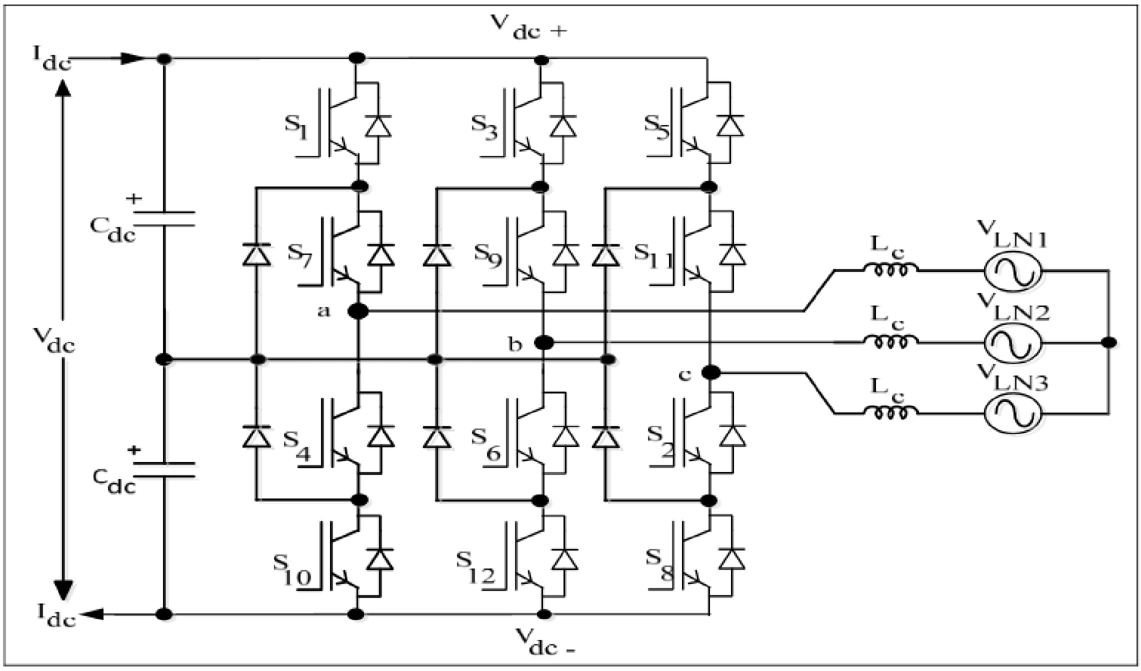


Fig.2.2: a three-level HVDC converter

The three-phase Multilevel Modular Converter (MMC) is made up of three arms, themselves made up of elementary sub-modules made up of a switching cell and a capacitor each connecting an AC AC line to a different DC DC line. In the case of the assembly used by Siemens, each sub-module contains 2 IGBTs in series connected on either side of the center of the capacitor. Each sub-module is therefore a voltage source equal to 0 or Usm (with U_{sm} the voltage across the capacitor). When a large number of sub-modules are connected in series, the switches can replicate the desired step voltage shape, in the case of high voltage direct current (HVDC) electrical power transmission applications, a sinusoid with a low Harmonic content is presented in several research works. Figure 2.3 shows a structural diagram of the MMC converter.

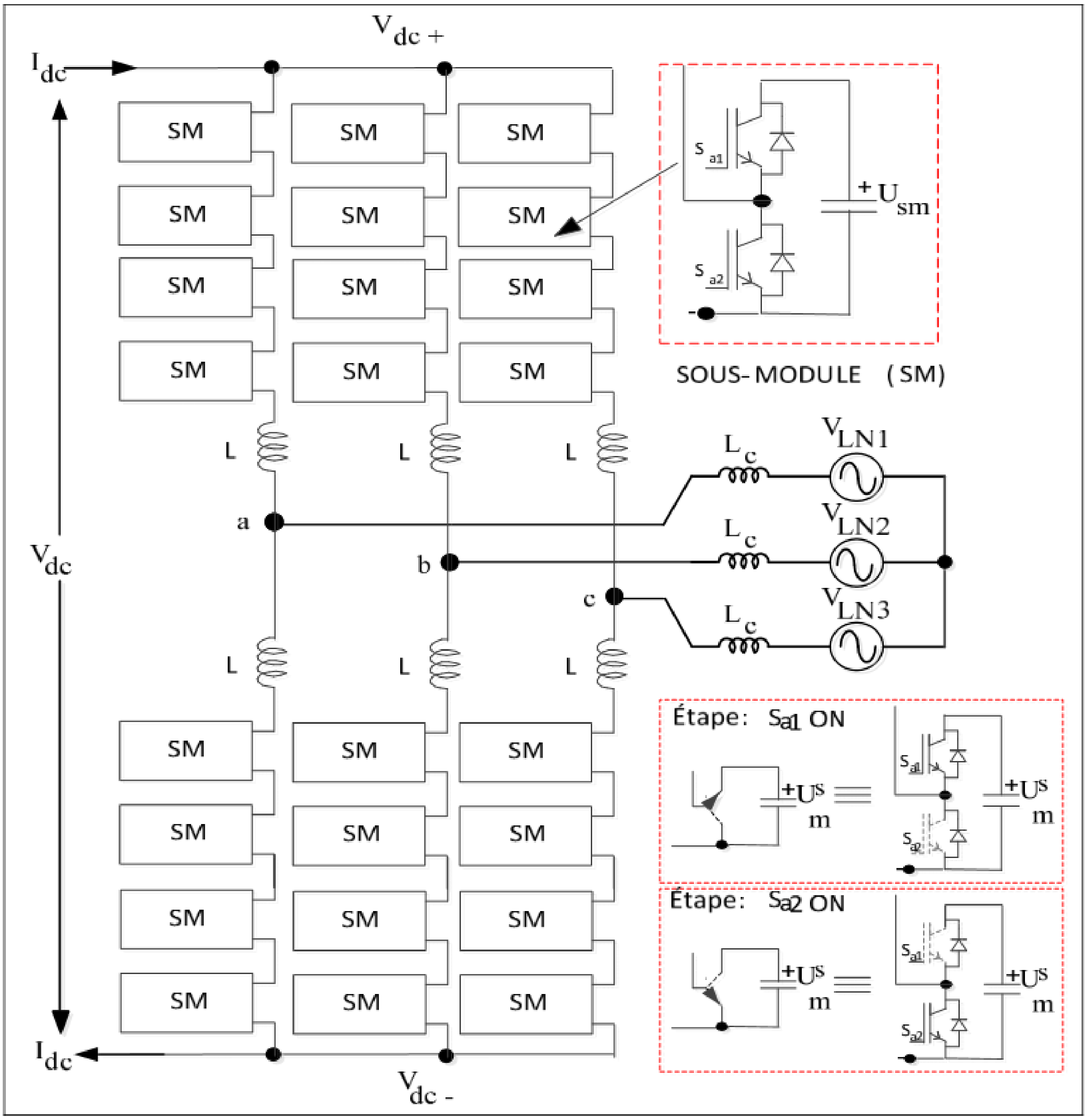


Fig.2.3: The three-phase Multilevel Modular Converter

2.3 Components of a VSC-HVDC link

The main function of a VSC-HVDC link is to transmit constant power from the station operating in rectifier mode to the inverter station. As shown in Figure 2.4, it consists of capacitors, two converters, filters, reactors, transformers and a DC cable.

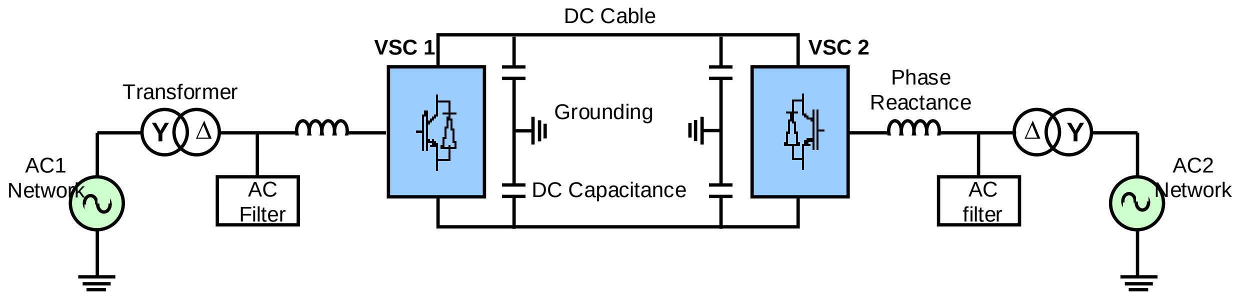


Fig. 2.4 : Components of a VSC-HVDC link

2.3.1 Converters

The converters are VSCs employing IGBT power semiconductors. The two converters are identical, one of them works as a rectifier and the other necessarily as an inverter. The two converters can be connected directly (back-to-back station), or through a DC cable. It depends on the application nature of the link.

2.3.2 Transformers

Obviously, converters are connected to AC systems through transformers. The most important function of transformers is to transform the AC voltage to adequate values for the correct operation of the converter. A transformer allows additional functions such as voltage adaptation, combination of conversion units or isolation from the zero-sequence component. The leakage inductance of transformers used in this mode of transport is generally between 0.1pu and 0.2pu.

2.3.3- Phase reactance

The phase reactance can be either an inductance or the leakage inductance of the interface transformer or a combination of both. This inductance is necessary to be able to connect the conversion unit and the AC network which are two voltage sources. It thus transforms a voltage difference between the network and the converter into current circulating between the latter. Phase reactors are used to control both active and reactive power. They also function as AC filters to reduce high order harmonics caused by the operation of VSC converters. Generally, the reactance value is 0.15 pu.

2.3.4 Continuous capacity

The function of the DC capacitor is to maintain a stable DC voltage during switching of the switches of the conversion unit. Its value must be sufficient to limit the ripple of the DC voltage but it is to the detriment of the cost, the response time of the system and the size which increase in proportion. The sizing of this capacitor depends on the DC voltage required.

Any parasitic inductance between this capacitor and the switches is harmful, particularly because of the over voltages appearing when breaking an inductive current. This capacitor must therefore be placed as close as possible to the switches, even if it is not represented in this way on the diagrams.

2.3.5 Filters

Depending on the AC network, filters may be required to prevent any harmonics from entering the converter station. These filters are often omitted, especially since no reagent compensation is needed. On the other hand, the high switching frequency in the conversion unit makes the harmonics it generates more harmful for the equipment but also easier to filter. Also, these filters make it possible to confine the HF harmonics inside the converter station.

Filters can be installed on the DC bus to limit the DC voltage ripple without increasing the value of the DC capacitance, in cases where the latter is limited by other constraints.

2.3.6 DC inductance

An inductor can be added in series in the DC circuit to attenuate the harmonics without increasing the DC capacitance. Another function of this inductance is to modify the resonance frequency of the DC circuit, in the event that this is too close to a frequency generated by the converter. It should be noted that a series inductance modifies the dynamics of the system by opposing the sudden variations of the direct current, therefore of the active power transmitted.

2.3.7 Neutral point grounding

The neutral point, midpoint of the DC capacitor, is grounded so as to impose two symmetrical voltages with respect to zero potential on the positive and negative poles, for optimum use of the cables connecting the two converter stations. This can be done by direct grounding or via passive elements (inductor, filter, resistor).

2.3.8 Main circuit breaker

A circuit breaker located at the connection point is used to (dis)connect the converter station and the AC network. It can be fitted with pre-insertion resistors to limit the inrush current peak when charging DC capacitors via the freewheel diodes.

2.3.9 Fast continuous circuit breaker

Voltage source converters fear short circuits on their DC side because the fault is fed by the diodes and can only be cleared by opening the main circuit breaker. In this case, the fault currents have time to reach prohibitive amplitudes for the power electronic components. These faults are extremely rare if the connection is made by cables but frequent in the case of overhead lines. An overhead line voltage source converter link may require the addition of a fast circuit breaker in series to protect it from DC faults. Given the opening time required (of the order of a millisecond), a static switch must be used, which poses problems of cost and joule losses in this additional component.

2.3.10 DC cables

Because of its sensitivity to continuous faults, this type of connection is mainly made by underground or submarine cables. In addition, since the polarity of the DC voltage never reverses, synthetic insulated cables are used which are more economical than traditional cables. The cable used in VSC-HVDC links is a newly developed type, where the insulation is made of an extruded polymer which is particularly resistant to DC voltage. This type of cables is the preferred choice for VSC-HVDC links, mainly because of their mechanical strength, flexibility and low weight.

2.4 Operating principle of a VSC-HVDC link between two active networks

As already mentioned, stand-alone converters using IGBTs and PWM switching effectively operate as static AC generators. They can supply or absorb reactive power and their voltage is controllable. Moreover, the active power can flow in both directions, from the AC side to the DC side of the converter and vice versa. Finally, the frequency and phase of these static generators are adjustable. As described by the following equation:

$$U_{CA} = \frac{1}{2} U_{dc} \cdot m \cdot \sin(\omega t + \delta) + harmonicsterms \tag{2.1}$$

With :

m is the modulation index
ω The pulse
δ The phase shift

The two variables m and δ can be independently set by the control system to give any combination of amplitude and phase shift from the fundamental frequency of the connected AC system. As a result, the voltage drop across the reactance terminals can be varied in order to control both active and reactive power.

2.4.1 - Composition of a conversion unit

Figure 2.5 shows the main elements of a conversion unit. This unit includes:

- A VSC with six IGBTs and six diodes;
- Capacitors C_1 connected in series;
- Three L_1 inductances
- Three resonant circuits L_2, C_2, R_2.

It is important to note that this static generator can not only convert DC power into three-phase AC power but it can also do the reverse transformation. Depending on its application, the "machine" therefore acts as a direct current generator from a three-phase network. Alternatively, it acts as an AC generator from a DC voltage source.

The x and y terminals of the converter are connected to a DC voltage source U_{dc}. The capacitors C_1 between the DC lines and the neutral N decrease the DC voltage fluctuations. At the same time, they carry the alternating currents associated with the reactive power absorbed or delivered by the three-phase side of the converter.

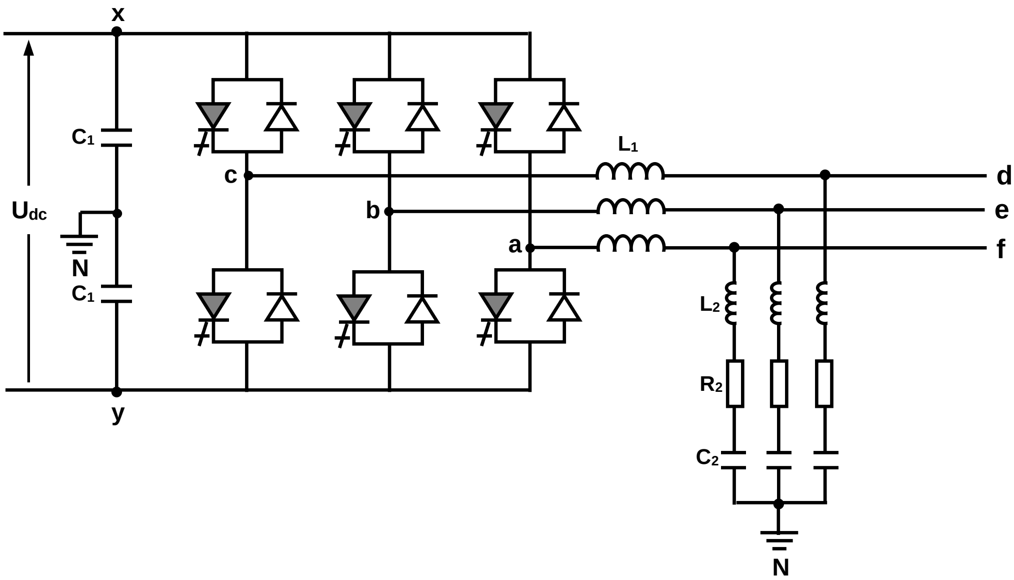


Fig. 2.5 : Composition of a conversion unit powered by a direct current source

We can consider that the voltage U_{dc} is several kilovolts, each IGBT/diode group represents in fact tens of similar semiconductors connected in series. The three-phase voltages appear between terminals d, e and f.

The voltages appearing between terminals a and N is a PWM wave whose amplitude fluctuates rapidly between + U_{dc} and – U_{dc} at the switching frequency f_C. The wave contains two components: (1) the fundamental line-to-neutral voltage U_{aN} of frequency f and (2) harmonics. In practice, we are only interested in line-to-line voltages. When the switching frequency f_C is odd and a multiple of 3, the main harmonics of the line-to-line voltages have the frequencies $f_{H1} = f_C + 2f$ and $f_{H2} = f_C - 2f$.

The inductors L_1 absorb and output energy, which makes it possible to transform the DC power into AC power and vice versa. These chokes are also used to reduce the harmonic currents circulating in the three-phase lines. At the fundamental frequency, they have a reactance X given by $X = 2\pi fL_1$.

Filters L_2, C_2 short the harmonic voltages between lines d, e, f and neutral N. resistor R_2 establishes the bandwidth of the filter, as well as the level of distortion of the voltage between terminals d, e and f.

2.4.2 - Overview of the transport system between two active networks

The basic configuration of a point-to-point HVDC VSC link consists of two VSC converter units and a DC cable as shown in Figure 2.6. Each end of the link can be connected to an AC system.

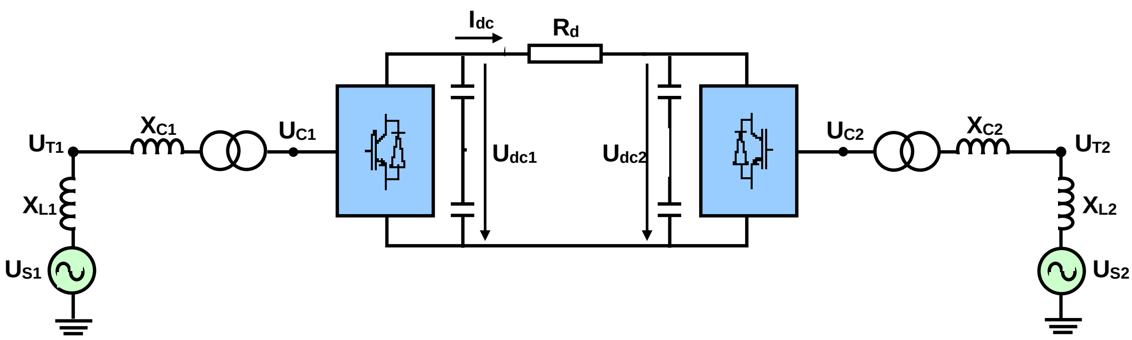


Fig. 2.6: Basic configuration of a point-to-point HVDC VSC link

To simplify our study, the transformers are represented as ideal transformers in series with their leakage reactance (X_C).

U_C is the output voltage of the converter (primary side of the transformer) and U_T is the terminal voltage of the converter (after the reactance of the transformer). The AC system is represented by an ideal U_S source in series with an X_L reactance. The three voltages (U_S, U_C, U_T) shown in Figure 3.3 are phase-to-phase voltages. On the DC side, U_{dc} is the DC voltage of the converter.

The formulas for AC voltage and current at both ends of the link are shown by the vector diagrams in Figures 2.7 and 2.8. In these diagrams is the phase angle between the power source voltage (U_S) and the converter output voltage (U_C). δ' is the phase angle between the power source voltage (U_S) and the terminal voltage of the converter (U_T).

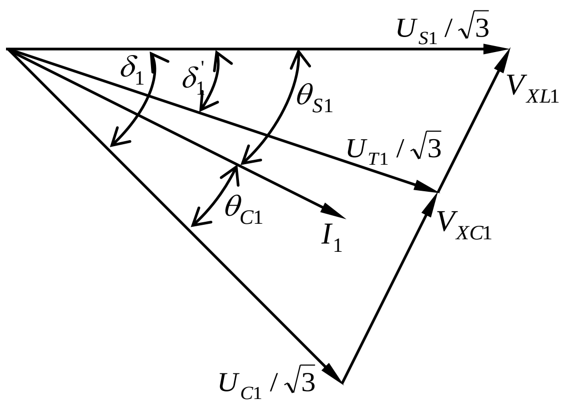


Fig. 2.7: Rectifier Side Vector Diagram

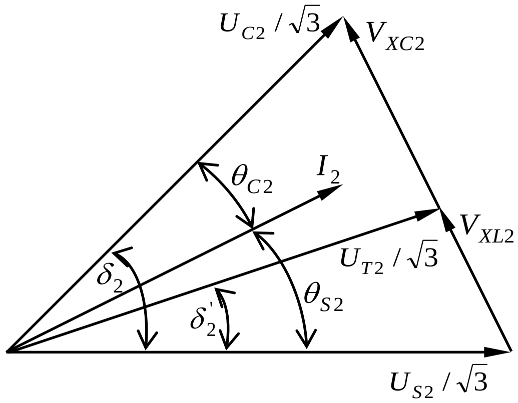


Fig. 2.8: Inverter side vector diagram

The following expressions determine the active and reactive powers at the two ends of the VSC-HVDC link (at the fundamental frequency):

$$P_1 = \frac{U_{S1}\cdot U_{C1}}{X_{L1}+X_{C1}}\sin(\delta_1) = \frac{U_{S1}\cdot U_{T1}}{X_{L1}}\sin(\delta_1') = \frac{U_{T1}\cdot U_{C1}}{X_{C1}}\sin(\delta_1-\delta_1') \tag{2.2}$$

$$P_2 = \frac{U_{S2}\cdot U_{C2}}{X_{L2}+X_{C2}}\sin(\delta_2) = \frac{U_{S2}\cdot U_{T2}}{X_{L2}}\sin(\delta_2') = \frac{U_{T2}\cdot U_{C2}}{X_{C2}}\sin(\delta_2-\delta_2') \tag{2.3}$$

$$Q_{SC1} = \frac{U_{S1}\cdot(U_{S1}-U_{C1}\cos(\delta_1))}{X_{L1}+X_{C1}} \tag{2.4}$$

$$Q_{SC2} = \frac{U_{S2}\cdot(U_{S2}-U_{C2}\cos(\delta_2))}{X_{L2}+X_{C2}} \tag{2.5}$$

The reactive powers between the voltage sources and their respective transformers are expressed by:

$$Q_{ST1} = \frac{U_{S1}\cdot(U_{S1}-U_{T1}\cos(\delta_1'))}{X_{L1}} \tag{2.6}$$

$$Q_{ST2} = \frac{U_{S2}\cdot(U_{S2}-U_{T2}\cos(\delta_2'))}{X_{L2}} \tag{2.7}$$

Ideally, the active power transfer should take place with minimal loss. This condition is ensured by the PWM control technique. Through the latter, control of the reactive power injected at each end of the link is carried out independently.

2.4. 3 Current and phase shift on the AC side

The following relationships apply to the diagram in Figure 2.4:

$$\left(U_{S1}/\sqrt{3}\right)-\left(U_{C1}/\sqrt{3}\right)\cos(\delta_1)=I_1\left(X_{L1}+X_{C1}\right)\sin\left(\theta_{S1}\right) \tag{2.8a}$$

$$I_1\left(X_{L1}+X_{C1}\right)\cos\left(\theta_{S1}\right)=\left(U_{C1}/\sqrt{3}\right)\sin(\delta_1) \tag{2.8b}$$

$$\left(U_{S1}/\sqrt{3}\right)\sin(\delta_1)=I_1\left(X_{L1}+X_{C1}\right)\cos\left(\theta_{S1}\right) \tag{2.8c}$$

Eliminating (θ_{S1}) between equations (2.8a) and (2.8b) gives:

$$\begin{aligned} I_1 &= \frac{\sqrt{U_{S1}^2+U_{C1}^2-2U_{S1}U_{C1}\cos(\delta_1)}}{\sqrt{3}\left(X_{L1}+X_{C1}\right)} \\ &= \frac{\sqrt{U_{S1}^2+U_{T1}^2-2U_{S1}U_{T1}\cos(\delta_1')}}{\sqrt{3}X_{L1}} \end{aligned} \tag{2.9}$$

By combining equations (2.8c) and (2.9),

$$\theta_{C1}=\cos^{-1}\left[\frac{U_{S1}}{\sqrt{U_{S1}^2+U_{C1}^2-2U_{S1}U_{C1}\cos(\delta_1)}}\sin(\delta_1)\right]$$

For $U_{C1}>U_{S1}\cos(\delta_1)$

Where

$$\theta_{C1}=-\cos^{-1}\left[\frac{U_{S1}}{\sqrt{U_{S1}^2+U_{C1}^2-2U_{S1}U_{C1}\cos(\delta_1)}}\sin(\delta_1)\right] \tag{2.10}$$

For $U_{C1}<U_{S1}\cos(\delta_1)$

And

$\theta_{S1}=\delta_1-\theta_{C1}$

The same reasoning for Figure 2.5,

$$I_2=\frac{\sqrt{U_{S2}^2+U_{C2}^2-2U_{S2}U_{C2}\cos(\delta_2)}}{\sqrt{3}\left(X_{L2}+X_{C2}\right)}=\frac{\sqrt{U_{S2}^2+U_{T2}^2-2U_{S2}U_{T2}\cos(\delta_2')}}{\sqrt{3}X_{L2}} \tag{2.11}$$

Where

$$\theta_{C2} = \cos^{-1}\left[\frac{U_{C2}}{\sqrt{U_{S2}^2 + U_{C2}^2 - 2U_{S2}U_{C2}\cos(\delta_2)}}\sin(\delta_2)\right] \quad \text{For} \quad U_{S2} > U_{C2}\cos(\delta_2)$$

Where

$$\theta_{C2} = -\cos^{-1}\left[\frac{U_{C2}}{\sqrt{U_{S2}^2 + U_{C2}^2 - 2U_{S2}U_{C2}\cos(\delta_2)}}\sin(\delta_2)\right] \tag{2.12}$$

For $U_{S2} \leq U_{C2}\cos(\delta_2)$

And

$$\theta_{C2} = \delta_2 - \theta_{S2}$$

The real and imaginary components of AC current (using their source voltages as a reference) are given by:

$$\begin{aligned} I_{\mathrm{Re}1} &= I_1\cos(\theta_{S1}) \qquad I_{\mathrm{Im}1} = I_1\sin(\theta_{S1}) \\ I_{\mathrm{Re}2} &= I_2\cos(\theta_{S2}) \qquad I_{\mathrm{Im}2} = I_2\sin(\theta_{S2}) \end{aligned} \tag{2.13}$$

2.4.4 AC current minimization

The AC current of the receiving network (inverter side) reaches its minimum value (for a given power P_2) when:

$$\frac{U_{C2}}{U_{S2}} = \sqrt{1 + \frac{P_2^2(X_{L2} + X_{C2})^2}{U_{S2}^4}} \tag{2.14}$$

Using the converter terminal voltage (U_T) as a reference, equation (2.14) becomes:

$$\frac{U_{T2}}{U_{S2}} = \sqrt{1 + \frac{P_2^2 X_{L2}^2}{U_{S2}^4}} \tag{2.15}$$

The term $P_2^2(X_{L2} + X_{C2})^2 / U_{S2}^4$ in equation (2.14) and the term $P_2^2 X_{L2}^2 / U_{S2}^4$ in equation (2.15) can be expressed as a function of the **SCR** (short circuit ratio), this gives:

$$\begin{aligned} \frac{P_2^2(X_{L2} + X_{C2})^2}{U_{S2}^4} &= \left[\frac{P_2}{P_{2rated}}\right]^2 \left[\frac{U_{S2rated}}{U_{S2}}\right]^4 \left[\frac{X_{L2} + X_{C2}}{X_{2rated}}\right]^2 \\ &= \left[\frac{P_2}{P_{2rated}}\right]^2 \left[\frac{U_{S2rated}}{U_{S2}}\right]^4 \left[\frac{1}{SCR_2}\right]^2 \end{aligned} \tag{2.16}$$

$$\frac{P_2^2 X_{L2}^2}{U_{S2}^4} = \left[\frac{P_2}{P_{2rated}}\right]^2 \left[\frac{U_{S2rated}}{U_{S2}}\right]^4 \left[\frac{X_{L2}}{X_{2rated}}\right]^2 = \left[\frac{P_2}{P_{2rated}}\right]^2 \left[\frac{U_{S2rated}}{U_{S2}}\right]^4 \left[\frac{1}{SCR_2'}\right]^2 \qquad (2.17)$$

Where U_{2rated} and P_{2rated} are respectively the values of base voltage and base power in pu (per unit).

To achieve the minimum AC alternating current, the two equations (2.14) and (2.15) indicate that the ratios (U_{C2}/U_{S2}) and (U_{T2}/U_{S2}) will have to increase the active power when the demand increases.

In addition, their maximum increase is strongly related to the impedance of the AC system, i.e. a strong AC system requires a small increase while a relatively weak AC system requires a large increase. Also, it should be noted that a slight variation in the AC mains voltage (U_{S2}) can cause a significant change in the ratio due to the fourth exponent.

For example, if the SCR of the receiving network (inverter side) is 2.5, and we want to transfer a nominal active power with a source voltage U_{S2} equal to 0.96 U_{2rated}, the necessary ratio is U_{C2}/U_{S2} = 1.091, and the converter output voltage should be adjusted for U_{C2} = 1.047 U_{2rated}.

A similar process, will allow the minimization of the AC current at the other end of the VSC-HVDC link (i.e. the rectifier side), still based on the PWM technique, where the injection of the reactive power necessary for a ratio U_{C1} Optimal /U_{S1} can be set independently of that on the inverter side.

2.5 Operating principle of a VSC-HVDC link connected to a passive network (isolated site)

We have seen that the transport of direct current energy is usually done between two strong networks both powered by high-capacity synchronous generators. The alternating voltages are stable, and the converters at both ends of the line continue whatever they are connected to. This allows the natural switching of the thyristors.

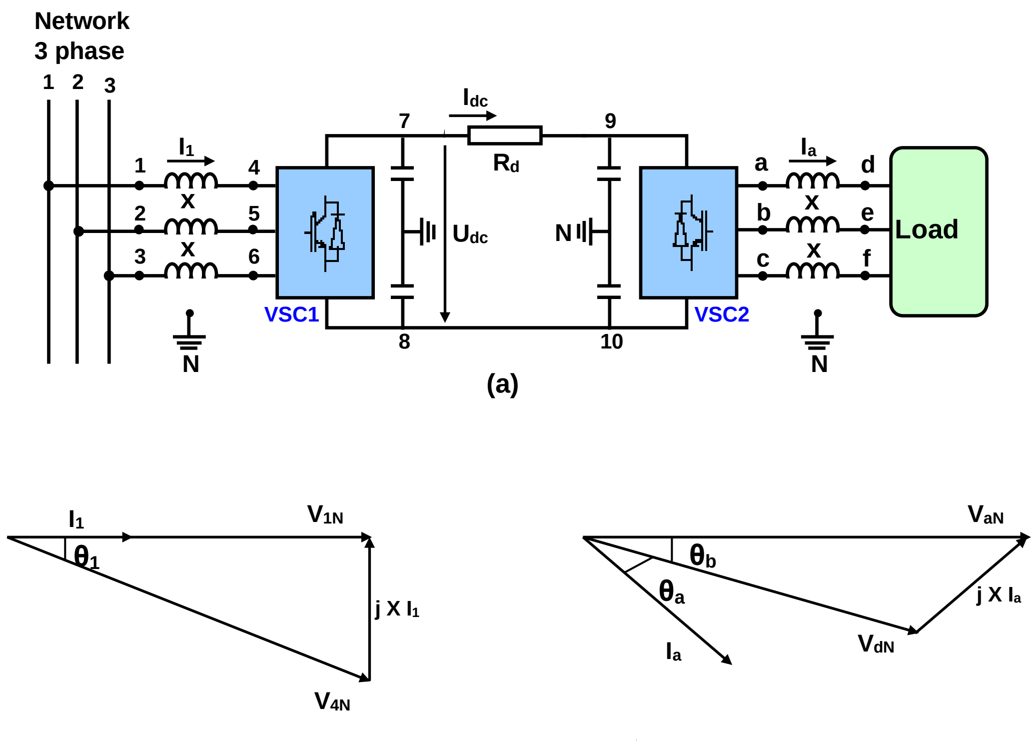
There are, however, a large number of isolated sites that need electricity but do not have synchronous generators. In this case, the energy can be supplied using an AC overhead line connected to an existing power supply network. When this solution is not possible, a generator can be installed to generate electricity on site. This solution is expensive because it requires maintenance and transportation of fuel to the site.

In some cases, an airline is excluded because rights of way cannot be obtained. It is then proposed to bury an underground AC cable. However, when the AC cable reaches a length of a few kilometers its capacitance prevents the efficient transmission of AC power. On the other hand, cables lend themselves well to direct current transmission because the reactive power constraints disappear.

A VSC can perfectly supply an AC network devoid of other voltage sources. In this case, it cannot regulate the active and reactive powers exchanged with this network due to the absence of a reference voltage source. It generates a reference voltage of nominal amplitude and frequency and the active and reactive powers will naturally be imposed by the loads present in the network.

2.5.1 Overview of the transport system

Figure 2.9 gives an overview of a VSC-HVDC link feeding a passive network. It includes a three-phase network, a DC cable that connects VSC1 to VSC2 at the remote site, and the load.



$$p_1 = \frac{V_{1N} \cdot V_{4N} \cdot \sin \theta_1}{X}$$

$$p_a = \frac{V_{aN} \cdot V_{dN} \cdot \sin \theta_b}{X} = V_{dN} \cdot I_a \cdot \cos \theta_a$$

(b) (c)

Fig. 2.9: (a)- Overview of a VSC-HVDC link feeding a passive network.
(b)- Network side vector diagram. (c)- Vector diagram at the site.

The VSC1 is connected to the three-phase network through three reactors (X) which correspond to the inductances L_1 mentioned above. Terminals 7 and 8 are connected to the DC cable. The other end of the cable is connected to terminals 9 and 10 of the VSC2. This supplies the load via three reactors x which are of the same type as those associated with VSC1. In order to simplify the circuit, the harmonic filters L_2, C_2, R_2 are not shown. They are connected between terminals 1, 2, 3 and neutral and between terminals d, e, f and neutral.

The VSC2 generates a three-phase fundamental voltage between terminals a, b and c. however, it is easier to follow its operation by observing the current and voltage of a single phase.

Let us therefore choose phase A, and suppose that the current I_a is θ_a degrees behind the voltage V_{dN}. As the voltage drop in the reactance X is jxI_a, the voltage generated by the converter is given by the vector $V_{aN} = V_{dN} + j\,x\,I_a$ (figure 2.6c). We note that V_{aN} is ahead of V_{dN} by θb degrees. The active power P therefore flows from the converter to the load and its value is given by the well-known expression:

$$P = \frac{V_{aN} \cdot V_{dN}}{X} \sin \theta_b \tag{2.18}$$

The active power, per phase, is also given by the expression:

$$P = V_{dN} \cdot I_a \cdot \cos \theta_a \tag{2.19}$$

The direct current cable carries only the active component of the power absorbed by the load. The total power transported is therefore (3 X P) as the DC voltage is U_{dc}, the DC current I_{dc} circulating in the cable is:

$$I_{dc} = 3 \cdot P / U_{dc} \tag{2.20}$$

What is the relationship between the AC line-to-line voltage U_{ab} and the DC voltage U_{dc}? To ensure a sinusoidal waveform, the peak value of the line-to-neutral voltage V_{aN} must never exceed $U_{dc}/2$. Suppose V_{aN} crest = 80% of $U_{dc}/2$. Under these circumstances, it can easily be demonstrated that the U_{dc} voltage is about twice the line-to-line rms voltage of the converter. We can therefore write:

$$U_{dc} = 2 \cdot U_{LL} \tag{2.21}$$

Where
U_{dc} = line-to-line DC voltage [kV]
U_{LL} = line-to-line AC rms voltage [kV]

For the moment let us neglect the losses in the converters and in the DC cable. In steady state, the active power 3P drawn from the network by the VSC1 is necessarily equal to that drawn by the load at the isolated site. Let's choose phase 1 of the network, and suppose that V_{1N} is ahead of V_{4N} by θ1 degrees. The power P is then given by the following expression:

$$P = \frac{V_{1N} \cdot V_{4N}}{X} \sin \theta_1 \tag{2.22}$$

The value and the phase of voltage V_{1N} are imposed by the network. Also, the value of X is fixed because the fundamental frequency is constant. In order to obtain the value P imposed by the load, the voltage V_{4N} and the angle θ_1 must be adjusted to appropriate values. What values should be chosen?

An interesting operation consists in adjusting the amplitude and the phase of V_{4N} so that the current I_1 is in phase with the voltage V_{1N} (figure 2.6b). Under these circumstances, the converter does not draw any reactive power from the network. This ability to operate the rectifier at unity power factor is another advantage of PWM converters. The VSC1 control system must therefore act so that the angle θ_1 and the voltage V_{4N} have the values required to achieve these objectives.

The total active power absorbed by the VSC1 is controlled by the DC voltage U_{dc} at the cable terminals. To facilitate the explanations, let us again neglect the losses in the converters and in the cable.

In steady state, the active power of the load is constant and the power drawn from the cable between terminals 9 and 10 is equal to the power absorbed by the cable between terminals 7 and 8 (figure 2.6a). Consequently, the voltage U_{dc} remains stable.

However, if the load supplied by the VSC2 decreases while the angle θ1 and the voltage V_{4N} remain unchanged, the power supplied to the cable becomes greater than that drawn from it. The difference between these two powers charges, which causes a very rapid increase in the voltage of the cable. This increase is detected by the VSC1 control system. The corrective signal then produces an immediate decrease in the angle θ_1. Consequently, the AC power drawn by the VSC1 decreases, which decreases the continuous power supplied to the cable. As soon as it is equal to the continuous power absorbed by the VSC2, the cable voltage returns to a value close to its nominal value.

Unlike conventional DC power transmission using thyristors, power control does not require an exchange of information between the two converters. In addition, there is no need for bulky and expensive filters because on a 50 Hz or 60 Hz network, the frequency of the main harmonics is around

40 times the fundamental frequency. A single L_2, C_2, R_2 filter is sufficient to suppress these harmonics. Recall that for conventional DC transport large filters were needed to absorb low order harmonics.

PWM converters therefore offer several advantages over thyristor converters using natural switching. When you add the advantage of a cable buried in the ground, sheltered from the weather and free of rights of way, PWM converters become even more attractive. Note however that the power of IGBTs does not yet reach that of thyristors.

2.6 Comparison between conventional HVDC and VSC-HVDC links

In this chapter, a comparison of the characteristics of the two types of energy transport in HVDC is presented, namely conventional links and VSC-HVDC links in terms of transmitted power, maximum voltage, and fields of application.

2.6.1 Types of used converters

There are basically two types of configuration possible for the three phase converters used for the process of AC to DC energy conversion or vice versa.

During the period 1950-1990, HVDC links were based almost exclusively on line-commutated current source converters (LCC) (Figure 2.10-b). These types of converters used valves based on mercury vapor mutators from the early 1950s to the mid 1970s, and thereafter, valves based on thyristors as a fundamental device.

From 1990, the self-commutated voltage source converter (VSC) (Figure 2.10-a) has become economically viable due to the availability of new self-commutated power semiconductors (such as the GTO and the IGBT), and on the other hand, the appearance of high-power DSPs for computing generate appropriate priming pulses.

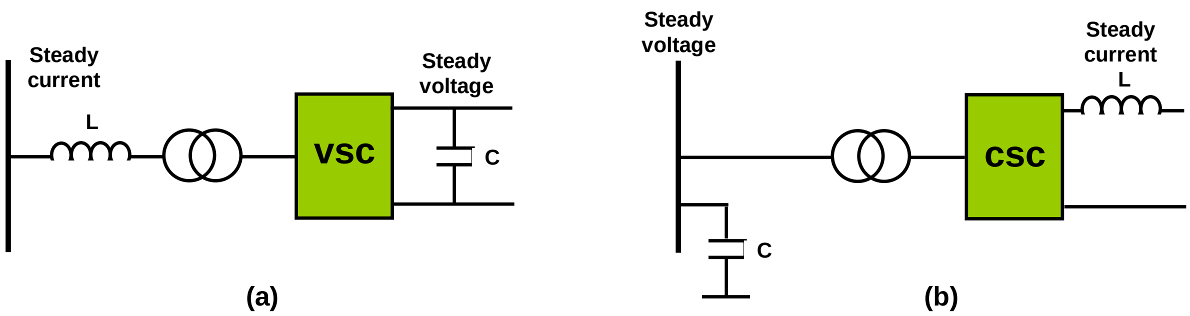


Fig. 2.10: (a)- Self Commutated Voltage Source Converter (VSC)
(b)- Line Commutated Current Source Converter (LCC).

Currently, modern HVDC systems can use either the conventional conversion technique or VSC converters. However, the criteria for choosing a type of conversion for such a project are based on economic and other technical factors. A comparison of the characteristics of the two converter types is shown in Table 2-1. However, at present VSC converters are still limited compared to conventional technology due to the practical and commercial limitations of the semiconductors used (ie GTO and IGBT).

Table 2-1: comparison between the two types of LCC and VSC converters.

	Line Commutated Current Source Converter (LCC)	**Self-commutated voltage source converter (VSC)**
AC side of the converter	• **Acts as a constant voltage source** • **Requires capacitor banks as an energy storage device** • **Requires large AC filters for harmonic elimination.** • **Need for reactive power compensation devices.**	• **Acts as a constant current source** • **Requires an inductor as an energy storage device** • **Need for small AC filters to eliminate high order harmonics.** • **No need for reactive power compensation.**
DC side of the converter	• **Acts as a constant current source** • **Requires an inductor as an energy storage device** • **Need for DC filters**	• **Acts as a constant voltage source** • **Requires capacitor banks as an energy storage device** • **Problem of the fault on the direct current line.**
Switches	• **Closing controlled semiconductors** • **Switching at mains frequency (i.e. only one switching per period)** • **Low switching losses**	• **Semi-conductors controlled in closing and opening** • **High frequency switching (i.e. several switchings per period)** • **High switching losses**
Range of power and voltage supported	• **Between 0 and 550 MW per converter** • **Up to 600kV**	• **Between 0 and 200 MW per converter** • **Up to 150kV**

2.6.2 Short-circuit power of the AC network connected

Conventional HVDC thyristor links are dependent on the AC network. The AC/DC converter requires a minimum short-circuit power (S_{cc}) from the connected AC network. These links are incapable of injecting electricity into a network that is not powered, or powered very weakly or by very distant resources. A key parameter of its operation is the short-circuit ratio (SCR) which corresponds to the short-circuit power (S_{cc}) on the nominal power (P_d) of the HVDC link:

$$SCR = \frac{S_{CC}}{P_d} \tag{2.23}$$

$$S_{CC} = \frac{U^2}{Z_S} \tag{2.24}$$

Where

S_{CC} : The short-circuit power of the network at the point of connection of the converter station to the alternating network (MVA).

P_d : The continuous power of the converter (MW).

U : The alternating voltage between phases.

Z_S : The impedance of the alternating network at the fundamental frequency.

We consider that :

• With a short-circuit ratio greater than three (SCR ≥ 3), interactions are limited and easily manageable.

• A short-circuit ratio of between two and three (3 > SCR ≥ 2), results in interdependence of the link and the AC network.

• On the other hand, a short-circuit ratio of less than two (SCR < 2) translates into strong interdependence between the connection and the AC network. Very specific provisions must then be studied and implemented.

For correct operation, this ratio must be at least 2.5 – 3.0, special solutions allowing to further reducing this threshold. Among these a very effective solution developed by ABB is the Capacitor Commutated Converter (CCC) which reduces the SCR to 1.0 or even less. The VSC-HVDC link requires no short-circuit power because the inverter does not need external generators.

2.6.3 Reactive power compensation

A major advantage of HVDC links is that they carry no reactive power. The traditional HVDC converter consumes reactive power, so it is common to add a reactive power source in the converter station, usually in the form of harmonic filters and capacitor banks - shunt, connected gradually by circuit breakers depending on the power transmitted and the needs of the AC network.

The CCC converter of the HVDC link consumes less reactive power because it includes a series capacitor. A traditional thyristor HVDC substation helps to stabilize the AC voltage by modulating its reactive power consumption by controlling the firing angle and by switching filters and shunt batteries.

A VSC converter can provide or consume reactive power over a wide range by controlling IGBT valves without switching, filters or shunt batteries. The VSC-HVDC solution therefore assumes a leading role in stabilizing the alternating voltage.

Chapter 03: Control of VSC-HVDC links

3.1 Introduction

The principle of transporting electrical energy with a VSC-HVDC link is practically the same as a conventional HVDC link: one of the converter stations controls the power transmitted; while the other station controls the DC voltage.

A DC link to VSC consists of two VSC converters, each connected to an AC network whose DC sides are connected by a cable. A VSC converter has at least two degrees of freedom which are the amplitude and the phase of the voltage generated. Any difference in amplitude or phase between the voltages of the network and the converter results in an exchange of reactive power or active power respectively with the AC network.

Indeed, stand-alone converters using IGBTs and PWM offer an interesting solution to this kind of problem. They can supply or absorb reactive power and their voltage is controllable. In addition, the active power can flow in both directions, from the AC side to the DC side of the converter and vice versa. Finally, the frequency and the phase of these static generators are adjustable, and the short-circuit capacity is electronically limited.

3.2 General philosophy of control

The common characteristic of all VSC configurations is the generation of an AC voltage (at a fundamental frequency) from a DC voltage. The control of this voltage in phase and in amplitude at the same time is the essential function of a VSC converter.

Because the stability of the power transmitted by the VSC-HVDC link is essential, the control of the DC voltage is necessary to ensure this task. Indeed, the active power delivered by one of the converter stations must be equal to the active power absorbed by the other station plus the losses in the system. Each difference causes a rapid change in DC voltage. The converter which does not regulate the DC voltage ensures the regulation of the power which it exchanges with the AC network to which it is connected. It can choose any value of the desired power while remaining within the operating limits of the system, while the DC voltage regulator ensures the maintenance of the balance of the power exchanged. This regulation can take on many aspects such as:

• Maintenance of a constant given power;

• Power modulation as a function of frequency;

• Evacuation of all the power available on the AC network (case of connection by a VSC link of a wind power plant).

The active power is controlled by the phase shift of the voltage generated by the converter at the fundamental frequency with respect to the voltage of the AC network. The direction of transfer of this power can be in either direction, either from the AC system to the converter or vice versa depending on the sign of the phase angle (δ), i.e. the VSC converter can operate either as a rectifier or as an inverter.

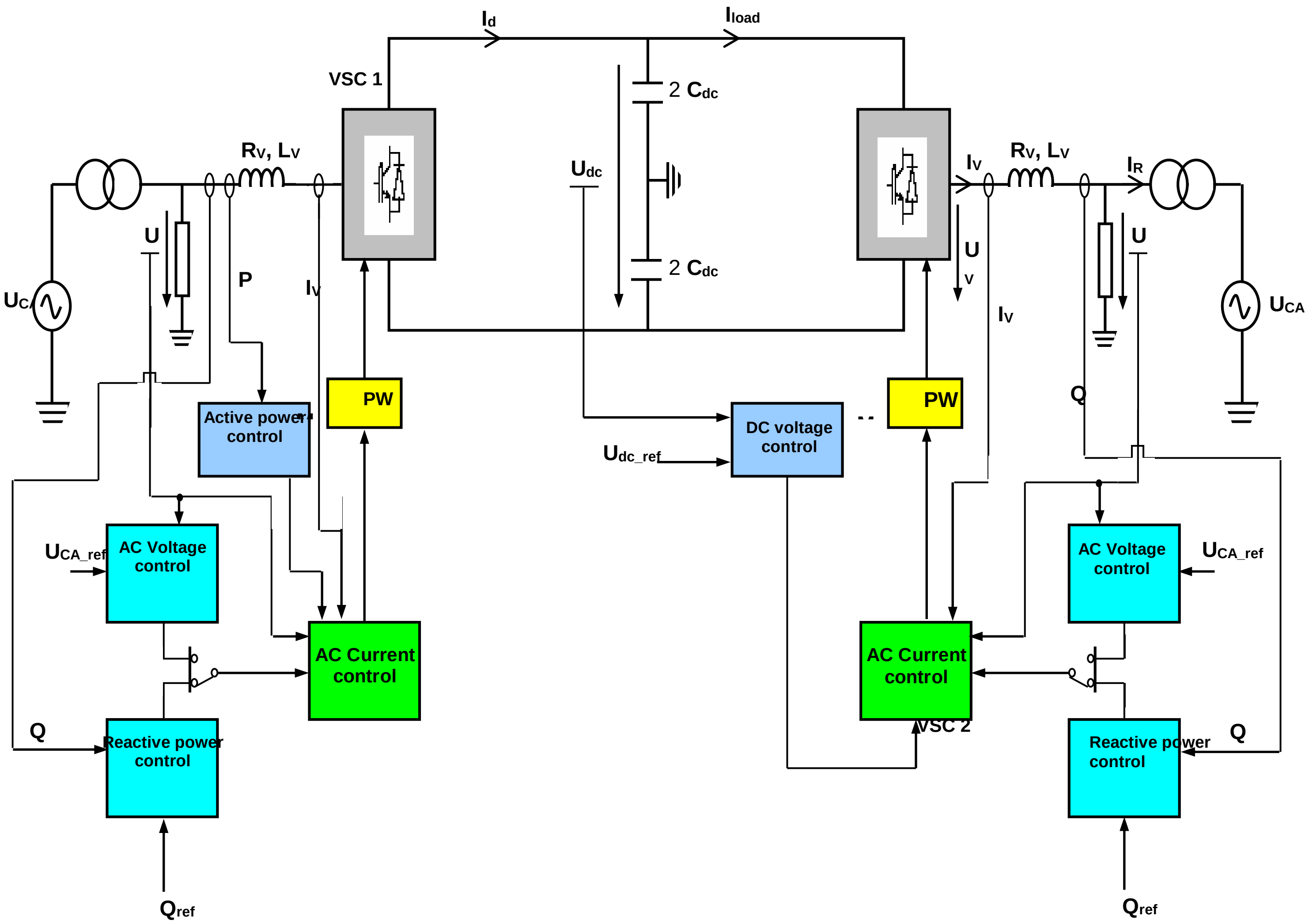
Control of the reactive power through the control of the amplitude of the AC voltage generated. This task is ensured through the modulation index (λ). When the value of this index is close to one (1) the voltage delivered by the converter is higher than the source voltage and the reactive power will be delivered by the converter to the AC network. However, when the index λ is lower (ie the voltage of the converter is lower than that of the network), the converter absorbs reactive power.

The control system of a two-ended VSC DC link is a cascade control system. It is based on an internal current adjustment loop which provides control of the alternating current. The alternating current references are provided by the external regulators. These include the regulators of the direct voltage, the alternating voltage, the active and reactive powers, and finally the frequency. Figure 3.1 shows that each end of a VSC-HVDC link can choose between AC voltage regulation and reactive power regulation. Each regulator generates a reference value for the AC regulator.

Obviously, not all regulators can be used at the same time. The choice of different types of regulators to calculate the reference values for the converter current will depend on the nature of the application, and sometimes requires advanced studies of the electrical system.

The active current reference value can be obtained by the three regulators of DC voltage, active power and frequency, while the reactive current reference value can be obtained by the two AC voltage and power regulators reactive.

Fig. 3.1 : Complete control diagram of a VSC-HVDC link



The current regulator and the various additional regulators are described in detail in this chapter.

3.3 Hierarchy of the control system

The control system of a VSC-HVDC system can be divided into three hierarchical levels, pulse control, converter control and system control (as shown in Figure 3.2)

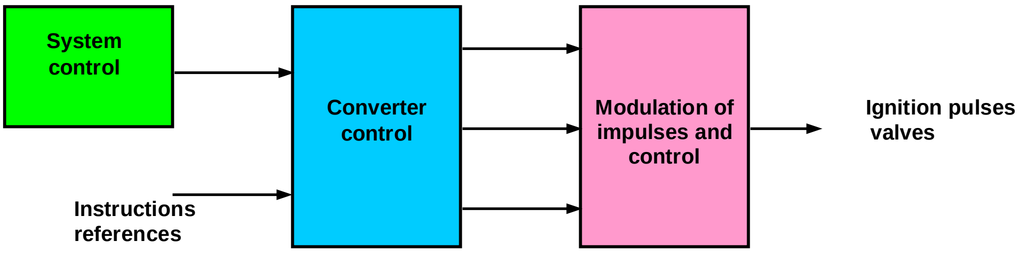


Fig. 3.2: Control system hierarchy

3.3.1 Pulse modulation and control

The type of valve pulses for the converter bridge depends essentially on the switching device and the configuration of the VSC converter. With PWM control, the sequence of pulses for the valves is strongly related to the type of PWM applied. In all cases, a compromise must be made between the level of emission of low order harmonics and the size of the filters to be used. The oscillator used in the pulse control is a phase locked loop (PLL) in case the pulses need to be synchronized with an active AC system. If the receiving system is isolated, the pulses are independently latched. The input to the PLL is the three-phase voltage measured at the point where the filter is connected. The output of the PLL is a phase shift, which should be equal to the phase shift of the steady-state bus filter vector voltage.

3.3.2 Converter control

If the VSC converter is controlled by the PWM, controlling the converter changes both the phase angle as well as the magnitude of the AC voltage generated by the converter. The VSC can also participate in controlling the frequency of the connected AC system, while adjusting the frequency of the oscillator in the pulse control (if it is supplying an isolated system), or modulating the power (in case of an active AC system).

3.3.3 System Control

System control can perform a variety of important functions, including controlling active and reactive power, controlling the amplitude and phase shift of the AC voltage generated by the converter, improving the transient stability of the system, and frequency control, etc.

3.4 Control of the alternating current

AC current control is often a desirable feature so that the converter valves are not overloaded. This control can be achieved directly or through vector control, where current control is an intermediate step in controlling other parameters such as active and reactive power.

The internal AC current adjustment loop is implemented in the dq frame, based on the model equations. To get a detailed overview of the control system, the control relies on the equations of the model shown in Figure 3.1 as follows:

The voltages delivered by the secondary of the transformer, and the currents which circulate in the converter are broken down into two balanced systems, of positive sequence (with index p) and negative (index n).

For the voltages :

$$\begin{aligned} u_{La} &= u_{Lap} + u_{Lan} \\ u_{Lb} &= u_{Lbp} + u_{Lbn} \\ u_{Lc} &= u_{Lcp} + u_{Lcn} \end{aligned} \tag{3.1}$$

And for currents:

$$\begin{aligned} i_{va} &= i_{vap} + i_{van} \\ i_{vb} &= i_{vbp} + i_{vbn} \\ i_{vc} &= i_{vcp} + i_{vcn} \end{aligned} \tag{3.2}$$

When the system is operating in a steady state (balanced system), $u_{Lan}, u_{Lbn}, u_{Lcn}, i_{van}, i_{vbn}, i_{vcn}$ are zero.

For each phase:

$$u_v - u_L = L_v \frac{di_v}{dt} + R_v i_v \tag{3.3}$$

During the fault regime (i.e. the unbalanced system), the equation of the voltage drop across the reactance terminals can be written as a function of the positive and negative sequences of the voltages and currents.

The positive sequence voltages across the reactance $R_v + j\omega L_v$ are described by the following differential equation:

$$\begin{aligned}\frac{d}{dt}\begin{bmatrix} i_{vap} \\ i_{vbp} \\ i_{vcp} \end{bmatrix} &= \begin{bmatrix} -\frac{R_v}{L_v} & 0 & 0 \\ 0 & -\frac{R_v}{L_v} & 0 \\ 0 & 0 & -\frac{R_v}{L_v} \end{bmatrix}\begin{bmatrix} i_{vap} \\ i_{vbp} \\ i_{vcp} \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{L_v} & 0 & 0 \\ 0 & \frac{1}{L_v} & 0 \\ 0 & 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{vap} \\ u_{vbp} \\ u_{vcp} \end{bmatrix} - \begin{bmatrix} \frac{1}{L_v} & 0 & 0 \\ 0 & \frac{1}{L_v} & 0 \\ 0 & 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{Lap} \\ u_{Lbp} \\ u_{Lcp} \end{bmatrix}\end{aligned} \tag{3.4}$$

And the negative sequence voltages:

$$\begin{aligned}\frac{d}{dt}\begin{bmatrix} i_{van} \\ i_{vbn} \\ i_{vcn} \end{bmatrix} &= \begin{bmatrix} -\frac{R_v}{L_v} & 0 & 0 \\ 0 & -\frac{R_v}{L_v} & 0 \\ 0 & 0 & -\frac{R_v}{L_v} \end{bmatrix}\begin{bmatrix} i_{van} \\ i_{vbn} \\ i_{vcn} \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{L_v} & 0 & 0 \\ 0 & \frac{1}{L_v} & 0 \\ 0 & 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{van} \\ u_{vbn} \\ u_{vcn} \end{bmatrix} - \begin{bmatrix} \frac{1}{L_v} & 0 & 0 \\ 0 & \frac{1}{L_v} & 0 \\ 0 & 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{Lan} \\ u_{Lbn} \\ u_{Lcn} \end{bmatrix}\end{aligned} \tag{3.5}$$

Equations (3.4) and (3.5) can be transformed to the αβ frame. This gives the positive sequence voltages and currents as follows:

$$\frac{d}{dt}\begin{bmatrix} i_{v\alpha p} \\ i_{v\beta p} \end{bmatrix} = \begin{bmatrix} -\frac{R_v}{L_v} & 0 \\ 0 & -\frac{R_v}{L_v} \end{bmatrix}\begin{bmatrix} i_{v\alpha p} \\ i_{v\beta p} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{v\alpha p} \\ u_{v\beta p} \end{bmatrix} - \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{L\alpha p} \\ u_{L\beta p} \end{bmatrix} \tag{3.6}$$

And for the negative sequence:

$$\frac{d}{dt}\begin{bmatrix} i_{v\alpha n} \\ i_{v\beta n} \end{bmatrix} = \begin{bmatrix} -\frac{R_v}{L_v} & 0 \\ 0 & -\frac{R_v}{L_v} \end{bmatrix}\begin{bmatrix} i_{v\alpha n} \\ i_{v\beta n} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{v\alpha n} \\ u_{v\beta n} \end{bmatrix} - \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix}\begin{bmatrix} u_{L\alpha n} \\ u_{L\beta n} \end{bmatrix} \tag{3.7}$$

Where the transformation from a three-phase system to a two-phase system in the frame αβ is given by equation (3.8), assuming $x_a + x_b + x_c = 0$:

$$\bar{x}_{\alpha\beta} = x_\alpha + jx_\beta = k\left[x_a + x_b e^{j\frac{2\pi}{3}} + x_c e^{j\frac{4\pi}{3}} \right] \tag{3.8}$$

Where k is equal to $\sqrt{\frac{2}{3}}$

Equation (3.8) can be written as follows:

$$\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} & -\sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{6}} \\ 0 & \sqrt{\frac{1}{2}} & -\sqrt{\frac{1}{2}} \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{3.9}$$

The inverse transformation is given by:

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & -\sqrt{\frac{1}{2}} \end{bmatrix}\begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{3.10}$$

The transformation of the variables (voltages, currents) of a three-phase system to symmetrical components is normally defined in the complex plane. This transformation is not very satisfactory for time domain signals because it requires a digital Fourier transform (DFT) and an inverse DFT to be applied. Several algorithms have been proposed which are more efficient in the time domain. The method used in this thesis is illustrated in Figure 3.3. The αβ transformation is the same for positive and negative sequences, so a single transformation is sufficient.

Figure 3.3 illustrates the diagram for calculating the positive and negative sequence of the dq components.

$$x_{\alpha n}(k) = \tfrac{1}{2}\left[x_{\alpha}(k) + x_{\beta}(k - \tfrac{1}{4}\frac{T}{T_S}) \right] \tag{3.11}$$

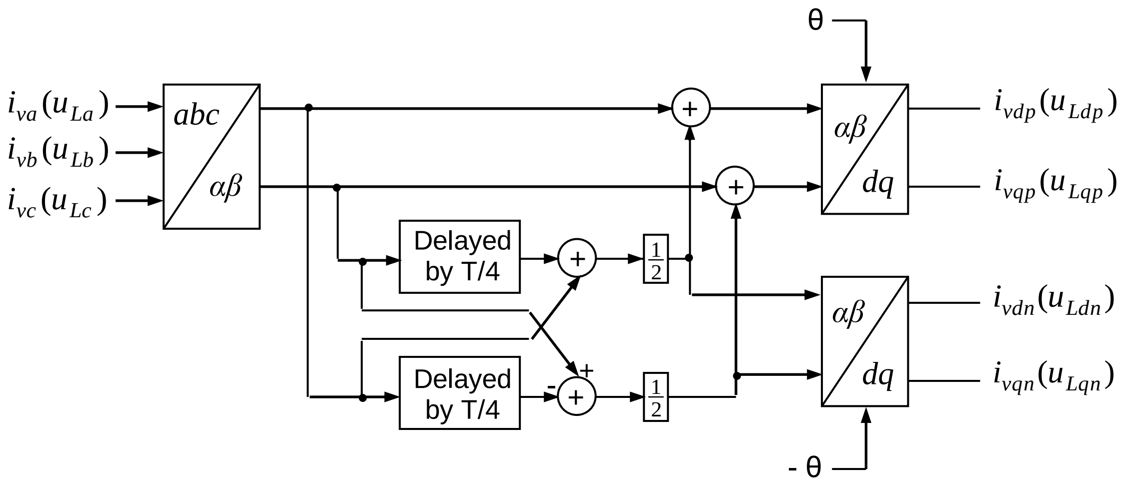


Fig. 3.3: Separation of positive and negative sequence components

$$x_{\beta n}(k) = \tfrac{1}{2}\left[x_{\beta}(k) + x_{\alpha}(k - \tfrac{1}{4}\frac{T}{T_S}) \right] \tag{3.12}$$

$$x_{\alpha p}(k) = x_{\alpha}(k) - x_{\alpha n}(k) = \tfrac{1}{2}\left[x_{\alpha}(k) + x_{\beta}(k - \tfrac{1}{4}\frac{T}{T_S}) \right] \tag{3.13}$$

$$x_{\beta p}(k) = x_{\beta}(k) - x_{\beta n}(k) = \tfrac{1}{2}\left[x_{\beta}(k) + x_{\alpha}(k - \tfrac{1}{4}\frac{T}{T_S}) \right] \tag{3.14}$$

Where $x_{\alpha p}$, $x_{\alpha n}$, $x_{\beta p}$ and $x_{\beta n}$, and are the positive and negative sequence components in the two axes α and β, respectively. T is the period of the alternating network. T_S is the sampling period of the control system. The voltage and current equations are then transformed from the αβ reference to the dq reference. For positive sequences, the transformation is given by:

$$\begin{bmatrix} x_{dp} \\ x_{qp} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{\alpha p} \\ x_{\beta p} \end{bmatrix} \tag{3.15}$$

For negative sequences (rotation in the opposite direction):

$$\begin{bmatrix} x_{dn} \\ x_{qn} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{\alpha n} \\ x_{\beta n} \end{bmatrix} \tag{3.16}$$

Where θ = ωt , and ω is the network pulsation. Equations (3.6) and (3.7) can still be written in the dq frame as follows:

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} i_{vdp} \\ i_{vqp} \end{bmatrix} &= \begin{bmatrix} -\frac{R_v}{L_v} & \omega \\ -\omega & -\frac{R_v}{L_v} \end{bmatrix} \begin{bmatrix} i_{vdp} \\ i_{vqp} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix} \begin{bmatrix} u_{vdp} \\ u_{vqp} \end{bmatrix} \\ &- \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix} \begin{bmatrix} u_{Ldp} \\ u_{Lqp} \end{bmatrix} \end{aligned} \tag{3.17}$$

and

$$\begin{aligned} \frac{d}{dt}\begin{bmatrix} i_{vdn} \\ i_{vqn} \end{bmatrix} &= \begin{bmatrix} -\frac{R_v}{L_v} & -\omega \\ \omega & -\frac{R_v}{L_v} \end{bmatrix} \begin{bmatrix} i_{vdn} \\ i_{vqn} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix} \begin{bmatrix} u_{vdn} \\ u_{vqn} \end{bmatrix} \\ &- \begin{bmatrix} \frac{1}{L_v} & 0 \\ 0 & \frac{1}{L_v} \end{bmatrix} \begin{bmatrix} u_{Ldn} \\ u_{Lqn} \end{bmatrix} \end{aligned} \tag{3.18}$$

where i_{vdp}, i_{vdn}, i_{vqp}, i_{vqn} are positive sequence active current, negative sequence active current, positive sequence reactive current, and negative sequence reactive current respectively. Similarly, the transformations of the reference dq towards the reference αβ are given by:

$$\begin{bmatrix} x_{\alpha p} \\ x_{\beta p} \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{dp} \\ x_{qp} \end{bmatrix} \tag{3.19}$$

For positive sequence components and for negative sequences by:

$$\begin{bmatrix} x_{\alpha n} \\ x_{\beta n} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x_{dn} \\ x_{qn} \end{bmatrix} \tag{3.20}$$

The positive and negative sequence voltages delivered by the VSC converter are obtained from (3.17) and (3.18):

$$u_{vdp} = u_{Ldp} + R_v i_{vdp} - \omega L_v i_{vqp} + L_v \frac{d}{dt} i_{vdp} \tag{3.21}$$

$$u_{vqp} = u_{Lqp} + R_v i_{vqp} - \omega L_v i_{vdp} + L_v \frac{d}{dt} i_{vqp} \tag{3.22}$$

and

$$u_{vdn} = u_{Ldn} + R_v i_{vdn} + \omega L_v i_{vqn} + L_v \frac{d}{dt} i_{vdn} \tag{3.23}$$

$$u_{vqn} = u_{Lqn} + R_v i_{vqn} - \omega L_v i_{vdn} + L_v \frac{d}{dt} i_{vqn} \tag{3.24}$$

The average values of the voltages over the sampling period (k to k+1) are obtained by integrating equations (3.21), (3.22), (3.23) and (3.24) in the interval k_{Ts} to (k + 1) Ts, and dividing by T_s (where T_s is the sampling period).

$$\bar{u}_{vdp} = \bar{u}_{Ldp} + R_v \bar{i}_{vdp} - \omega L_v \bar{i}_{vqp} + \frac{L_v}{T_S} \{ i_{vdp}(k+1) - i_{vdp}(k) \} \tag{3.25}$$

$$\bar{u}_{vqp} = \bar{u}_{Lqp} + R_v \bar{i}_{vqp} + \omega L_v \bar{i}_{vdp} + \frac{L_v}{T_S} \{ i_{vqp}(k+1) - i_{vqp}(k) \} \tag{3.26}$$

and

$$\bar{u}_{vdn} = \bar{u}_{Ldn} + R_v \bar{i}_{vdn} + \omega L_v \bar{i}_{vqn} + \frac{L_v}{T_S} \{ i_{vdn}(k+1) - i_{vdn}(k) \} \tag{3.27}$$

$$\bar{u}_{vqn} = \bar{u}_{Lqn} + R_v \bar{i}_{vqn} - \omega L_v \bar{i}_{vdn} + \frac{L_v}{T_S} \{ i_{vqn}(k+1) - i_{vqn}(k) \} \tag{3.28}$$

Where the average values of the voltages during a sampling period are defined as follows:

$$\bar{u}_{vdp} = \frac{1}{T_S} \int_{kT_S}^{(k+1)T_S} u_{vdp}(t)dt$$

$$\bar{u}_{vqp} = \frac{1}{T_S} \int_{kT_S}^{(k+1)T_S} u_{vqp}(t)dt$$

$$\bar{u}_{vdn} = \frac{1}{T_S}\int_{kT_S}^{(k+1)T_S} u_{vdn}(t)dt$$

$$\bar{u}_{vqn} = \frac{1}{T_S}\int_{kT_S}^{(k+1)T_S} u_{vqn}(t)dt$$

Assuming that the network current is linear and its voltage is constant (The network voltage does not vary abruptly during a switching period), during a sampling period T_s, we obtain from (3.25) to (3.28):

$$u_{vdp}(k+1) = u_{Ldp}(k) + \frac{R_v}{2}\left\{i_{vdp}(k+1) + i_{vdp}(k)\right\} - \frac{\omega L_v}{2}\left\{i_{vqp}(k+1) + i_{vqp}(k)\right\} + \frac{L_v}{T_S}\left\{i_{vdp}(k+1) - i_{vdp}(k)\right\} \tag{3.29}$$

$$u_{vqp}(k+1) = u_{Lqp}(k) + \frac{R_v}{2}\left\{i_{vqp}(k+1) + i_{vqp}(k)\right\} + \frac{\omega L_v}{2}\left\{i_{vdp}(k+1) + i_{vdp}(k)\right\} + \frac{L_v}{T_S}\left\{i_{vqp}(k+1) - i_{vqp}(k)\right\} \tag{3.30}$$

$$u_{vdn}(k+1) = u_{Ldn}(k) + \frac{R_v}{2}\left\{i_{vdn}(k+1) + i_{vdn}(k)\right\} + \frac{\omega L_v}{2}\left\{i_{vqn}(k+1) + i_{vqn}(k)\right\} + \frac{L_v}{T_S}\left\{i_{vdn}(k+1) - i_{vdn}(k)\right\} \tag{3.31}$$

$$u_{vqn}(k+1) = u_{Lqn}(k) + \frac{R_v}{2}\left\{i_{vqn}(k+1) + i_{vqn}(k)\right\} - \frac{\omega L_v}{2}\left\{i_{vdn}(k+1) + i_{vdn}(k)\right\} + \frac{L_v}{T_S}\left\{i_{vqn}(k+1) - i_{vqn}(k)\right\} \tag{3.32}$$

The control is based on the equations (3.29), (3.30), (3.31) and (3.32).

Also, the inner current adjustment loop usually gives a delay of a sample due to the calculation time and the introduction of a very short time between the opening (turn-off) of a valve and the closing (turn-on) of another valve of the same arm of the converter in order to avoid a short circuit of the bridge on the continuous side.

The voltages and currents at time (k+1) are equal to their reference values at time k.

$$u_{vdp}(k+1) = u^{*}{}_{vdp}(k) \tag{3.33}$$

$$u_{vqp}(k+1) = u^*{}_{vqp}(k) \quad (3.34)$$

$$u_{vdn}(k+1) = u^*{}_{vdn}(k) \quad (3.35)$$

$$u_{vqn}(k+1) = u^*{}_{vqn}(k) \quad (3.36)$$

$$i_{vdp}(k+1) = i^*{}_{vdp}(k) \quad (3.37)$$

$$i_{vqp}(k+1) = i^*{}_{vqp}(k) \quad (3.38)$$

$$i_{vdn}(k+1) = i^*{}_{vdn}(k) \quad (3.39)$$

$$i_{vqn}(k+1) = i^*{}_{vqn}(k) \quad (3.40)$$

Where $u^*{}_{vdp}(k)$, $u^*{}_{vdn}(k)$, $i^*{}_{vdp}(k)$, $i^*{}_{vdn}(k)$, $u^*{}_{vqp}(k)$, $u^*{}_{vqn}(k)$, $i^*{}_{vqp}(k)$, $i^*{}_{vqn}(k)$ the reference values of the active voltages and currents of positive and negative sequences, and the reactive voltages and currents of positive and negative sequences, respectively. The control equations can be written as:

$$\begin{aligned} u^*_{vdp}(k) &= u_{Ldp}(k) + R_v i_{vdp}(k) - \frac{\omega L_v}{2}(i^*_{vqp}(k) + i_{vqp}(k)) \\ &+ k_p(i^*_{vdp}(k) - i_{vdp}(k)) \end{aligned} \quad (3.41)$$

$$\begin{aligned} u^*_{vqp}(k) &= u_{Lqp}(k) + R_v i_{vqp}(k) + \frac{\omega L_v}{2}(i^*_{vdp}(k) + i_{vdp}(k)) \\ &+ k_p(i^*_{vqp}(k) - i_{vqp}(k)) \end{aligned} \quad (3.42)$$

$$\begin{aligned} u^*_{vdn}(k) &= u_{Ldn}(k) + R_v i_{vdn}(k) + \frac{\omega L_v}{2}(i^*_{vqn}(k) + i_{vqn}(k)) \\ &+ k_p(i^*_{vdn}(k) - i_{vdn}(k)) \end{aligned} \quad (3.43)$$

$$\begin{aligned} u^*_{vqn}(k) &= u_{Lqn}(k) + R_v i_{vqn}(k) + \frac{\omega L_v}{2}(i^*_{vdn}(k) + i_{vdn}(k)) \\ &+ k_p(i^*_{vqn}(k) - i_{vqn}(k)) \end{aligned} \quad (3.44)$$

Where the gain is:

$$k_p = k_{pf}\left(\frac{L_v}{T_S} + \frac{R_v}{2}\right) \quad (3.45)$$

Since the positive and negative impedance circuits are identical, the same decoupling factor can be used for the positive and negative current regulators.

Finally, the three reference voltages to control the VSC are obtained through:

1. Convert the derivatives $u^*_{vdp}(k), u^*_{vdn}(k), u^*_{vqp}(k), u^*_{vqn}(k)$ into the αβ frame.

2. The separation of the positive and negative sequences of the tensions in the two dens αβ and dq and to obtain the reference tensions in these latter dens.

3. Convert the results obtained in step (2) to a three-phase system to obtain the three reference voltages.

The diagram of the current regulator is shown in figure (3.4). Reference values for active and reactive current $i^*_{vdp}, i^*_{vqp}, i^*_{vdn}, i^*_{vqn}$ (respectively) are obtained from external regulators.

System stability analysis can give the correct value for the k_{pf} gain factor of the regulators.

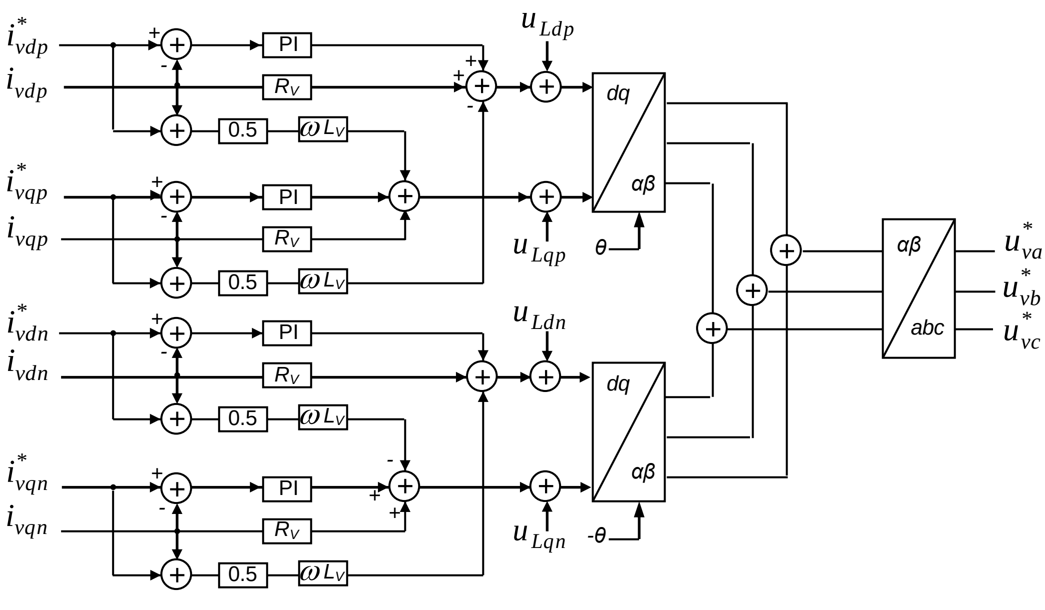


Fig. 3.4: AC Current Regulator

3.5 External regulators

3.5.1 DC voltage control

One of the converters regulates the DC voltage by varying the active power that it exchanges with its AC network. If the DC voltage decreases, it will phase shift (phase lag) the generated AC voltage to further absorb the active power from the AC grid and thus cause the DC voltage to increase. Conversely, if the DC voltage is excessive, the converter will phase shift (phase advance) the generated AC voltage to supply more active power to the AC network and thus cause the DC voltage to decrease.

A task achieved by setting the small additional power required to charge or discharge the capacitor to maintain a desired DC voltage. A proportional (P) or proportional integral (PI) controller is required for this task.

The instantaneous active power $P_{CA(abc)}$ and reactive power $Q_{CA(abc)}$ transmitted in the AC system (AC side of VSC converter), and DC power P_{dc} transmitted through the DC link (DC side of VSC converter) shown in figure (3.1) are expressed by the following relations:

$$P_{CA(abc)} = u_{La} \cdot i_{va} + u_{Lb} \cdot i_{vb} + u_{Lc} \cdot i_{vc} \tag{3.46}$$

$$Q_{CA(abc)} = (u_{La} - u_{Lb})i_{vc} + (u_{Lb} - u_{Lc})i_{va} + (u_{Lc} - u_{La})i_{vb} \tag{3.47}$$

$$P_{dc} = u_{dc} \cdot i_{dc} \tag{3.48}$$

As it has already been moved, the voltages of the AC system are balanced in normal operation, therefore the components $u_{Lan,}\ u_{Lbn,}\ u_{Lcn,}$ are zero, this means that the components $u_{L\alpha n,}\ u_{L\beta n}$, and $u_{Ldn,}\ u_{Lqn}$ in the two references (αβ) and (dq) respectively, are also zero. Then the components $u_{Ldp,}\ u_{Lqp}$ can be described as follows:

$$\begin{aligned} u_{Ldp} &= 0 \\ u_{Lqp} &= U \end{aligned} \tag{3.49}$$

Where U is the magnitude of the voltage. The two instantaneous powers, active and reactive $P_{CA(dq)}$ and $Q_{CA(dq)}$ in the frame dq are obtained from equations (3.46), (3.47), (3.48) and (3.49).

$$\begin{aligned} P_{CA(dq)} &= u_{Ldp} \cdot i_{vdp} + u_{Lqp} \cdot i_{vqp} \\ &= u_{Lqp} \cdot i_{vqp} \end{aligned} \tag{3.50}$$

$$\begin{aligned} Q_{CA(dq)} &= u_{Lqp} \cdot i_{vdp} - u_{Ldp} \cdot i_{vqp} \\ &= u_{Lqp} \cdot i_{vdp} \end{aligned} \tag{3.51}$$

Here it is assumed that only the network voltage is balanced. No assumptions have been made regarding the voltage and current delivered by the converter. Normally, the response of the current regulator is very fast compared to that of the DC voltage regulator.

For the DC voltage regulator, it is assumed that the current value is equal to their reference value. The expressions for active and reactive power will be:

$$P_{CA(dq)} = u_{Lqp} \cdot i_{vqp}^{*} \tag{3.52}$$

$$Q_{CA(dq)} = u_{Lqp} \cdot i_{vdp}^{*} \tag{3.53}$$

If we neglect the losses in the converter and the reactance, the transmitted power is:

$$P_{CA(dq)} = u_{Lqp} \cdot i_{vqp}^{*} = P_{dc} = u_{dc} \cdot i_{dc} \tag{3.54}$$

Then

$$i_{dc} = \frac{u_{Lqp} \cdot i_{vqp}^{*}}{u_{dc}} \tag{3.55}$$

Any imbalance between the two AC and DC powers causes a change in the voltage across the DC capacitors. The equation for DC voltage across capacitors is:

$$C_{dc} \frac{d}{dt} u_{dc} = i_{dc} - i_{charge} \tag{3.56}$$

Where i_{charge} is the direct current of the DC line (or cable). By integrating equation (3.56) over the interval kT_s and (k + 1)T and then dividing it by T_s, we get:

$$\frac{C_{dc}}{T_s} \{u_{dc}(k+1) - u_{dc}(k)\} = \bar{i}_{dc} - \bar{i}_{chrage} \tag{3.57}$$

Where the average values of the currents during a sampling period are defined as follows:

$$\bar{i}_{dc} = \frac{1}{T_s} \int_{kT_s}^{(k+1)T_s} i_{dc}(t)dt$$

$$\bar{i}_{charge} = \frac{1}{T_s} \int_{kT_s}^{(k+1)T_s} i_{charge}(t)dt$$

Here, the dc currents i_{dc} and i_{charge} are both constant at the normal rate. Then, their average values are equal to these constant values, which give:

$$\frac{C_{dc}}{T_s} \{u_{dc}(k+1) - u_{dc}(k)\} = i_{dc}(k) - i_{chrage}(k) \tag{3.58}$$

The reference voltage can be obtained due to a delay of one sampling period in the regulator.

$$u_{dc}(k+1)=u_{dc}^{*}(k) \tag{3.59}$$

Substituting (3.55) and (3.59) in (3.58) gives:

$$\frac{C_{dc}}{T_s}\left(u_{dc}^{*}(k)-u_{dc}(k)\right)=\frac{u_{Lqp}(k)\cdot i_{vqp}^{*}(k)}{u_{dc}(k)}-i_{charge}(k) \tag{3.60}$$

So, the current reference can be obtained by equation (3.60), that is:

$$i_{vqp}^{*}(k)=\frac{u_{dc}(k)}{u_{Lqp}(k)}\left\{\frac{C_{dc}}{T_s}\left(u_{dc}^{*}(k)-u_{dc}(k)\right)+i_{charge}(k)\right\} \tag{3.61}$$

$$i_{vqp}^{*}(k)=k_{dcp}\left(u_{dc}^{*}(k)-u_{dc}(k)\right)+k_{charge}\cdot i_{charge}(k) \tag{3.62}$$

Where

$$\begin{aligned} k_{dcp}&=k_{dcpf}\frac{u_{dc}(k)}{u_{Lqp}(k)}\frac{C_{dc}}{T_s}\\ &=k_{dcpf}\frac{u_{dc}^{*}(k)}{u_{Lqp}(k)}\frac{C_{dc}}{T_s}\end{aligned} \tag{3.63}$$

$$\begin{aligned} k_{charge}&=\frac{u_{dc}(k)}{u_{Lqp}(k)}\\ &=\frac{u_{dc}^{*}(k)}{u_{Lqp}(k)}\end{aligned} \tag{3.64}$$

The factor k_{dcpf} can modify the gain of the DC voltage regulator to stabilize it. The diagram of the DC voltage regulator is shown in figure (3.5).

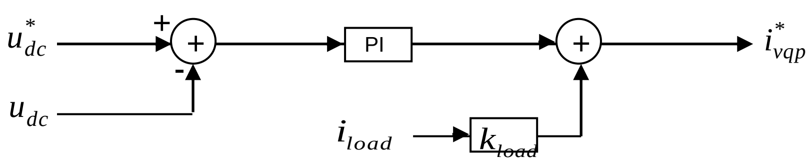


Fig.3.5 : DC voltage control

3.5.2 Control of the AC side active power

The converter which does not regulate the DC voltage regulates the power which it exchanges with its AC network. In the case of a multi-terminal link, a single converter regulates the DC voltage and the others each regulate the active power that they exchange with their AC network.

Control of the transmitted active power is achieved by adjusting the phase angle of the AC voltage generated by the converter at the fundamental frequency. Depending on the sign of this angle, active power will either be absorbed or delivered to the AC system. The transfer of active power through the VSC-HVDC link requires simultaneous coordination of the two converter stations at the ends of the link. When the voltage generated is in phase with the network, the current is perpendicular to the voltage and the active power exchanged with the network is zero. If a voltage is generated in advance of that of the network, the current has a collinear component with the voltage of the network, which means that the VSC exchanges active power with the network (here, the VSC provides active power) . Conversely, if the voltage generated lags behind that of the network, the VSC absorbs active power from the network.

The simplest method to control active power is to use an open loop regulator. The active current reference is obtained by using equation (3.52) (which assumes that the voltages are balanced), which gives:

$$i_{vqp}^{*} = \frac{p^{*}}{u_{Lqp}} \tag{3.65}$$

If more than one active power regulator is needed, a combination of feedback loop and open loop can be used. The structure of the regulator resulting from the active power is shown in the figure (3.6).

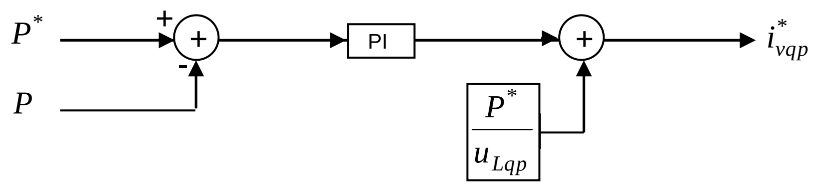


Fig. 3.6 : Control of active power

3.5.3 AC side reactive power control

On the AC side, the principle of the voltage source converter is to generate a three-phase voltage synchronous with that of the network, and thus to impose a controlled potential difference across the terminals of the phase reactance as. We first assume that the voltage generated is in phase with that of the network. If the voltage generated is of lower amplitude than that of the network, the current induced through the reactance by the potential difference, in quadrature lag with respect to the latter, is in quadrature advance with respect to the network voltage.

Thus the converter behaves like a capacitor and supplies reactive energy to the network. Conversely, if the amplitude of the voltage generated is lower than that of the network, the VSC behaves on the AC side like a reactance and absorbs reactive energy from the network. The reactive power generated or absorbed by the VSC converter is controlled by the magnitude of the AC voltage generated by the converter through the modulation index (using PWM). Use of this feature is important when the other converters in the transmission system are operating to maintain their AC voltages.

The reactive power regulator is similar to the active power regulator. An open loop regulator is obtained by using equation (3.52), which is:

$$i^*_{vdp} = \frac{Q^*}{u_{Lqp}} \tag{3.66}$$

Another method is to combine a feedback loop with an open loop. The diagram of the reactive power regulator is shown in figure (3.7).

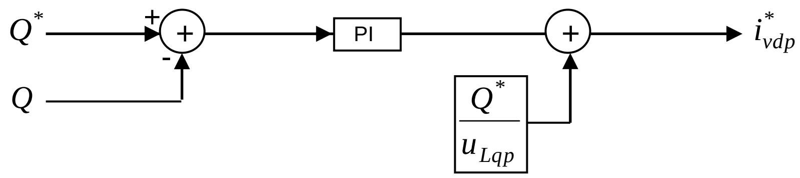


Fig. 3.7: Reactive power regulator

3.5.4 Frequency control

Control of the frequency of the oscillator which determines the sequence of pulses for the valves of the converter is essential when the VSC is the only source of power, i.e. when the VSC-HVDC link feeds an isolated network or a passive load. However, when the VSC is connected to an active system, it can participate in the frequency control system by adjusting the power supplied or absorbing from the connected AC network.

The purpose of a frequency regulator is to maintain the frequency at its reference value. The change in power, for a change in frequency in an interconnected network is known as the system stiffness. The power-frequency characteristic can be approximated by a straight line:

$$\frac{\Delta P}{\Delta f} = K \tag{3.67}$$

Where :
ΔP the drop in power,
Δf the frequency drift,
K a constant.

According to both equations (3.52) and (3.67), it suffices to use PI regulators in the frequency controlled feedback loop and the control error can be reduced to zero at normal regime. The diagram of the frequency regulator is shown in figure (3.8).

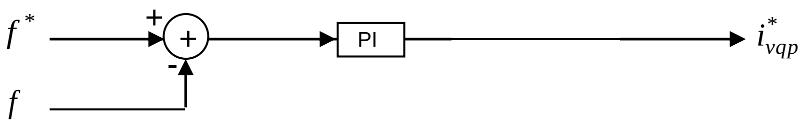


Fig. 3.8 : frequency control

It should be noted that a frequency regulator can only be used for systems without other frequency control sources. In a system that has frequency controlling sources, a proportional (P) regulator should be used to share the load variations of the source.

3.5.5 Control of the AC alternating voltage

The AC voltage can be controlled by adjusting the magnitude of the AC voltage produced by the VSC converter on the transformer side. If the VSC converter is supplying an isolated AC system, the AC voltage controller also provides automatic control of the power supplied by the VSC to the load (assuming that the rectifier station is controlling the DC voltage of the link). The conversion transformer maintains the voltage with changeable taps (On-Load Tap-Changer) and subsequently therefore the modulation index.

As shown in Figure 3.9, the voltage drop ΔV across the reactance can be described as:

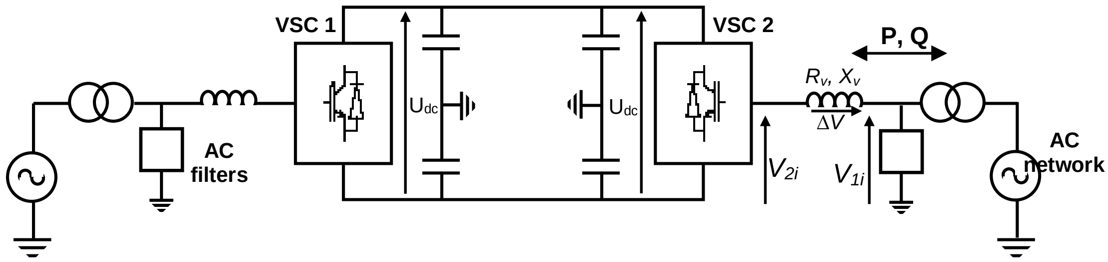


Fig. 3.9: Topology of a VSC-HVDC link

$$\begin{aligned}\Delta V &= V_{2i} - V_{1i} \\ &= \Delta V_p + j\Delta V_q \\ &= \frac{R_v \cdot P + X_v \cdot Q}{V_{1i}} + j\,\frac{X_v \cdot P - R_v \cdot Q}{V_{1i}}\end{aligned} \tag{3.68}$$

If

$$\Delta V_q \langle\langle \quad V_{1i} + \Delta V_p \tag{3.69}$$

Then

$$\Delta V \approx \frac{R_v \cdot P + X_v \cdot Q}{V_{1i}} \tag{3.70}$$

For most AC networks the reactance $X_v \rangle\rangle R_v$, so the voltage drop ΔV only depends on the reactive power. So the change in AC voltage (V_{1i}) only depends on the reactive power. From equations (3.53) and (3.70), the diagram of the AC voltage regulator can be obtained as shown in figure (3.10).

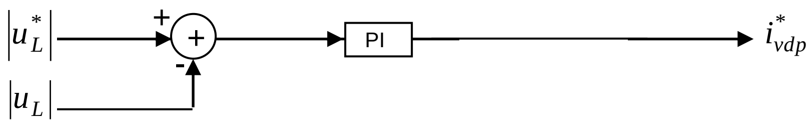


Fig. 3.10: AC voltage regulator

Where $|u_L|$ is the magnitude of the line voltage, $|u_L^*|$ it is the reference value of the magnitude of the line voltage.

Finally, it should be noted that implementing a control in the (dq) frame has a disadvantage in that the measured AC voltages and currents must be transformed into the (dq) frame through a phase-locked loop. (PLL) which synchronizes the converter control system with line voltage (usually AC bus voltage is used). The behavior of the PLL design will determine the performance of the control system.

3.6 Coordination of the control of a VSC-HVDC link

At startup, the two stations are powered separately. When the AC circuit breakers are closed, the DC buses are powered through the anti-parallel diodes in each bridge. Once the semiconductors (often IGBTs) are charged, the converters in the two stations can be connected. The first converter that will be unlocked controls the DC voltage.

Normally, one or more of the converters will be used to set the active power needed to keep the DC voltage within the desired limits. The converters at both ends of a point-to-point link must be controlled to work together for desired active power transfer. This action is to put an appropriate phase shift for the AC voltage to the converter on their respective sides.

When both reactive power and AC voltage control are used together, possible interference between them can be avoided by selecting only converters that are not used for

AC voltage control to provide power control reactive. If all converters working in close proximity control the same quantities, it is possible for each to participate in controlling the AC voltage produced through a carefully designed feature. However, if their control functions are different, the characteristic may be difficult to define. As previously explained, AC current control is an inherent feature of the vector control strategy; this is important to ensure that the AC current through the VSC converter is within the allowable operating range to prevent overload.

When the VSC converter supplies an active AC system, where the frequency is set by the synchronous generators and the load frequency control system, the VSC converter can participate in frequency control by setting the power to generate, or absorb, from the connected AC system. However, if the VSC converter is powering a passive AC system, the frequency of the AC voltage produced is controlled directly by the frequency of the oscillator which determines the pulse sequences.

In normal operation, each converter station controls its reactive power independently. On the other hand, the active power delivered by the rectifier station must be equal to the set of the two powers; that of the inverter station plus the losses in the DC link. Any difference will result in an increase or decrease in DC voltage. To ensure the balance of the transmitted power, one of the converter stations must control the DC voltage, while the other station controls the active power. The station that controls the DC voltage will adjust its power in order to ensure power balance (which involves keeping the DC voltage constant); this is achieved without the need for telecommunications between the two converter stations, but purely based on DC voltage measurement.

However, the imbalance of the transmitted power occurs during the transient state. Assume for the moment that the converter which feeds the AC system (ie rectifier) is temporarily blocked, for this purpose the energy stored in the DC circuit (DC link) will charge the DC capacitors and subsequently the DC voltage increase; this problem will be neutralized by the station which controls the DC voltage, which will reduce it, and even reverse the direction of the active power to maintain the DC voltage constant.

During emergency situations, changing the power flow through the link can be implemented very quickly. From a control point of view, the converter can change the direction of the transmitted power in a few milliseconds, but this speed is limited by the network components. The change of the direction of the transfer of the power can be ensured without the need for the change of mode neither of regulation nor to block the converters. It is ensured by changing the direction of the current, while the voltage always remains constant. In the presence of PWM control, the reactive power regulators at each end of the link continue to operate independently of the active power direction.

As the alternating current can be controlled, the contribution of an HVDC link to the short-circuit power should be low. However, simulation studies carried out by ABB have shown that, unlike a conventional HVDC link, a VSC-HVDC link can contribute certain short-circuit current, which varies inversely with the short-circuit ratio (SCR), and the maximum contribution occurs when the converters operate at zero active power. The contribution depends on the control strategy used. With reactive power control, the short-circuit current contribution will be small, because the current limit decreases with voltage. With an AC voltage control mode, the contribution increases with decreasing active power, if the current limit does not change. Of course, the increase in short-circuit contribution is associated with improved performance for voltage stability, and this means that voltage drops during faults are reduced. During AC faults, the current control will quickly drop the bridge voltage (at the fundamental frequency) to reduce the current to its pre-fault value.

3.7 Limiting strategies

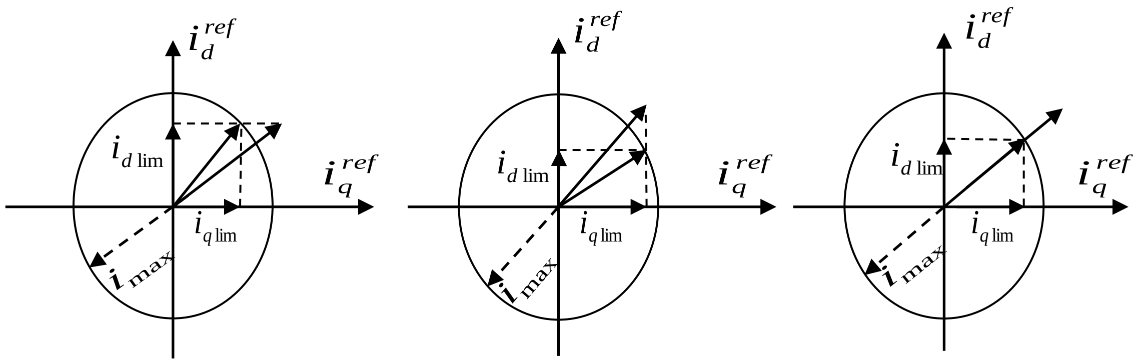
Since the VSC-HVDC does not have any overload capability as synchronous generators have, over-currents due to disturbances will lead to thermal degradation of the valves or instantly to permanent damage. The VSC-HVDC shall be operated within its capability limits. Therefore, a current limiter must be implemented in the control system. Moreover, in order to maintain a proper control and reduce the lower order frequency harmonics due to over-modulation, the maximum reference voltage generated by the inner current loop shall be limited. The maximum value is such that modulation index is less or equal to one for SPWM.

The current limit $i_{\max}$ is compared with the current magnitude computed from the active and reactive reference currents. When the current limit is exceeded, both the active and reactive reference currents will be limited to $i_{d\lim}$ and $i_{q\lim}$. The choice of the limiting strategy depends on the application.

The first strategy could be to give the active reference current high priority when the current limit is exceeded as shown in Figure 3.11.This strategy is used for instance when the converter is connected to a strong grid to produce more power.

The second strategy could be, for instance when the converter is connected to a weak grid or used to supply an industrial plant, to give high priority to the reactive reference current when the current limit is exceeded as shown in Figure 3.11 (b).This strategy helps to support the AC-side voltage by allowing the converter to increase it reactive power support equal to its rating during voltage dips.

The last strategy could be to give equal scaling to the active and reactive current references when the current limit is exceeded as shown in Figure 3.11 (c).



a) **b)** **c)**

Fig. 3.11: Current limiting strategies

3.7.1 Controller integral windup

When designing the control laws, the control signal cannot be arbitrary large due to design limitation of the converters. Therefore the control signal must be limited(saturated) as discussed above. This causes the integral part of the PI controller to accumulate the control error during limiting of the output signal, so called integral windup. This might cause overshoots in the controlled variable.

Integral windup can be avoided by making sure that the integral is kept to a proper value or disconnected during saturation, so that the controller is ready to resume action as soon as the control error changes.

3.7.2 Tuning of PI controllers

In tuning of PI controllers for VSC-HVDC, the tuning is done following the criteria adopted for electrical drives. Cascaded control requires the speed of response to increase towards the inner loop.

The well known tuning rule, internal model control (IMC) is adopted for tuning the inner current controller. The gain parameters of the inner current loop are calculated. Moreover, care must be taken in the proportional constants in RMS calculations for iteration convergence.

$$\begin{aligned} K_p &= \alpha L \quad T_i = L/R \\ K_i &= \alpha R \quad t_r = \frac{\ln 9}{R} \end{aligned} \tag{3.71}$$

Where α is a design parameter that is equal to the closed loop bandwidth and t_r is the rise time, the time needed to take a step response from 10 % to 90 %. A rise time of t =2 ms, equivalentlyα=1098 rad/s will be used for the inner current loop. However, the performance of the control system will get better if the inner loop is made to respond instantaneous. But in reality instantaneous response means usually infinite amplification of noise.

IMC is also used to tune the direct voltage controller. The gain parameters are calculated based where the equations are reproduced here as Eqn. (3.72).

$$\begin{aligned} K_p &= \alpha_d C_{dc} \\ K_i &= \alpha_d^2 C_{dc} \end{aligned} \quad G_a = \alpha_d C_{dc} \tag{3.72}$$

Where α_d =220 rad/ s is used as an initial value. The actual gains used are a bit modified from the ones calculated based on Eqn. (3.72) to get the desired response time, slower than the inner current controller.

For the AC voltage and Reactive power controllers, there are no general tuning rules as the controller gain depends on the network impedance. Therefore it is made via trial and error to get a reasonable speed of response, slower than the inner current and direct voltage controllers.

Chapter 04: HVDC for offshore wind Farms: applications

4.1 Introduction

Today, the offshore wind farm becomes more attractive compared to the onshore one, because the latter has the disadvantages of lack of space, noise problem and visual impact. Another advantage of the offshore wind farm which is the wind availability at high speeds leading to more power generated and also more space to build the wind farm. Using AC cables for long distance power transmission is not the right solution for many of the reasons mentioned above. HVDC high voltage direct current link especially HVDC-VSC technology could be an attractive transmission system, instead of using AC high voltage cable transmission.

The main objective of this chapter is to present an offshore wind farm connected to an HVDC link based on a diode rectifier and a VSC inverter. This large offshore wind farm is divided into five groups. Each group consists of a few wind turbines that are similar in all parameters. Then, each group can be replaced by a single equivalent unit whose power equals the sum of the individual power of the wind turbines. The five groups have a total power equal to 800 MW, constitutes the system which will be studied in this chapter. The components that are part of the offshore wind farm are the wind turbines and the offshore AC grid. Each turbine in turn consists of the wind rotor, the mechanical transmission system, the permanent magnet synchronous generator, the double power converter and the transformer.

The HVDC link consists of an uncontrolled diode rectifier, an underwater cable and a VSC voltage source converter which acts as an inverter. The rectifier in turn includes diode bridges, AC filters, transformers and the DC side filter. The uncontrolled rectifier is used to replace the VSC rectifier. It is located between two controlled converters, so it cannot affect the operation of the system. In the following steps, the operation, modeling and control of the system will be studied in detail.

4.2 HVDC-VSC transmission system for the connection of wind energy sources

At the end of the 19th century, a heated debate focused on the production of electricity and its distribution as well as its transmission. The result identified the structure of the power grid we know today. A conflict known as the "Battle of the Currents" took place between Nikola Tesla, an Alternating Current (AC) electrical distribution supporter, and Thomas Edison, a Direct Current (DC) supporter. The outcome of the battle was well known and alternating current dominated in many areas, but today we see a revival of direct current in several areas: the integration of renewable energy, especially wind power and solar energy, electric vehicle charging and, in our case, the use of direct current for HVDC interconnections [13].

Great strides have been made in the development of HVDC converters whose use is driven by many factors [14]. HVDC-VSC links are marketed under the name "HVDC Light" by ABB and "HVDC Plus" by SIEMENS. HVDC system based on voltage source converter (HVDC-VSC) is the latest transmission technology to connect remote offshore wind which requires long distance cable connection. The HVDC-VSC system offers an asynchronous connection between the offshore wind grid and the onshore power grid, and also it offers independent control of active power and reactive power. These links are intended to improve the integration of wind farms into the electricity grid. Another advantage becomes from the use of the HVDC-VSC system, is that the wind turbine generators, themselves, use power electronics converters, thus increasing their own control and flexibility, which offers new possibilities for improve the power quality of AC networks [15].

The connection of a large wind farm is necessary for the transmission and distribution of the generated electrical energy [16]. HVDC-VSC is the cheapest option for connecting a wind farm to the grid when the capacity of the installation is greater than 100 MW and the distance is greater than 90 km compared to conventional HVAC or HVDC systems.

4.3 An HVDC system based on an uncontrolled rectifier and a VSC inverter for the connection of offshore wind farms

Many researchers presented the HVDC system based on a diode rectifier as a solution that can be used in the case of unidirectional power flow, for example, the transmission of power from large offshore wind farms to the main onshore grid. Compared to LCC or VSC technologies, the advantages that can be derived from the use of this technology are: less conduction losses, less installation cost and higher reliability [17]. But this technology has some drawbacks like lack of control system in diode rectifier and also lack of protection system. These drawbacks can be resolved by inserting compensation systems and also inserting a protection strategy on the control system [18].

Installation costs in offshore wind installations are much higher and therefore any reduction in aspects such as equipment weight, maintenance requirements or transmission losses will have a more obvious effect on the transmission costs. For this reason, the proposal to use diode rectifiers becomes more attractive to reduce these costs [19,20]. Figure 4.1 shows an offshore wind farm connected to the onshore grid via an HVDC system with an uncontrolled rectifier and a VSC inverter.

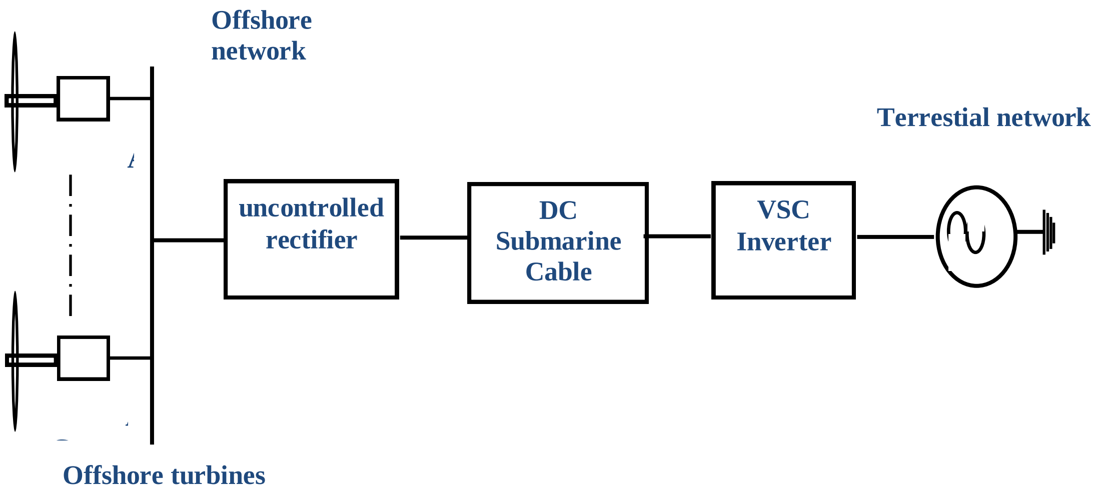


Fig. 4.1: Offshore wind farm connected to HVDC system of uncontrolled rectifier and VSC inverter

4.4 HVDC-(Diodes-VSC) system for wind connection

Figure 4.2 shows a typical system which consists of an offshore wind farm with a number of wind turbines. This system is connected to a common offshore coupling point. The HVDC link consists of an uncontrolled 12-pulse diode rectifier and an underwater DC cable and finally a VSC inverter. The two AC sides of the link converters are connected to the AC networks via transformers. The main components of the system to be studied are:

4.4.1 Wind farm

The wind farm consists of 160 wind turbines. Each wind turbine based on the 5MW

GSAP permanent magnet synchronous generator connects to two back-to-back controlled converters.

4.4.2 HVDC link converters

The two converters used for the HVDC link are an uncontrolled diode-based converter and a VSC-based converter employing IGBT power semiconductors. The first converter functions as a rectifier and the other as an inverter.

4.4.3 Transformers

Obviously, converters are connected to AC systems through transformers. The most important function of transformers is to transform the AC voltage to adequate values for the correct operation of the converter. A transformer allows additional functions such as voltage adaptation, combination of conversion units or isolation from the zero-sequence component. The leakage inductance of transformers used in this mode of transport is generally between 0.1pu and 0.2pu. On the one hand a T_R transformer without tap changer connected the rectifier with the alternating current network at sea, and on the other hand another T_V transformer connects the inverter with the terrestrial network.

4.4.4 Filters and shunt capacitors

Depending on the AC network, filters may be required to prevent any harmonics from entering the converter station. On the other hand, the high switching frequency in the conversion unit makes the harmonics it generates more harmful for the equipment but also easier to filter. Z_{FR} represents both the shunt capacitor C_F of the rectifier and the harmonic filter bank.

Filters can be installed on the DC bus to limit the DC voltage ripple without increasing the value of the DC capacitance, in cases where the latter is limited by other constraints.

4.4.5 DC cables

Because of its sensitivity to continuous faults, this type of connection is mainly made by underground or submarine cables. In addition, since the polarity of the DC voltage never reverses, synthetic insulated cables are used which are more economical than traditional cables. The cable used in the HVDC-VSC links is a newly developed type, where the insulation is made of an extruded polymer which is particularly resistant to DC voltage. This type of cables is the preferred choice for HVDC-VSC links, mainly due to their mechanical strength, flexibility and low weight.

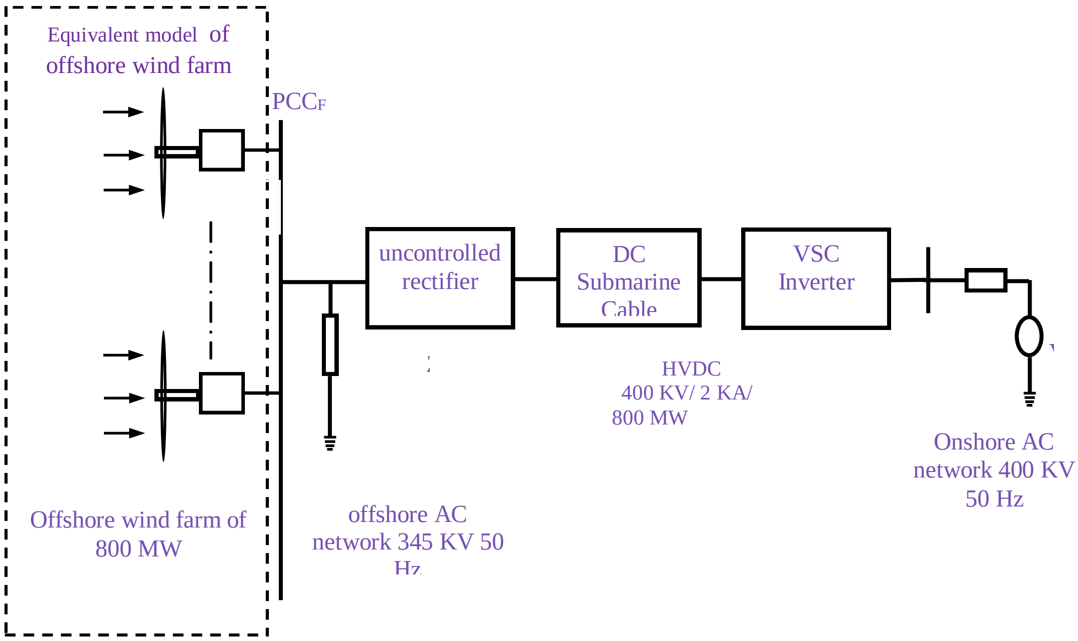


Fig. 4.2: The configuration of a wind farm connected to an HVDC system based on an uncontrolled rectifier and a VSC inverter

4.5 Wind energy

Wind energy is a rapidly developing field. Installed wind power has increased significantly over the last ten years and the trend is to install larger wind turbines and consolidate them into large wind farms connected to the grid by HVDC links [21].

4.5.1 wind distribution

Wind speed can be modeled as a continuous random variable, using the Rayleigh distribution. The Rayleigh distribution is a simplification of the Weibull distribution. The most common probability density function for describing wind speed is given by [22,23]:

$$f\left(\omega_{\omega}\right)=\frac{k}{c}\left(\frac{\omega_{\omega}}{c}\right)^{k-1}\exp^{\left[-\left(\frac{\omega_{\omega}}{c}\right)^{k}\right]} \quad (4.1)$$

Where:

Wind probability density function;

: Mean wind speed; : Shape parameter; : Scale parameter and given by:

$$c=\frac{2}{\sqrt{\pi}}\overline{\omega}_{\omega} \quad (4.2)$$

Where: W_w is the average annual wind speed. To simplify, we put the probability distribution is given by the average wind speed:

$$f\left(\omega_{\omega}\right)=\frac{\pi\omega_{\omega}}{2\overline{\omega}_{\omega}^{2}}\exp^{\left[-\frac{\pi\omega_{\omega}^{2}}{4\overline{\omega}_{\omega}^{2}}\right]} \quad (4.3)$$

To use the Rayleigh distribution, simply define the annual average wind speed. The probability distributions for different mean wind speeds using the Rayleigh distribution are shown in Figure 4.3, in which 5 distributions of 5 different annual mean wind speeds are shown.

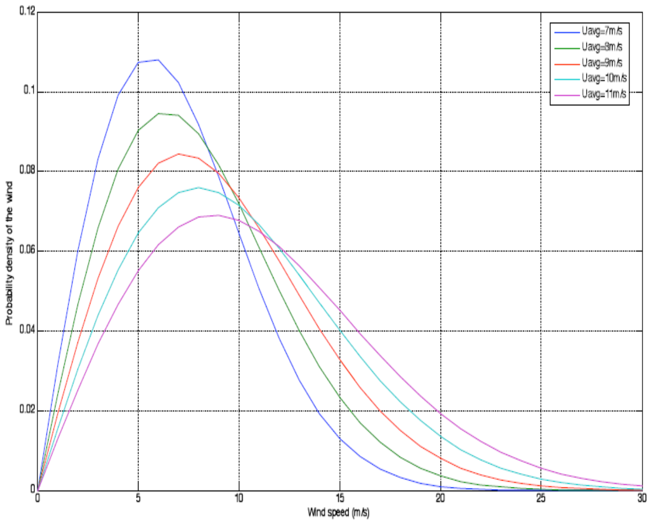


Fig. 4.3 Wind speed probability distribution

4.6 General Description of the system to be studied

A proposed point-to-point system is shown in Figures 4.4 and 4.5. It consists of three clearly defined parts: the offshore wind farm, a DC link and an AC onshore grid. The wind farm consists of 160 wind turbines of 5 MW. The total installed power is therefore 800 MW. The HVDC link consists of an uncontrolled diode rectifier, an undersea cable approximately 100 kilometers long and a VSC voltage converter which acts as an inverter. The terrestrial network is simply modeled by its Thevenin equivalent. All wind turbines show the same behavior if the wind incident was also the same. As the extension of the wind farm is large, it is assumed that the wind incident will not be the same for all wind turbines. To accommodate this difference and have a more flexible system, there were five groups of 4, 16, 28, 44, and 68 wind turbines. In each group of wind turbines, the wind incident is the same and this group is modeled by an equivalent wind farm.

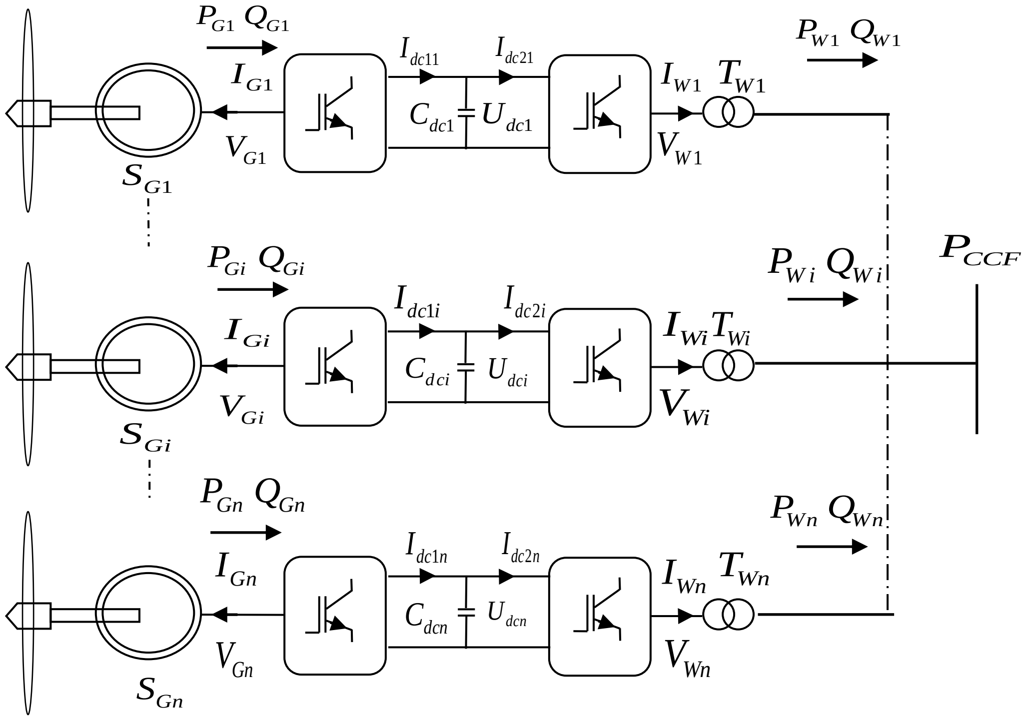


Fig. 4.4 : Offshore wind farm (i = 1,2,3,4,5) connected to point PCC_F

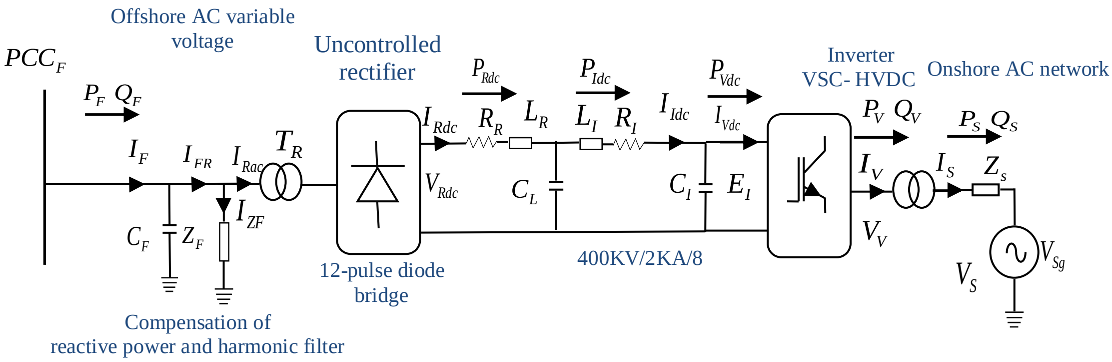


Fig. 4.5: Transmission HVDC-(Diodes - VSC)

4.7 Operation of the wind turbine

The wind turbine is a machine that converts the kinetic energy of the wind into mechanical energy which is in turn converted into electrical energy. The wind farm can produce energy only in response to an immediately available resource: the wind; because it is not possible to store the wind and use it later. For this reason, any system to which a wind turbine is connected must take this availability into account [24].

A simplified diagram of the wind turbine components is shown in Figure 4.4; as shown in this diagram, the elements of the wind turbine are:

• the wind turbine rotor;

• Mechanical transmission system;

• Permanent magnet synchronous generator;

• Back-to-back converters; • Transformer. From this figure, it is clear that the power produced by the wind turbine is transferred through the power converters back to back; Therefore, the dynamic operation of the electrical generator is effectively isolated from the electrical network. In other words, the electric frequency of the generator is independent of the frequency of the network, thus allowing a variable speed operation of the wind turbine.

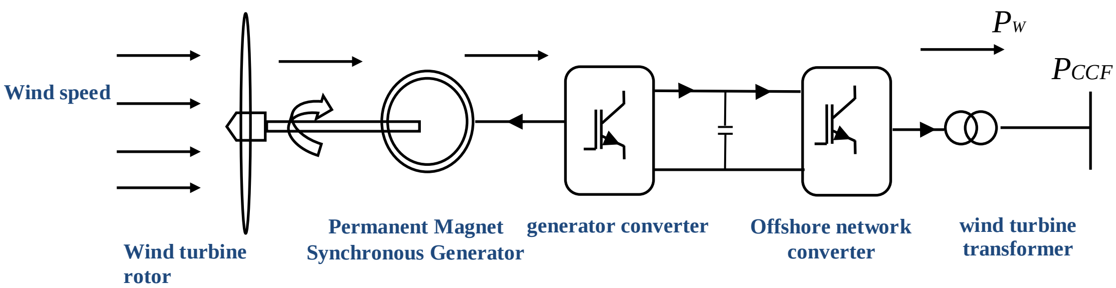


Fig. 4.6: Wind turbine components

4.7.1 Offshore wind farm modeling

The following equations represent the electrical model of the wind turbine cluster connected to the common coupling point of the offshore AC grid.

• The d-q axis equations used to model the synchronous permanent magnet generator are:

$$V_{Gdi} = R_{Gi} I_{Gdi} + L_{Gdi} \frac{dI_{Gdi}}{dt} - \omega_{Gi} \lambda_{Gqi} \quad (4.4)$$

$$V_{Gqi} = R_{Gi} I_{Gqi} + L_{Gqi} \frac{dI_{Gqi}}{dt} + \omega_{Gi} \lambda_{Gdi} \qquad (4.5)$$

• Flux couplings can be defined-in Wb by the following equations:

$$\lambda_{Gdi} = L_{Gdi} I_{Gdi} + \lambda_m \qquad (4.6)$$

$$\lambda_{Gqi} = L_{Gqi} I_{Gqi} \qquad (4.7)$$

• the equation of the power balance on the converter side of the generator:

$$P_{Gi} = -3\left(V_{Gdi} I_{Gdi} + V_{Gqi} I_{Gqi}\right) \qquad (4.8)$$

$$P_{dc1i} = U_{dci} I_{dc1i} \qquad (4.9)$$

• The voltage dynamic U_{dci} is defined by the capacitance equation and it can be expressed as follows:

$$I_{dc1i} - I_{dc2i} = C_{dci} \frac{dU_{dci}}{dt} \qquad (4.10)$$

• the equation of the power balance on the converter side of the offshore network:

$$P_{dc2i} = U_{dci} \left(I_{dc2i}\right) n_i \qquad (4.11)$$

• With is the number of wind turbines constituted the group

$$P_{Wi} = 3\left(V_{Wdi} I_{Wdi} + V_{Wqi} I_{Wqi}\right) \qquad (4.12)$$

• The dynamics of the offshore grid integration can be written in synchronous d-q coordinates rotating ω_{dq} at as follows :

$$\frac{d}{dt} I_{Wdi} = -\frac{R_{TWi}}{L_{TWi}} I_{Wdi} + w_{dq} I_{Wqi} + \frac{1}{L_{Twi}} V_{Wdi} - \frac{1}{L_{TWi}} V_{Fd} \qquad (4.13)$$

$$\frac{d}{dt} I_{Wqi} = -w_{dq} I_{Wdi} - \frac{R_{TWi}}{L_{Twi}} I_{Wqi} + \frac{1}{L_{TWi}} V_{Wqi} - \frac{1}{L_{TWi}} V_{Fq} \qquad (4.14)$$

and also

$$I_{Fd} = \sum_{i=1}^{5} I_{Wdi} \qquad (4.15)$$

$$I_{Fq} = \sum_{i=1}^{5} I_{Wqi} \qquad (4.16)$$

- The dynamics of the offshore grid voltage can be written in synchronous d-q coordinates rotating ω_{dq} at as follows:

$$\frac{d}{dt}V_{Fd} = \frac{1}{C_F}\sum_{i=1}^{m} I_{Wdi} - \frac{1}{C_F} I_{FRd} + \omega_{dq} V_{Fq} \qquad (4.17)$$

$$\frac{d}{dt}V_{Fq} = \frac{1}{C_F}\sum_{i=1}^{m} I_{Wqi} - \frac{1}{C_F} I_{FRq} - \omega_{dq} V_{Fd} \qquad (4.18)$$

4.8 The HVDC-(Diodes-VSC) link

The HVDC link used in the studied system consists of an offshore uncontrolled diode rectifier, an underwater DC cable and an onshore VSC inverter. On the one hand, this link is connected to the PCCF point at sea via two transformers and also a bank of capacitors and filters; on the other hand it is connected to the land network by another transformer. The main components of the proposed HVDC transmission system are shown in Figure 4.7.

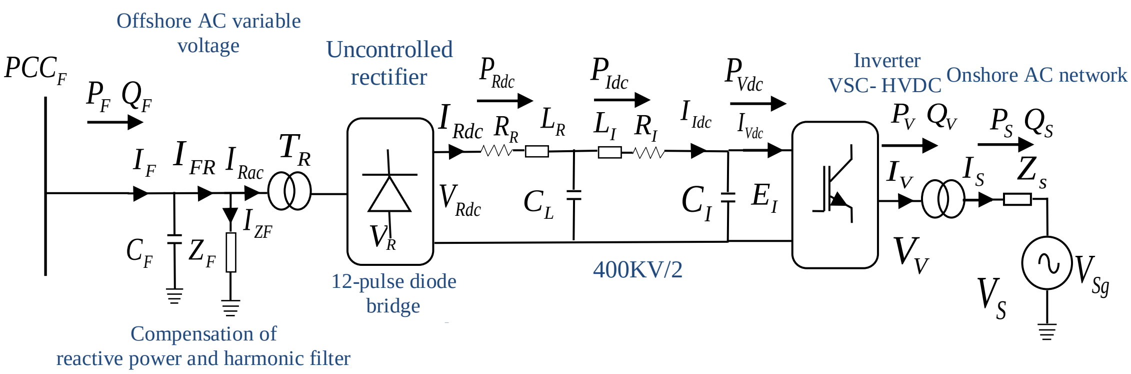


Fig. 4.7: HVDC transmission configuration

4.8.1 The uncontrolled rectifier

A 12-pulse diode uncontrolled rectifier is used in HVDC transmission. This converter is placed between two other controlled elements: the converters (front end) of the wind turbines and the terrestrial inverter VSC, so that the use of the uncontrolled rectifier cannot affect the correct operation of the system. Two transformers, one connected Y-Y and the other Y-Δ, are used to power the bridges with a three-phase voltage offset of 300 between them. Figure 4.8 shows an uncontrolled rectifier, capacitor, and filter bank.

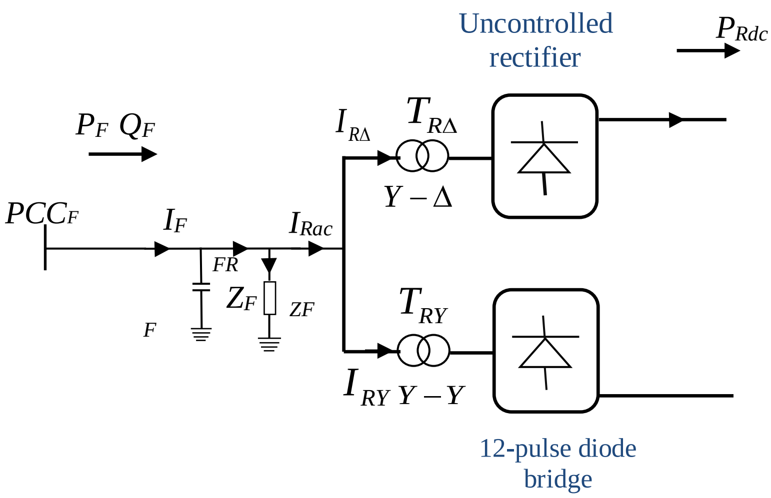


Fig. 4.8: Uncontrolled rectifier, capacitor, filter bank, and transformers

Transformers require a special design because they have to withstand the current harmonics caused by the diodes.

4.8.2 Submarine cable

A submarine cable is used to transport electricity from the offshore station to the land station. The cable is modeled using an equivalent DC transmission T-line as shown in Figure 4.9. The cable is used for a voltage of 400 kV and an admissible power is about 800 MW.

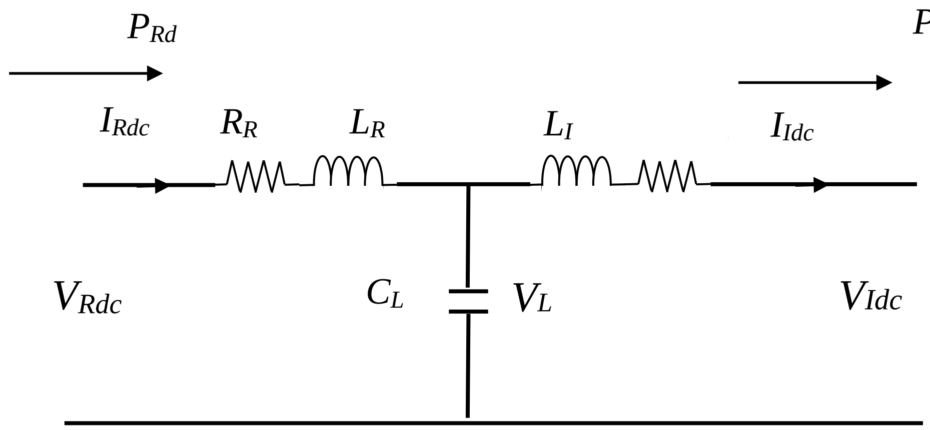


Fig. 4.9: Model of the submarine "T" cable

4.8.3 The HVDC-VSC inverter

A common configuration for a three-phase forced-switching VSC converter using IGBT valves with antiparallel diodes is shown in Figure 4.10. Each bridge arm can conduct current in both directions due to the unidirectional offered by the diodes and the voltage polarity on each IGBT and diode switch combination. A change in the direction of the power flow can now be achieved by changing the direction of the direct current. This is done by changing the DC voltage of the opposing converter stations allowing the DC current to flow in the desired direction. The DC source is provided by the DC capacitors which can store a significant amount of energy. Design considerations include active and reactive power capacity, harmonic injection limits, valve switching losses, and cost implications [25].

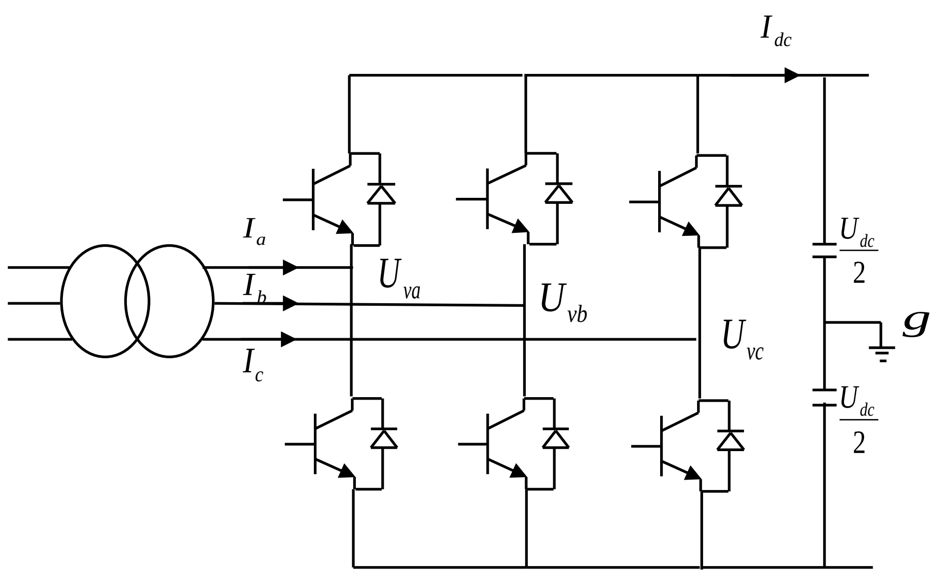


Fig. 4.10: Basic VSC circuit layout

For two interconnected AC systems, the active and reactive power flow is determined by the connection impedance as well as the magnitude and angle between the two voltage vectors. In this case, the VSC diagram represents a voltage source connected to an AC system through the combined impedances of the converter transformer and the series inductor as shown in Figure 4.11:

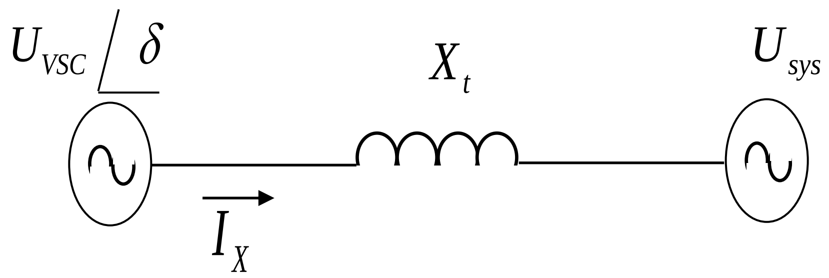


Fig. 4.11: Relative angle of voltage and impedance

The actual power P flowing from the converter to the AC system is given by the relationship:

$$p = \frac{U_{sys} U_{VSC}}{X_t} \sin(\delta) \qquad (4.19)$$

The reactive power that will be exchanged between the VSC and the system is given by the following relationship:

$$Q = \frac{U_{VSC}\left(U_{VSC} - U_{sys}\cos(\delta)\right)}{X_t} \qquad (4.20)$$

From these equations it can be seen that for no voltage angle difference, the real power is zero and the reactive power is determined by the difference in voltage magnitudes.

If $U_{sys} > U_{vsc}$ Q is less than zero and implies inductive operation (VSC absorbs reactive power).

If $U_{vsc} > U_{sys}$, Q is greater than zero and implies capacitive operation (VSC delivers reactive power to the grid).

For equal magnitudes of voltage, the reactive power is zero and the real power is determined by the voltage angle between the two vectors. If $\delta > 0$, power flows from VSC to AC system (inverter operation) and if $\delta < 0$, power flows from AC system to VSC (rectifier operation).

From the active and reactive power flow equations (4.19) - (4.20) it has been shown that four quadrant power control is possible and although active and reactive power can be controlled almost independently, there is a some measure of coupling introduced by the VSC scheme itself, as well as the connected AC systems. For reactive power control, the modulation index controls the amplitude of the AC voltage and the flow of reactive power and the ignition timing of the valves in relation to the AC side voltage determines the phase angle of voltage and power flow. For the voltages and currents shown in Figure 4.12, the converter equations can be defined:

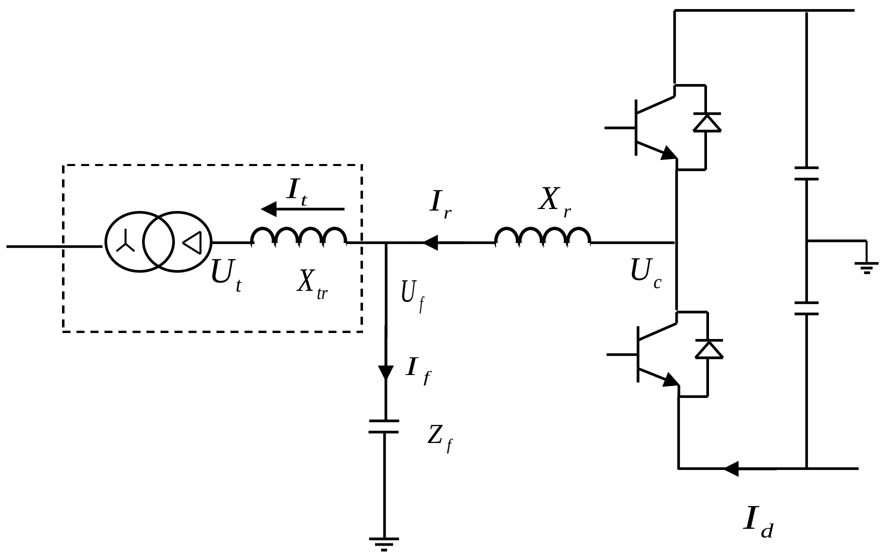


Fig. 4.12: Equivalent diagram of the VSC circuit

The voltage of the converter is given by the relation:

$$U_c = U_f + X_r I_r \qquad (4..21)$$

Where U_f is the AC filter node voltage, X_r is the reactance of the converter inductor and I_r is the current through the converter inductor.

The current I_r is given by the relation:

$$I_r = I_t + I_f \qquad (4.22)$$

where I_t is the total current through the transformer of the converter and X_{tr} is the current through the impedance of the filter.

The AC filter node voltage U_f is given by the relationship:

$$U_f = U_t + X_{tr} I_t \qquad (4.23)$$

where is the voltage on the primary side of the converter transformer and is the reactance of the converter transformer.

The filter current is given by the following relation:

$$I_f = \frac{U_f}{Z_f} \qquad (4.24)$$

The converter equations defined in equations (4.21) - (4.24) are represented by a vector diagram in Fig. 4.13.

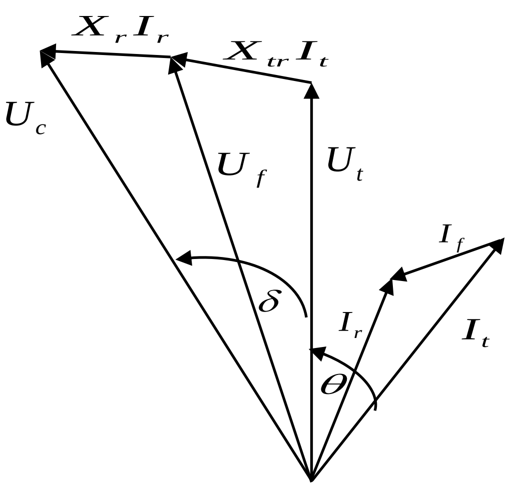


Fig. 4.13: Vector Representation of the VSC Circuit

From figure 4.13, U_c can be equated to converter voltage U_{VSC} and U_t at system voltage U_{SYS} without transformer and tap-changer ratio. The angle δ is the voltage angle across the converter inductance and the transformer impedances and the angle θ is the angle between the output voltage and the current.

The inverter is composed of a voltage converter (VSC), as shown in Figure 4.14. The converter is connected between a capacitance, which stabilizes the DC voltage needed for the VSC, and a step-up transformer.

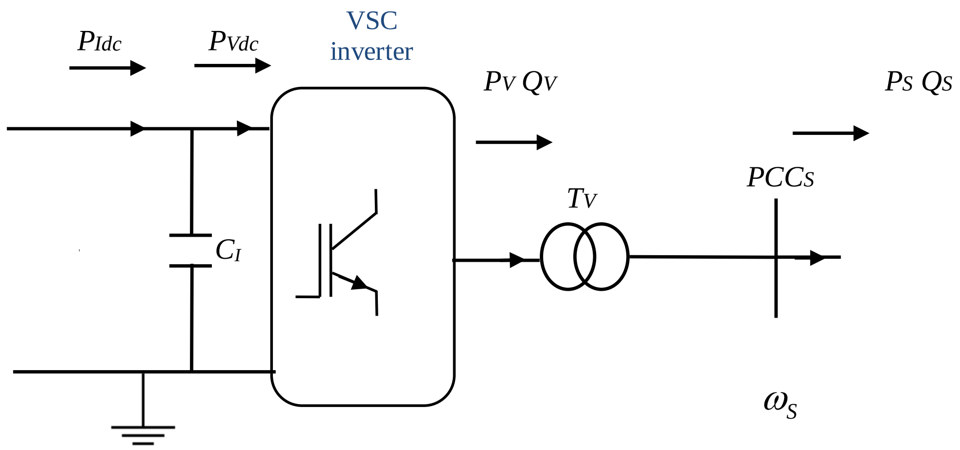


Fig. 4.14: VSC Terrestrial Inverter

4.8.4 The AC terrestrial network

The energy produced by the offshore wind farm and transported by the HVDC link is finally delivered to the onshore network. To characterize the behavior of the network at the PCCS connection point, we use a simplified model consisting of an equivalent Thevenin network, formed by an impedance Z_S and a voltage source V_{Sg} as shown in Figure 4.15 [26]. The impedance is constituted by a resistance R_S in series with an inductance L_S.

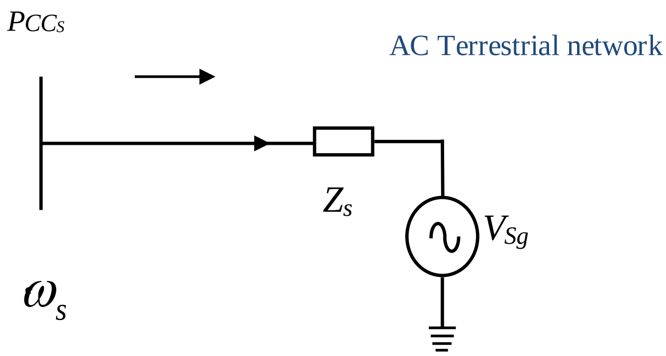


Fig. 4.15: Terrestrial Network Model

4.9 Control of the studied system

This section presents the design of control strategies for an offshore wind farm connected to the HVDC transmission system consisting of a diode rectifier and a VSC inverter. The behavior of the components of the whole system is evaluated. Control strategies that ensure a good behavior of the system under short circuits applied in both sides of the AC networks are proposed.

In addition, surge protection systems are added to the turbine's dual converter and the VSC inverter of the HVDC link, in the form of dynamic braking resistors.

The main purpose of the control system used is to let the offshore wind farm produce the maximum amount of active power at all times and to let the HVDC transmission system ensure that the AC grid has stable operating conditions with reduced fluctuations of voltage and frequency. This is achieved through the following control objectives:

- The speed of the wind turbine is controlled by varying the pitch angle;
- The converter on the generator side of the wind turbine controls the DC voltage;
- The converter on the AC grid side of the wind turbine controls the frequency and another quantity, which can be the grid voltage or the power delivered by the wind turbines;
- The offshore rectifier of the HVDC link is not controlled;
- The VSC shore inverter of the HVDC link ensures stable operating conditions for the offshore converter by controlling DC DC voltage and reactive power.

4.9.1 Control strategies

The control system of the HVDC system connected to the wind farm has at its basic level an internal fast current regulation loop controlling the AC currents. The AC current references are given by the external regulators. Slow external regulators contain DC voltage regulator, AC voltage regulator, active power regulator, reactive power regulator and frequency regulator. Therefore, the active current reference can be obtained from DC voltage regulator, active power regulator or AC voltage regulator. On the other hand, the reactive current reference can be derived from the reactive power regulator or the frequency regulator.

It is obvious that the regulators cannot be used at the same time. The choice of the different types of external regulators is made according to the applied case.

In our application case, for HVDC transmission based on diode rectifier and VSC inverter, the system is used to supply power from offshore wind farm and the active power flow is unidirectional because the offshore side supplies active power to the land side and not vice versa. In the HVDC link, as shown in Figure 4.16, the diode rectifier is uncontrolled and the control of the terrestrial inverter VSC regulates the DC voltage and reactive power. For the offshore wind turbine, the generator side converter regulator controls the DC DC voltage with the active current equal to zero, while the AC grid side converter regulator of the wind turbine maintains the AC voltage and frequency. The speed of the wind turbine will be assumed constant, therefore no variation on the pitch angle as shown in Figure 4.17. In the following sections, this control strategy will be described in detail.

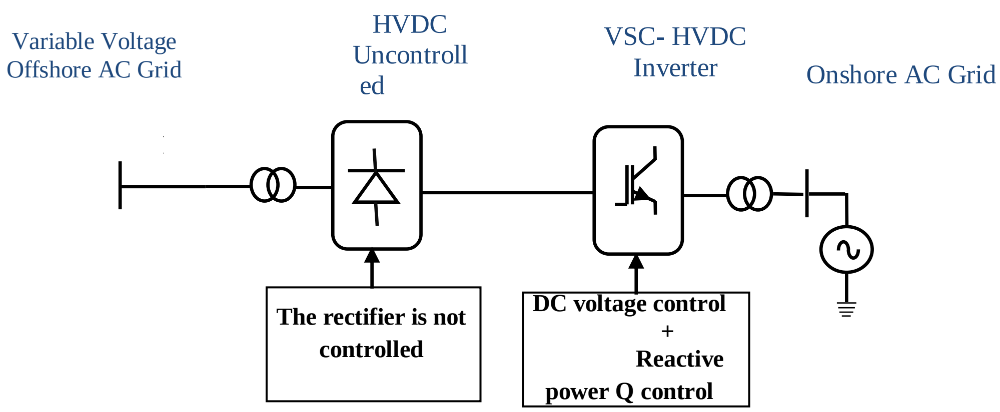


Fig. 4.16: HVDC-(Diodes-VSC) Overall Transmission Control System

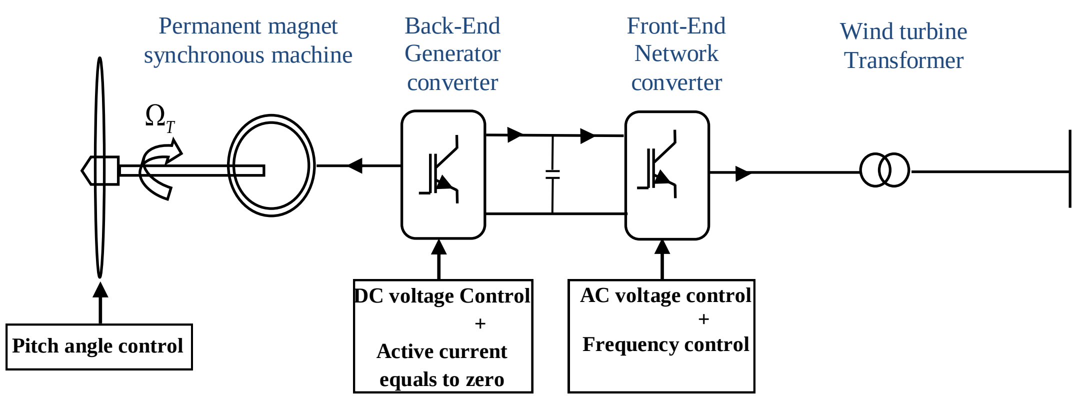


Fig. 4.17: Global Equivalent Offshore Wind Farm Control System

4.9.2 Generator Control and DC Voltage Converter Control

The control of the synchronous generator with permanent magnets is carried out on the d-q axes oriented to the magnetic field of the rotor and it is desired that the torque angle remains constant and equal to 90^0 [27]. For this reason, the reference current is zero, which makes the expression for the mechanical torque as follows:

$$T_R \approx -3p\lambda_m I_{Giq} \qquad (4.25)$$

Thus, the torque per unit current is maximum and it is controlled only with the current q. For dual current control, the input voltages can be taken from the equations:

$$u_{Gd} = V_{Gd} + \omega_G L_{Gq} I_{Gq} \qquad (4.26)$$

$$u_{Gq} = V_{Gq} - \omega_G \left(L_{Gd} I_{Gd} - \lambda_m \right) \qquad (4.27)$$

Then the dynamics of the generator can be written as follows:

$$u_{Gd} = R_G I_{Gd} + L_{Gd} \frac{dI_{Gd}}{dt} \qquad (4.28)$$

$$u_{Gq} = R_G I_{Gq} + L_{Gq} \frac{dI_{Gq}}{dt} \qquad (4.29)$$

The resulting system is a first-order system and can be controlled by a PI controller in the d-q synchronous axes. The generator converter (back-end) is responsible for controlling the generator currents, making it easier to add limits to these currents. Limiting currents is of great importance to maintain component integrity, especially in the event of faults in the system. In front of the internal current loop, another slow regulation loop is used to control the voltage of the link's double converter. Neglecting the losses in the generator of the converter:

$$-3\left(V_{Gd} I_{Gd} + V_{Gq} I_{Gq}\right) = U_{dc} I_{dc1} \qquad (4.30)$$

The voltage dynamic is defined by the DC link capacitance equation and can be expressed as:

$$I_{dc1} - I_{dc2} = C_{dc1} \frac{dU_{dc}}{dt} \qquad (4.31)$$

Assuming the field current reference is set to zero , then:

$$-3V_{Gq}I_{Gq}=U_{dc}I_{dc1} \qquad (4.32)$$

So we can write equation 4.32 as follows:

$$-3V_{Gq}I_{Gq}=C_{dc1}U_{dc}\frac{dU_{dc}}{dt}+U_{dc}I_{dc2} \qquad (4.33)$$

We can define the following expression as a mathematical artifice:

$$\frac{dU_{dc}^{2}}{dt}=2U_{dc}\frac{dU_{dc}}{dt} \qquad (4.34)$$

We can therefore write equation 4.33 as follows:

$$\frac{dU_{dc}^{2}}{dt}=-\frac{1}{C_{dc1}}\left(6V_{Gq}I_{Gq}+2U_{dc}I_{dc2}\right) \qquad (4.35)$$

In order to perform dynamic decoupling, the following expression is defined:

$$U_{U_{dc}}=-\frac{1}{C_{dc1}}\left(6V_{Gq}I_{Gq}+2U_{dc}I_{dc2}\right) \qquad (4.36)$$

Therefore, the dynamic of U_{dc}^2 is reduced to the following expression:

$$U_{U_{dc}}=\frac{dU_{dc}^{2}}{dt} \qquad (4.37)$$

The corresponding transfer function can be defined as follows:

$$U_{dc}^{2}=\frac{1}{s}U_{U_{dc}}(s) \qquad (4.38)$$

According to Equation 4.36, it is possible to tune U_{dc}^2 to the desired values using the generator current reference as follows:

$$I_{Gq}=-\frac{C_{dc1}}{6V_{Gq}}U_{U_{DC}}-\frac{U_{dc}I_{dc2}}{3V_{Gq}}=-\frac{C_{dc1}}{6V_{Gq}}\left(U_{U_{dc}}+\frac{2U_{dc}I_{dc2}}{C_{dc1}}\right) \qquad (4.39)$$

Where Uu_{dc} is the output of the PI controller used in the control loop of U_{dc}^2 . Also, the torque current reference of the generator I_{Gq} has been limited, so the generator will never run in the motorization region. The proposed control loop of is shown in Figure 4.18. [28].

If the voltage U_{dc} remains constant, the power P_G delivered by the generator will follow the variations in power P_w delivered by the network which is connected to the P_{CCF} common connection point. This result allows the use of the grid converter of the wind turbine to follow the maximum power point.

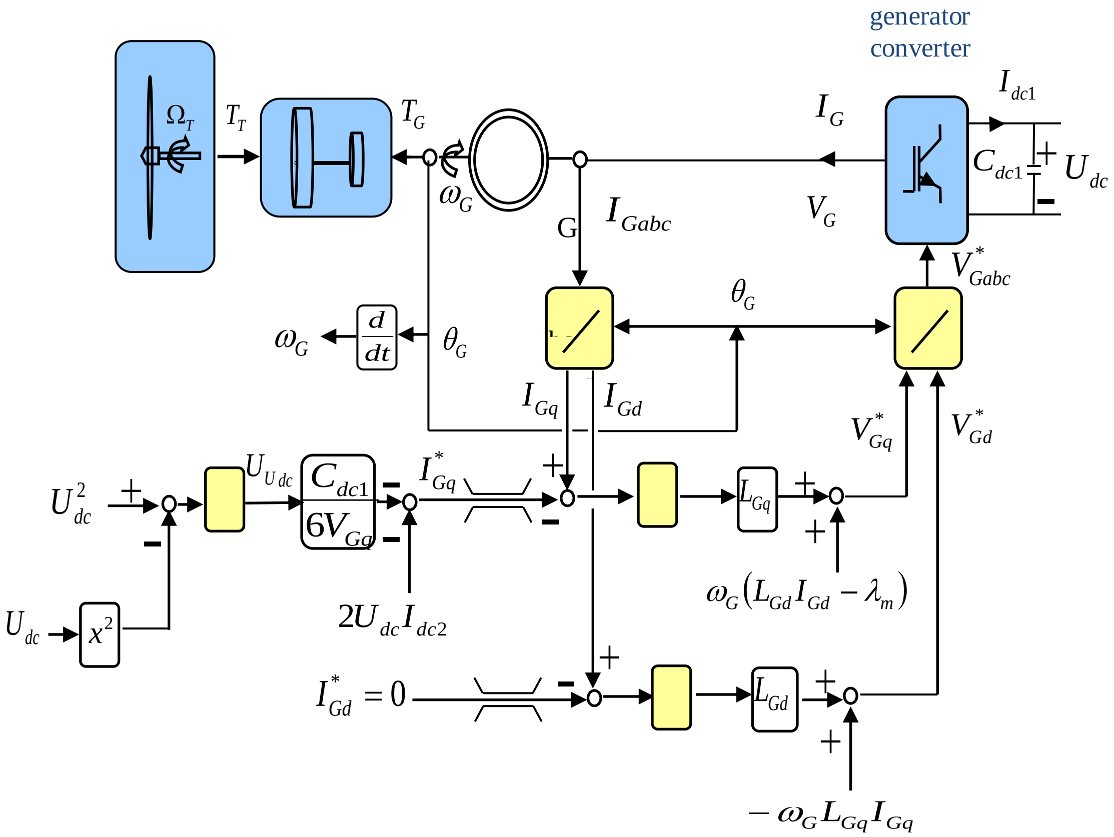


Fig. 4.18: GSAP Generator Converter Control Block Diagram

4.9.3 Control of alternating voltage and frequency of the AC offshore network

The following set of equations can be derived from the five network-connected grouped models:

$$\frac{d}{dt}I_{Wdi} = -\frac{R_{TWi}}{L_{TWi}}I_{Wdi} + w_F I_{Wqi} + \frac{1}{L_{Twi}}V_{Wdi} - \frac{1}{L_{TWi}}V_{Fd} \quad (4.40)$$

$$\frac{d}{dt}I_{Wqi} = -w_F I_{Wdi} - \frac{R_{TWi}}{L_{Twi}} I_{Wqi} + \frac{1}{L_{TWi}} V_{Wqi} \quad (4.41)$$

The result is therefore a first-order system that can be controlled by a PI Regulator. Figure 4.19 shows the control of the d-q currents of the network converter. The total generated power is divided into m energy sources. It is therefore necessary to define a participation coefficient for each group according to its nominal power. This participation coefficient will be defined for each group as follows:

$$K_{dqi} = \frac{Rated\ \ power\ of\ \ the\ i^{th}\ \ group}{Overall\ \ power\ of\ \ the\ offshore\ wind\ \ farm} \quad (4.42)$$

Noted that $K_{di} = K_{qi}$

and

$$\sum_{i=1}^{m} K_{dqi} = 1 \quad (4.43)$$

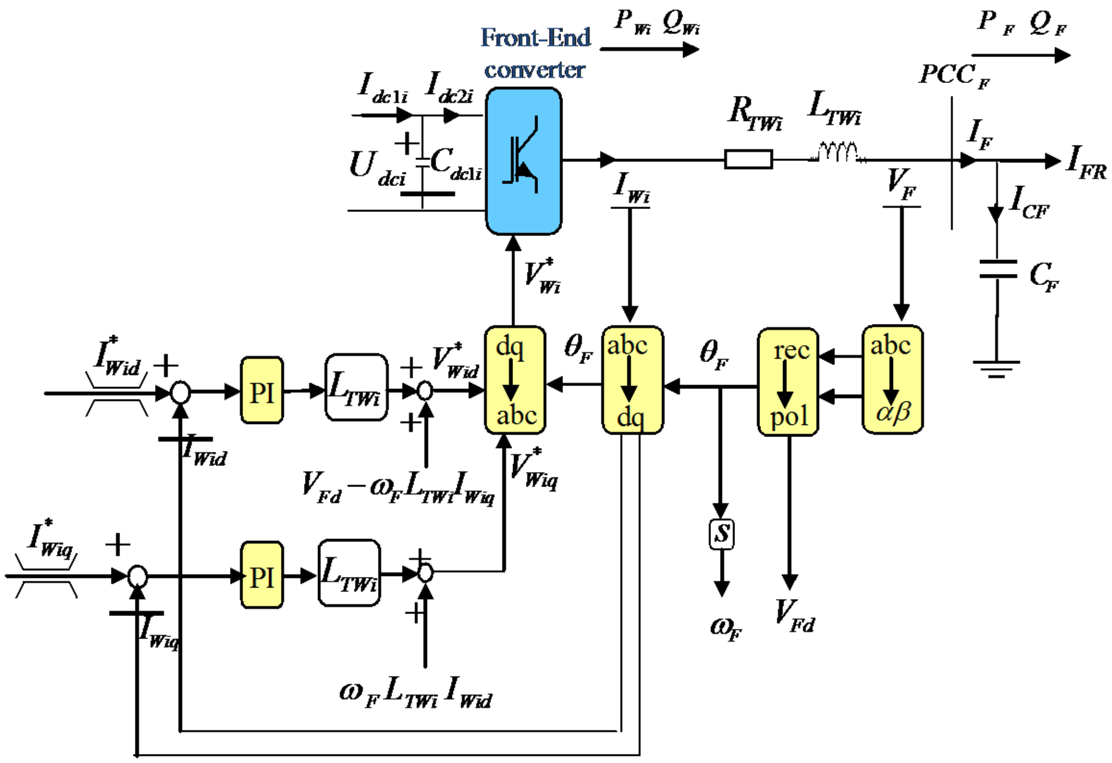


Fig. 4.19 : Current control block diagram

To control the voltage (amplitude) and frequency of the offshore network, capacitor dynamics are used. In this case, if the input variable is set:

$$u_V = \frac{1}{C_F}\left(I_{Fd} - I_{FRd}\right) \tag{4.44}$$

Then, we get a first-order system:

$$u_V = \frac{dV_{Fd}}{dt} \tag{4.45}$$

So the voltage V_{FD} can also be controlled with a PI regulator. On the other hand to control the frequency, a P regulator can be used, so that:

$$I_{Fq} = C_F V_{Fd} \omega_F + I_{FRq} \tag{4.46}$$

As the point P_{CCF} the voltage and frequency are common to all wind turbines, a distributed control is used so that the currents I_{Fd}, I_{Fq} are supplied by all the wind turbines, which is done in proportion to its nominal power control:

$$I^*_{Wdi} = K_{di} I^*_{Fd} \tag{4.47}$$

$$I^*_{Wqi} = K_{qi} I^*_{Fq} \tag{4.48}$$

Figure 4.20 shows the voltage and frequency control loops of the AC offshore grid, including the terms of the protections.

It is necessary to centralize the integral term of the voltage error and this requires the use of communications between wind turbines. Contrary to what is usual in AC electrical systems, in this case the topology and behavior of the C_F capacitor determines that the active current I_{wid} controls the AC voltage and the reactive current I_{wiq} controls the frequency.

In Figure 4.20 P_{Giopt} is the optimum power delivered by the wind turbine. This power is derived from the optimum power characteristic of the wind turbine [29]. This power can be given by:

$$P_{Giopt} = K_{opt} \Omega_T^3 \tag{4.49}$$

Where Ω_T is the speed of the wind turbine, K_{opt} is an optimum constant that depends on the physical characteristic of the wind turbine rotor and the air density.

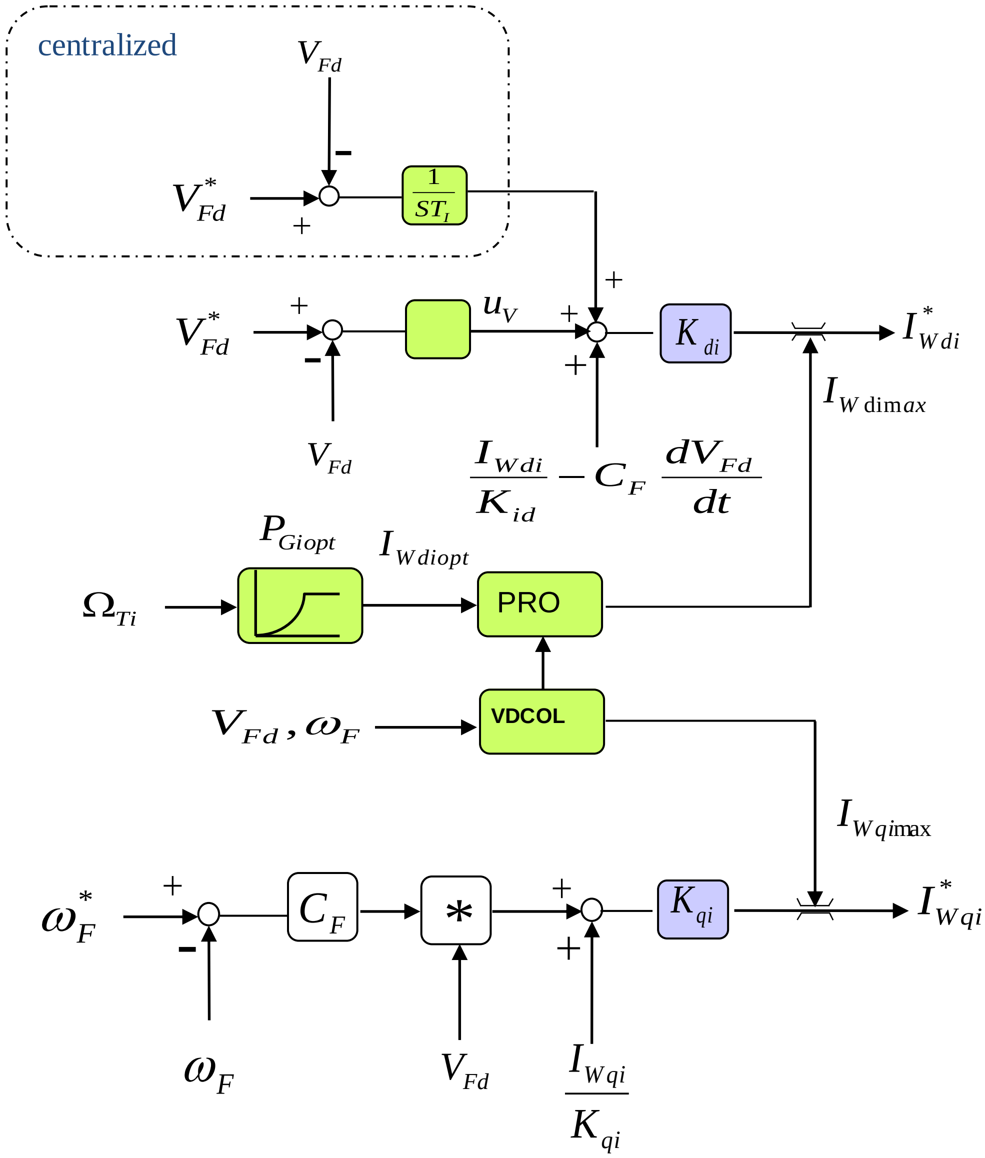


Fig. 4.20: Offshore Grid Voltage and Frequency Control Diagram

When the system is operating under normal conditions, the control described allows each wind turbine to obtain additional work at the point of maximum power. For this, it is used as a reference voltage $V_{Fd} = 1.1$ pu and the current is limited to a maximum value I_W which is given by the optimum wind power in Figure 4.20. Although, because of this, the voltage control is lost, so it does not undergo large variations, since the HVDC rectifier couples this voltage with the DC voltage:

$$V_{Rdc} = \frac{3\sqrt{6}}{\pi} BNV_{Fd} - \frac{3}{\pi} B\omega_F L_{TR} I_{Rdc} \qquad (4.50)$$

This DC voltage is regulated by the inverter of the HVDC link. The VDCOL block limits the currents during short circuits in the offshore network when the V_{Fd} voltage is reduced.

4.9.4 VSC terrestrial inverter control

The HVDC link inverter consists of a VSC converter. The control system consists of an inner loop which represents control of currents and an outer loop represents control of offshore AC voltage and frequency.

4.9.5 VSC terrestrial inverter current

To control the currents of the VSC inverter, a strategy similar to that used in the grid converter of the wind turbine is used, with the difference that the axes are oriented with the voltage V_s , therefore V_{sd} =0. The input voltages are defined:

$$u_{Vd} = \frac{1}{L_V}\left(V_{Vd} + \omega_S L_V I_{Vq} - V_{Sd}\right) \qquad (4.51)$$

$$u_{Vq} = \frac{1}{L_V}\left(V_{Vq} - \omega_S L_V I_{Vd}\right) \qquad (4.52)$$

The following transformer equations:

$$u_{Vd} = \frac{R_V}{L_V} I_{Vd} + \frac{dI_{Vd}}{dt} \qquad (4.53)$$

$$u_{Vd} = \frac{R_V}{L_V} I_{Vq} + \frac{dI_{Vq}}{dt} \qquad (4.54)$$

So, again, the system that can be controlled by a PI regulator. Figure 4.21 shows the current control of the VSC converter. Again, limits are included in the currents to protect system components [30].

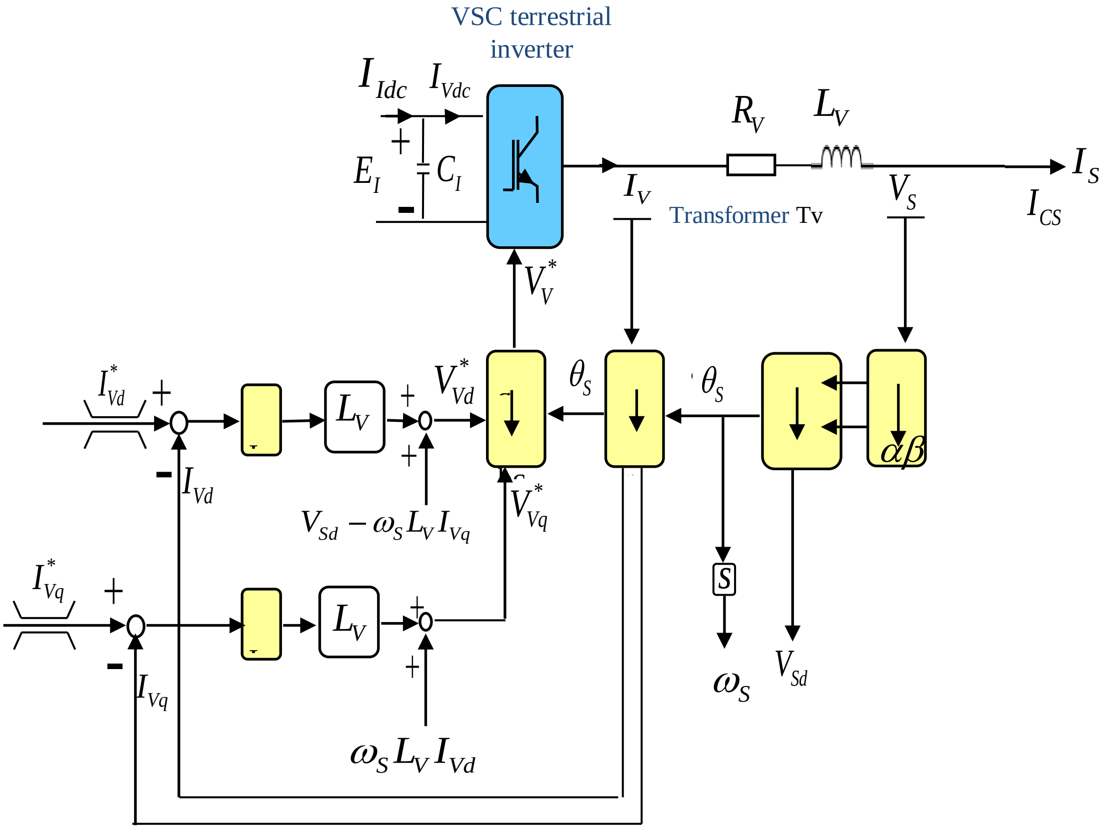


Fig. 4.21: Block Diagram of VSC Converter Current Control

With the two current regulation loops that are implemented, two other external loops will be introduced: a slow loop to control the DC voltage of the HVDC link and another to control the reactive power.

4.9.5.1 DC voltage control of the HVDC link

The voltage control of the HVDC link is designed from the capacitor equation:

$$I_{Idc} - I_{Vdc} = C_I \frac{dE_I}{dt} \tag{4.55}$$

Neglecting the losses in the VSC converter:

$$3\left(V_{Vd} I_{Vd} + V_{Vq} I_{Vq}\right) = E_I I_{Vdc} \tag{4.56}$$

So :

$$E_I I_{Idc} - 3V_{Vd} I_{Vd} - 3V_{Vq} I_{Vq} = \frac{C_I}{2} \frac{dE_I^2}{dt} \tag{4.57}$$

Thus by linearizing the previous equation and assuming: $\Delta V_{Vd} \approx 0, V_{Vq0} \approx 0$ et $\Delta V_{Vq} \approx 0$

So :

$$\Delta P_{Idc} - 3V_{Vd0}\Delta I_{Vd} = \frac{C_I}{2}\Delta\left(\frac{dE_I^2}{dt}\right) \qquad (4.58)$$

Where $P_{IDC} =$.

The input is defined:

$$u_{EI} = \frac{1}{C_I}\left(P_{Idc} - 3V_{Vd0}I_{Vd}\right) \qquad (4.59)$$

And simplifying the notation, then:

$$u_{EI} = \frac{1}{2}\frac{dE_I^2}{dt} \qquad (4.60)$$

A first-order system is obtained. It can be controlled by a PI controller. Figure 4.22 shows the HVDC link voltage control whereVv = 230/ √3 kV.

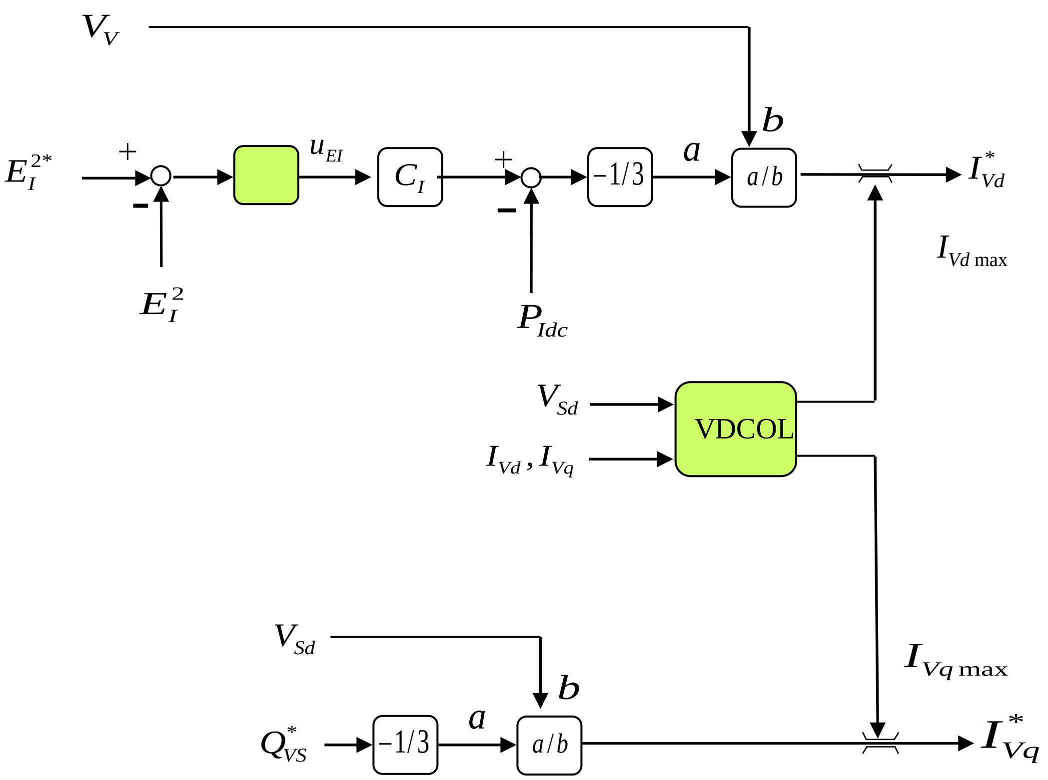


Fig. 4.22 : VSC converter external control block diagram

4.9.5.2 Reactive power control

Reactive power control is also illustrated in Figure 4.21. The expression for the reactive power of the VSC converter injected into the grid is used in d-q coordinates:

$$Q_{VS} = -3V_{Sd} I_{Vq} \tag{4.61}$$

Controlling the reactive current loop allows writing I_{Vq} then:

$$I_{Vq}^{*} = \frac{-1}{3V_{Sd}} Q_{VS}^{*} \tag{4.62}$$

The VDCOL function (Voltage-Dependent Current-Order Limit) has been introduced to limit the currents during a short-circuit in the terrestrial network, when the voltage is dropped.

4.10 Short-circuit protection strategy

In this section, control strategies are explained when short circuits occur in the system which cause over currents in the wind turbine grid converter or VSC inverter. Therefore, it is necessary to introduce protection systems.

4.10.1 Protection of the offshore grid converter

The VDCOL function is introduced in the control system as shown in figure 2.21. In the event of a severe fault on the AC offshore side, it automatically reduces the wind grid currents via the I_{wdmax} and I_{wqmax} limits, and therefore a fast restoration of the transmitted power is ensured. Reducing currents also reduces the reactive power draw on the offshore AC grid.

The current distribution I_{wmax} between the limits I_{wdmax} and I_{wqmax} is as follows:

$$I_{Wq,\max} = \left| I_W \right|_{\max} \tag{4.63}$$

$$I_{Wd,\max} = \sqrt{\left| I_W \right|_{\max}^2 - I_{Wq,\max}^2} \tag{4.64}$$

4.10.2 VSC inverter protection

The same is done for the protection of the terrestrial inverter VSC. When a three-phase short circuit occurs in the AC earth grid, the VDCOL function limits the inverter currents through the limits I_{vdmax} and I_{vqmax} and therefore the system components are protected.

The current distribution between I_{vmax} the limits I_{vdmax} and I_{vqmax} is as follows:

$$I_{Vd,\max} = \left|I_V\right|_{\max} \tag{4.65}$$

$$I_{Vq,\max} = \sqrt{\left|I_V\right|_{\max}^2 - I_{Vd,\max}^2} \tag{4.66}$$

4.11 Conclusion

In this chapter, the main components of the offshore wind farm connected to the HVDC transmission system based on a diode rectifier and a VSC inverter have been presented. The HVDC link uses a diode bridge rectifier that cannot be controlled. This apparent limitation is solved by the control available in the converter of the offshore grid wind turbine.

The VSC voltage source converter was considered ideal, neglecting conduction and switching losses, as well as harmonics. As for the terrestrial network, a simple model is used by Thevenin equivalent, with a relatively high short-circuit power.

The first converter of the wind turbine dual converter which functions as a rectifier was used to adjust the DC voltage of the back-to-back DC link while the second converter was operated to adjust the AC voltage and frequency of the offshore grid. The control of the VSC inverter of the HVDC link was based on the adjustment of the direct voltage of the link and the adjustment of the reactive power on the terrestrial network side. The control strategy used for the offshore converter and the onshore VSC inverter allowed the uncontrolled rectifier of the HVDC link not to affect the correct operation of the system.

The control strategies of the offshore wind farm connected to the HVDC transmission system, allowed to properly manage the transmission of the power of all the five groups at the common coupling point and consequently the transmission of this power to the terrestrial network by means of the system. HVDC. Also, protection strategies have been inserted in the control system through the use of the VDCOL function which acts when a short circuit occurs on the offshore and onshore AC networks.

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