Cooperative Power Sharing control in Multi-terminal VSC-HVDC

by

Hasan Alrajhi Alsiraji

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2014

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The Multi-terminal high voltage DC (MTDC) system is a viable solution for increasing an electrical power generation to interconnect renewable resources into an AC grid. Using a voltage source converter (VSC) allows independent control of a reactive and an active power flow. Based on the literature, there is a trend to implement MTDC into a distribution grid system in the future. Power sharing control among MTDCs is an important and critical consideration from the point of view of stability and operation. MTDC systems consist of multi-input converters (rectifiers) and single or multi-output converters (inverters), thus controlling and operating MTDC systems pose many challenges due to their complexity. Since the DC link in MTDC systems might have several connection nodes all having a common DC voltage value, using the DC voltage value as a common reference for all terminal control loops makes it possible to get a cooperative control performance.

An economical autonomous control to share active power among MTDC systems based on the availability of active power or power management policy is proposed in this thesis. Power sharing among MTDC systems has a priority or sequential procedural problem because of the use of the conventional droop strategy. On the other hand, using predefined or constant power sharing does not provide the available power that can be shared when it is not being consumed by another inverter. The proposed strategy solves these issues using different options. In this thesis, the test system consists of four simulated VSC terminals based on a detailed switching VSC model with two AC voltage levels. The MTDC system is simulated in a PSCAD/EMTDC environment. The simulation results show a significant decrease in operational costs and protection from overloading which had been an issue.

Acknowledgements

First and foremost, all my thankfulness is to Allah who helped and guided me to carry out this work. I would like to thank Professor Ehab El-Saadany for his valuable suggestions, support, encouragement, and patience during my master's program.

Also, I would like to express my thanks to all the members of my research group and a special thanks to Maher and Amr for their recommendations and friendship. Much appreciation goes to my best friend in the University of Waterloo Muhammad Nassar for his friendship.

Moreover, I would like to thank to Prof. Magdy Salama and Dr. Mohamed-Yahia Dabbagh for being readers of my thesis.

I am especially grateful to my family for their patience, prayers, understanding and for believing in me. They have given me much care, love and support throughout the research. I would also like to thank my brother Majed in Australia for his support.

Dedication

This thesis is dedicated to my lovely parents, brothers, and only sister.

Table of Contents

List of Figures

List of Tables

Nomenclature

CHBC	Cascaded H-Bridge Converter
DCC	Diode Clamped Converter
DPC	Direct Power Control
FCC	Fying Capacitor Converter
GSVSC	Grid Side Voltage Source Converters
HV	High Voltage
HVAC	High Voltage Alternative Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
KVL	Kirchhoff's Voltage Law
LCC	Line Commutated Converter
MTDC	Multi-terminal High Voltage Direct Current
PCC	Point of Common Coupling
PI	Proportional-Integral
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
ROW	Right of Way
SPWM	Sinusoidal Pulse Width Modulation
UPFC	Unified Power Flow Control
VMS	Voltage Margin Strategy
VSC	Voltage Source Converter

Chapter 1
Introduction

1.1 Preface

Nowadays, renewable energy is becoming a valuable option to interconnect into traditional AC grid systems. The rationale for this interconnection is the correlation between the increase in electrical power demand and greenhouse emissions. Thus, it is necessary to meet the required electrical power demand while seeking to diminish greenhouse emissions. Although using renewable wind energy may be the best option for some countries like Europe, a more attractive choice for Middle East countries may be to use solar energy. Determining which type of renewable energy to use depends on the countries' location and the weather. In general, wind energy has had exponential installation growth in the last decade due to power electronics development. Utilizing wind farm energy to meet the electrical power demand is increasing, as shown in Figure 1.1 which visualizes the increasing trend of deploying wind energy installations in the world.

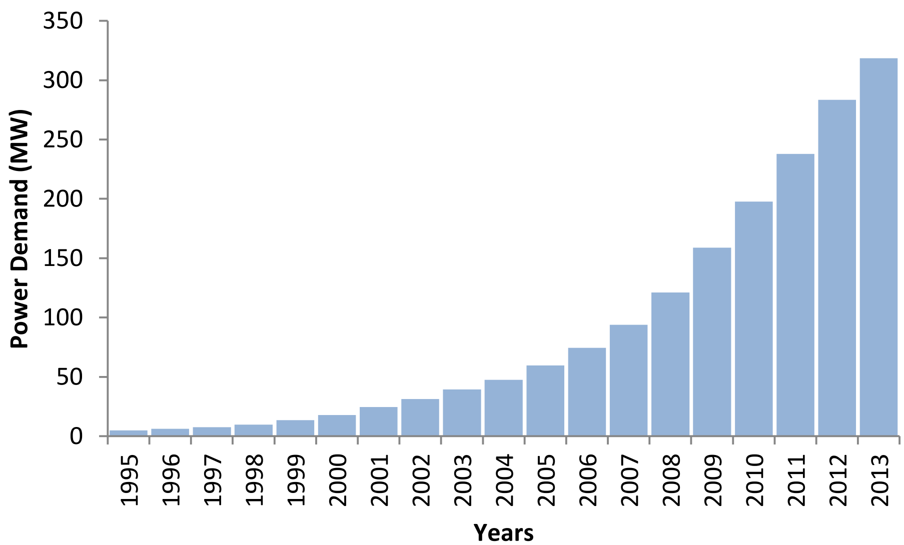


Figure 1.1 Wind Power Capacity Installed Worldwide [1]

Interconnecting renewable energy into classical AC grid systems can be done by using either an AC or DC connection. However, each type of connection has its own advantages and disadvantages. Roughly, comparing the AC connection option with the DC connection option is that for short distances between the renewable source and AC systems, the AC connection option is more reasonable due to the fact that there is not much reactive power flowing because of less capacitance in the transmission lines. On the other hand, using the DC connection option for very short distances is costly due to the construction of inverter stations [2].

1.2 High Voltage Direct Current Verses High Voltage Alternative Current

High voltage (HV) is a preferable option to be used in the interconnection instead of medium voltage because it leads to a decrease in line losses. Using an HVAC or HVDC connection type is a critical decision in interconnecting different AC systems with each other due to the fact that each type of connection has advantages and disadvantages. An in depth comparison between HVAC and HVDC connection types will clarify and justify the final decision in the interconnection among different AC systems or wind energy to an AC system. Two different points of view should be taken into account when choosing between these two options: technical and economical.

In comparing an HVAC versus an HVDC connection it is necessary to show the technical issues with each system. The first point is stability. Although there are three different limits to the HVAC connection type, (voltage regulation limit, stability limit, and thermal limit), the HVDC connection type only has one; the thermal limit. Whereas the HVAC connection type suffers from reactive power loss due to the existence of capacitance and inductance in the transmission lines, there is no reactive power loss in the HVDC connection type. Current carrying capacity is another issue in the HVAC connection type, while this is not a problem with the HVDC connection type. However, the most important technical point to be compared between the HVAC and HVDC connection types is the power flow control. The power flow control in the HVAC connection type requires external equipment such as a phase shifter transformer, and a unified power flow control (UPFC), whereas the power flow control in the HVDC connection type can be managed by changing the current direction or voltage polarity [3].

The economical comparison between the HVAC and HVDC connection types is significant due to the overall cost. The total cost of transmission lines for both HVAC and HVDC connection types involves main equipment and components, right of way (ROW), conductors, insulators, and operational costs which include line losses [4] &[5]. Therefore, building an HVDC system requires less space compared to an HVAC system with the same rating, and for long distance HVDC systems is more economic and less expensive compared to HVAC. The reason behind this is that designing an HVDC system depends on a peak voltage value, while an HVAC system depends upon its R.M.S voltage value. Shown in Figure 1.2 is the comparison between the HVDC and HVAC systems including station cost, line cost, and losses at different distances. Improved energy transmission facilities would introduce to existing power plants a more efficient utilization [6].

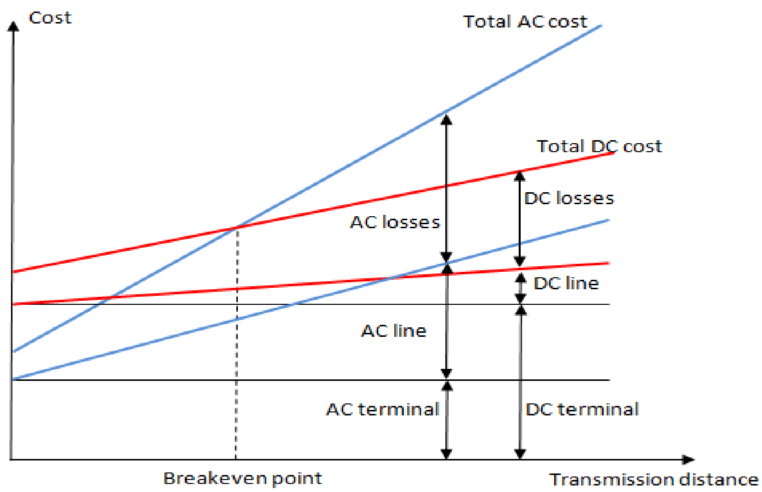


Figure 1.2 HVAC verses HVDC cost [2].

As seen in Figure 1.2, HVDC technology is more economical for long transmission lines in transferring bulk electrical power and it is the best choice for interconnecting two or more different AC systems. This technology is also preferred to HVAC at normal conditions because its control is simple.

Based on the connection type comparison, there is no doubt that HVDC is the best option for interconnecting different AC systems to each other or for interconnecting renewable energy systems to AC systems. Interconnection different AC systems through HVDC links does not require synchronization between AC systems, and in case of a contingency such as a short circuit at the AC side of one system, the DC link connection insulates the effect of the contingency to the other system. Transmission of bulk power over long distance does not need reactive power compensation. Moreover, DC connection types are more practical and economical to be used with offshore wind farm due to cable cost.

1.2.1 VSC verses Line Commutated converter (LCC)

Based on the previous section, considering the DC connection option requires converters to rectify or to invert from AC to DC and vice versa. The development of power electronics equipment provides two options for converters types: voltage source converters (VSCs) , and line commutated converters (LCCs) as shown in Figure 1.3 [7]. Each type of converter has advantages and drawbacks. Therefore, it is important to choose converters that can simplify control methodology and minimize harmonics distortion in order to diminsh the total cost.

In general, the technology of LCC converters depends on thyristor switches, so the optimum operating conditions of thyristors must be met in order to achieve safe operation of the converter. The operating conditions of thyristors are divided between turning on and off-modes. For turning a thyristor on, it must be in a forward bias, and have a sufficiently large current and pulse to help the current flow through the switch, but for turning a thyristor off, it must be in a reverse bias, and the forward current must be below a holding current value. Subsequently, thyristors require low control signals to be in on-mode, but a power circuit to be in off-mode. It is clear that the forced commutation converter type affects the total cost of the converter and it introduces a technical problem: commutation failure. On the other hand, the VSCs technology is based on an insulated gate bipolar transistor (IGBT) that is connected with an anti-parallel diode so the switch can be turned on or off with an external control circuit that has a low voltage level. In other words, VSC is self-commutation technology, so it does not have commutation failure problems like the LCC. The voltage level of the external control circuit is very low compared to the LCC power circuit control, and it is independent from the switch’s current [8].

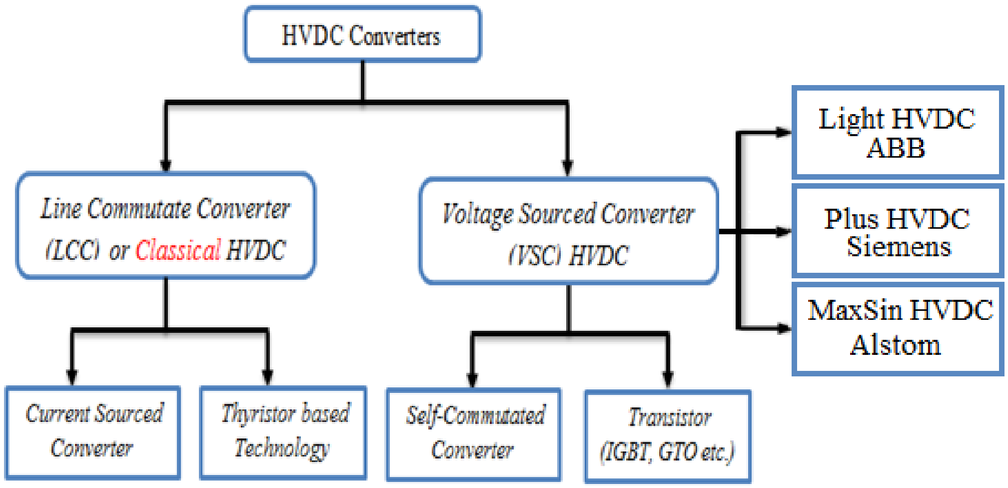


Figure 1.3 Converters' Classification

Since converter types play an important role in implementing multi-terminal HVDC systems, the critical benefits and the radical differences between these types must be taken into account. In fact, due to the increase of electrical power demand, expanding and interconnecting AC power systems are growing dramatically, so referring to [9-14], using VSCs is the optimum choice compared to LCCs due to its advantages. Table 1.1 shows the advantages and disadvantages between VSC and LCC.

Based on section 1.2 and 1.2.1, the decision in this thesis is to consider implementing a multi-terminal high voltage DC (MTDC) voltage source converter (VSC) based system. It becomes a viable solution to interconnect renewable resources into an AC grid or to connect multiple AC systems with each other.

Table 1-1 LCC versus VSC [9-14]

Functionality	Line commutated converters	Voltage source converter
Based on	Thyristors	IGBT's with anti-parallel diodes
Semiconductors	Withstand voltage in both directions	Pass current in both direction
Commercially rated	8.5 kV, 4kAmp	6.5kV, 2kAmp
Works as	A constant current	A constant Voltage
Power flow reversal	Limited by reversing the polarity of DC voltage	Full by changing the polarity of DC current
Harmonics	Higher AC filtering	Lower AC filtering
AC system support	Not available	Available
Reactive power	Consumed and required	Not needed
Load types	Just an active load	Active and passive load
AC systems' stiffness	Should be strong	No influence on the AC voltage
Active and reactive power	Requires more equipment	Independent
Commutation Failure	Possible	Impossible
Black-start Capability	Not available	Available
Implementation of multi-terminal	Difficult due to VDC polarities	No problem
Terminals limits	Just three terminals	No limits
Typical system Losses	2.5%-4.5% of the rated	4.5%-6% of the rated
Power capability	High	Low

1.3 Multi-terminal HVDC VSC Based

HVDC technology is not new. HVDC was first commercially available in 1954 [11]. Applying HVDC on power systems has become a reliable trend. HVDC applications include many options such as asynchronous systems inter-connection, and transmission of bulk power over long distances [12]. However, due to the high amount of power to be collected from wind farms either offshore or onshore, power electronics technology has rated limits. Therefore, building just one terminal is not beneficial and reliable, as it will be too expensive. In addition, during abnormal conditions the outage of the terminal leads to no power flow in the DC link might cause a black out in an AC system due to the giant amount of power suddenly removed. A multi-terminal

HVDC system is the best solution to overcoming these issues, while improving system reliability and decreasing system cost [13].

1.4 The Motivation of the Thesis

The demand for electrical power is globally increasing with a positive slope trend. Interconnecting renewable resources into AC grids is an important and critical factor to be considered based on stability and operational points of view. However, using DC connection types is more practical and economical for offshore or onshore wind farms. The output of the wind generator has a variable frequency due to the variation of wind speed, so it is not feasible to interconnect this variable frequency resource directly to the AC grid without rectification or modification.

Transmitting offshore wind power into AC systems requires an AC to DC converter due to DC links advantages such as no reactive power compensation needed, and less cable requirement compared to an AC connection. Therefore, collecting a bulk amount of wind power introduces the need for multi-terminal HVDC (MTDC) because of the wind farm locations, the power electronics cost and power rated limitations. On the other hand, sharing the wind power among multi-terminals is an important issue that needs more investigation. Moreover, many projects and studies are underway to integrate offshore wind farms through MTDC into AC grids such as the European offshore wind farms [14]. Furthermore, in Canada, wind farms will provide more than 20% of electrical power demand by 2025 [15].

Although many studies were focusing on the power sharing control among MTDC systems using different strategies, not all previous work considered the additional available power that can be shared among MTDC systems. However, there is no consideration of the priority to share the active power among MTDC converters economically[16]. Therefore, using the variable droop control is based on a priority for a dominant inverter to be served first with the remaining power going to the others. In case of power variation, the dominant terminal will get its order of power first, which may result in the other inverters receiving an irregular amount of power. This thesis will propose a solution for this issue by sharing power among MTDC systems based on an agreement and power management policy.

1.5 Thesis's Objectives

This research work has several objectives that can be categorized as follows:

- Analysing and understanding the concept of voltage source converter (VSC) and its behavior.
- Implementation of an MTDC system and design with its control based on a detailed switching VSC model in a PSCAD/EMTDC environment.
- Proposing cooperative control strategy for power sharing in MTDC systems that includes equal power sharing in case of equally rated terminals, and the additional available power that can be shared.
- Sharing power among MTDC systems economically.
- Interconnecting different AC systems through MTDC systems.

1.6 Thesis's Outline

The organization of this thesis consists of five chapters as follows:

- Chapter #2 delivers a literature survey of the voltage source converter (VSC) concept, operation, and control strategy. Moreover, the topologies of VSC in high power applications such as HVDC are discussed. Power sharing among a multi-terminal HVDC (MTDC) depends on an outer loops control, so several strategies are compared and discussed briefly.

- Chapter #3 introduces the methodology of a cooperative strategy and it explains the proposed cooperative strategy of power sharing among the MTDC systems and its implementation. Also, this chapter presents the MTDC system configuration and its parameters.

- Chapter #4 shows a verification of the proposed strategy based on a simulation test. In this chapter, four different cases are studied and they are divided into two categories which are: with communication, and with communication failure. Moreover, in this chapter adaptive and conventional droop are investigated to demonstrate the power sharing problem.

- Chapter #5 summarizes the conclusions of the proposed strategy and recommends the future work needed on this topic.

Chapter 2
Literature Survey

2.1 Introduction

This chapter provides an introduction and the state of art of VSC followed by the discussion of the main gap in previous research works on power sharing among MTDC terminals.

2.2 VSCs' Concept

Analysing the operation of buck and boost DC current converters leads to an understanding of the concept of VSC, due to the fact that VSC is a combination of these converters [17]. The boost current converter consists of an inductance, a diode, and a switch which is similar to a buck current converter, but with a different construction as shown in Figure 2.1.

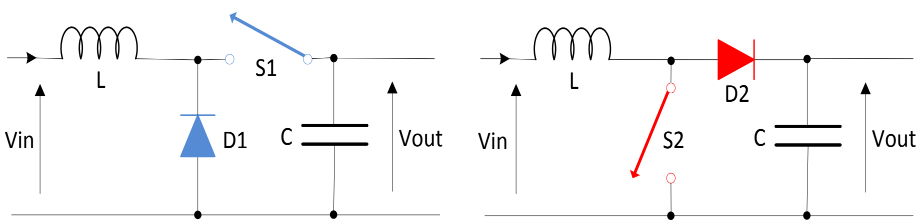


Figure 2.1 Circuit Diagram of Boost and Buck Current Converters

These types of converters have different values of output voltages making it simple to interchange power between the output and the input terminal. The essential factor in controlling these types of converters is a switching signal. Thus, the relationship between the input and output voltages for both converters are different, and they depend on a switching signal called a duty ratio (D) as shown in (2.1) & (2.2) [8].

$$V_{in} = D_{on} \times V_{out} \tag{2.1}$$

$$V_{in} = (1 - D_{off}) \times V_{out} \tag{2.2}$$

Equations (2.1) and (2.2) show the relationship of the voltages of a boost and buck current converters respectively. Therefore, the value of D can be easily determined based on the switching signal period as depicted in Figure 2.2.

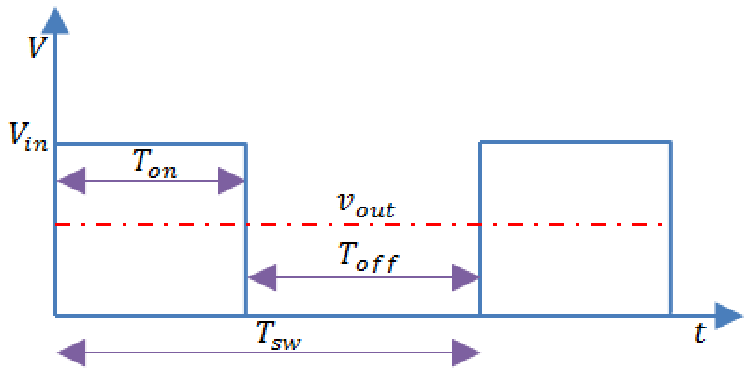


Figure 2.2 Switching Pattern

From Figure 2.2, the duty ratio for both converters is obtained as follows:

$$D_{on} = T_{on}/T_{sw} \quad (2.3)$$

Where $T_{on} = 1/f_{sw}$, and f_{sw} is switching frequency.

It is clear that power flow through a boost and buck current converter can be controlled by varying the width of T_{on}. The boost and buck current converters have unidirectional power flow; however, merging these converters with each other has the benefit of a bidirectional power flow as depicted in Figure 2.3. In fact, there is a condition for the modified converters to be bidirectional; that is the relationship between the input and output voltage is necessary to be equal in terms of D_{on} and D_{off} as written in (2.4).

$$V_{in} = D_{on} \times V_{out} = \left(1 - D_{off}\right) \times V_{out} \quad (2.4)$$

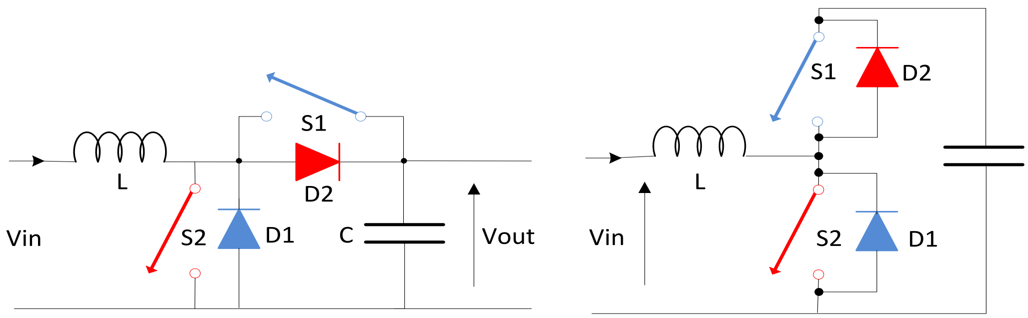


Figure 2.3 Combining of Boost and Buck Current Converter

Referring to [17]&[18], dividing the output voltage into half value through splitting the output capacitor with a ground point leads to a half bridge converter as shown in Figure 2.4.

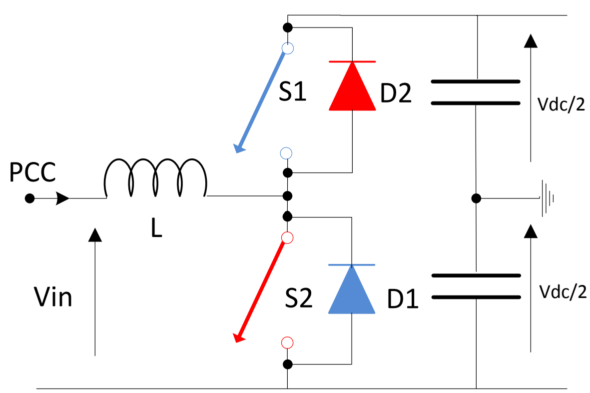


Figure 2.4 Half Bridge Converter Circuit

Using sinusoidal pulse width modulation will provide at point of common coupling (PCC) an AC voltage as shown in Figure 2.4. This technique of gating the switches is called a sinusoidal pulse width modulation which is considered in this thesis. Connecting three legs of a half bridge converter in parallel provides a three phase bidirectional converter that is called a voltage source converter (VSC). This combination of the half bridge converter has a fixed DC voltage polarity, so the direction of the current controls the power direction.

This type of VSC consists of two AC voltage levels as shown in Figure 2.5, and the fundamental component of the square pulses is a sinusoidal signal that is a phase voltage. The two levels of AC voltage topology are considered in this thesis.

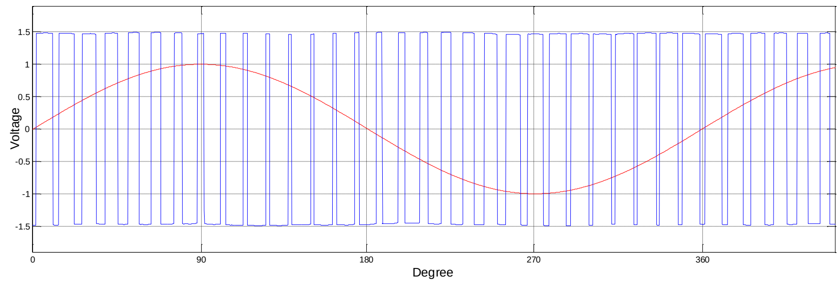


Figure 2.5 Two AC Voltage Levels

Nevertheless, there are three different types of VSC with multilevel AC voltages, namely the flying capacitor converter (FCC), the cascaded H-Bridge converter (CHBC), and the diode clamped converter (DCC). Each type of these VSC have some advantages and disadvantages as shown in table 2-1.

Table 2-1 A Brief Comparison of the Different Types of VSC [19]

Type of VSC	Advantage	Disadvantage
FCC	• It is available to balance capacitors' voltage level. • It is easy to control both reactive and active power.	• Tracking voltage level for capacitors needs a complex control. • Transferring active power and efficiency are poor.
CHBC	• It is simple to regulate DC bus. • Soft-switching is possible to use to avoid snubber circuit losses.	• It is required communication • It is necessary to have a separate DC source for active power conversion.
DCC	• Sharing DC voltage between inverter legs reduces the capacitance required for an inverter. • Pre-charge capacitors can be used.	• Flowing active power is hard for one inverter. • The required number of clamping diodes depends on the number of levels.

2.3 VSC Operation

The goal of using pulse width modulation with a sinusoidal signal technique is to control the AC voltage frequency, and to mitigate the voltage's harmonics. The essential concept of sinusoidal pulse width modulation (SPWM) is to compare a sinusoidal signal (modulation index) with a triangular signal through a comparator to get pulses with different widths. Thus, turning on or off a converter's switches will depend on these pulses as shown in Figure 2.6. When the modulating index is greater than the triangular signal, the top switch in the bridge converter will be turned on corresponding to the phase voltage; on the other hand, when the modulating index is less than the triangular signal, the bottom switch in the bridge converter will be turned on.

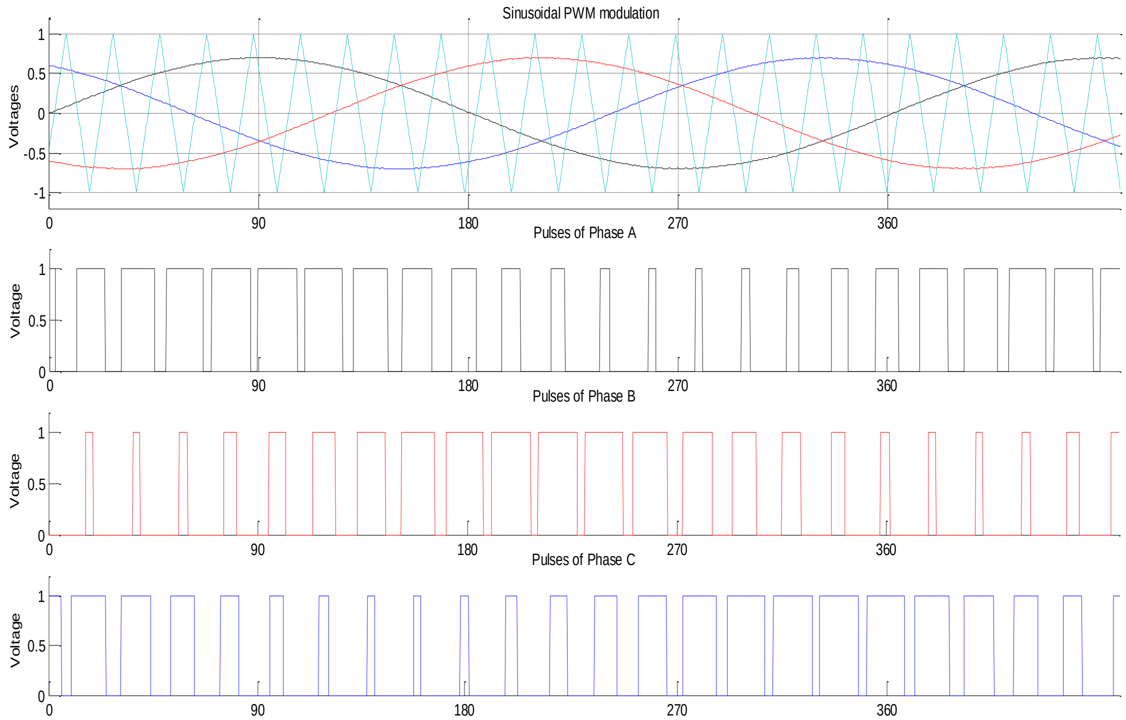


Figure 2.6 Sinusoidal Pulse Width Modulation

As mentioned in section 2.1, VSC has a bidirectional power flow, so the change of phase voltage angle across the inductor controls the active power flow through the VSC, while the reactive power will be controlled by changing the AC voltage's magnitude [17].

2.4 VSC Control Strategies

A phase voltage difference between the two points on the AC side of the VSC which are point of common coupling (PCC) and point of converter connection (CONV) is responsible for active power transferring. Therefore, the position of the phase voltage (δ) will determine the direction of power flow. It is clear that if δ is positive, the power flows from the PCC side to the DC side and vice versa. On the other hand, the highest magnitude of the AC voltage will be responsible for controlling reactive power. From Figure 2.7, the definition of the reactive and active powers relationship based on δ and V are shown:

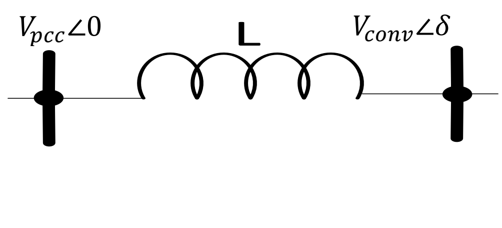


Figure 2.7 AC Line Inductance

Based on Figure 2.7, the active and reactive power equation are shown [20]:

$$P = \frac{|V_{PCC}| \times |V_{conv}|}{wL} \cdot \sin\delta \tag{2.5}$$

$$Q = \frac{|V_{PCC}|^2}{wL} - \frac{|V_{PCC}| \times |V_{conv}|}{wL} \cos\delta \tag{2.6}$$

It is obvious that the active power flow mainly depends on the phase voltage angle. However, the main factor that dominates the reactive power is the voltage magnitude. Based on the literature there are two strategies to control the active and reactive power: direct power control (DPC) [21], and vector control which is the most commonly used.

2.4.1 Direct Power Control (DPC)

This strategy does not depend on a PWM technique, so a VSC will be fired based on the instantaneous difference between the desired and predicted power [21]. In other words, this strategy has different switching periods that means more harmonics. Moreover, there is no inner current control loops to decouple a reactive power from an active power. The control of the active and reactive power is correlated; thus, the deviation in the value of the active power will immediately affect the reactive power. There is no doubt that this strategy does not provide independent power control. Indeed, the DPC is simple to implement, but it is not widely used due to the coupling among P and Q.

2.4.2 Vector Control

This control strategy is used mostly for VSC applications due to the fact that it produces less voltage harmonics than DPC. Also, this strategy allows independent control of a reactive and an active power. The voltage and current vectors during steady state operation stay at a constant value with a small margin of error that can be fixed using a proportional-integral controller (PI). The vector representation quantities of AC voltages and currents can be achieved using Park transformation. Thus, the variable quantities of the AC components transform into direct constant components. Therefore, transforming AC components will follow two steps to get constant components: Clark and Park transformations. In the Clark transformation, the three AC voltages and currents will transform into two stationary coordinates system that is called alpha beta stationary coordinates. In the Park transformation, the two alpha beta stationary coordinates will transform into *dq* rotating coordinates system.

2.4.2.1 Clark Transformation

The three vectors with 120° phase shift of the AC voltages can be transformed to two orthogonal vectors. One of the two orthogonal vectors will align horizontally with the first phase, while the second vector will align vertically on the three vectors as shown in Figure 2.8.

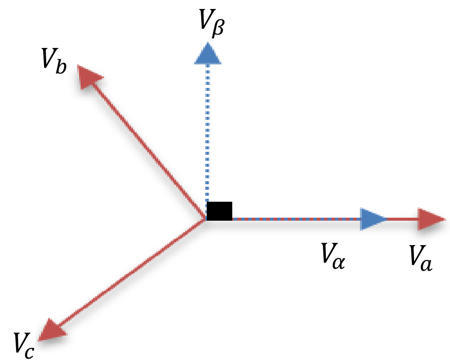


Figure 2.8 Three Phase and Stationary Reference

The three phase voltages vectors V_a, V_b, and V_c can be converted into two vectors in terms of $V_\alpha, and\ V_\beta$ mathematically as follows:

$$\begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} = k \cdot \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{pmatrix} \cdot \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \tag{2.7}$$

In equation 2.7, if the constant value of K is equal to $(2/3)$, it will mean that the magnitude of $V_\alpha, and\ V_\beta$ are equal to the magnitude of sinusoidal signals; on the other hand, if the constant value of K is equal to ($\sqrt{2/3}$) that means the three phase power is equal to the two phase power [22].

2.4.2.2 Park Transformation

Multiplying V_α and V_β that have been taken from the previous section by rotation orthogonal matrix gives V_d and V_q; thus the values of V_d and V_q become constant rotational vectors as shown in Figure 2.9. There is an angle between V_d and V_α that is called the rotor angle (θ).This angle can be found using phase locked loop (PLL). The vectors value of $V_d, and\ V_q$ are given in equation 2.8.

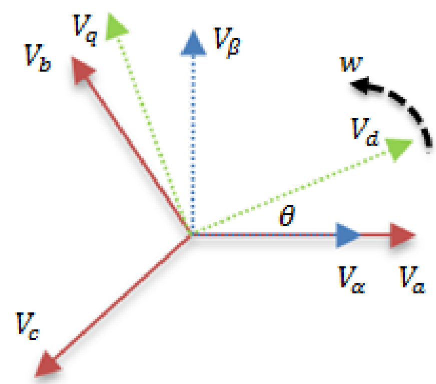


Figure 2.9 d-q Vectors Representation

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = k \cdot \begin{pmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{pmatrix} \cdot \begin{pmatrix} V_\alpha \\ V_\beta \end{pmatrix} \tag{2.8}$$

The dq transformation for the three phase balanced system allows for reduced filter size and independent control of a reactive and an active power.

2.4.3 VSC's Control Stratergies Summary [21]

Using direct power control strategy does not cancel the coupling effect among the electrical control variables; therefore, changing one of the electrical control variables will affect the other control variable. On the other hand, vector control strategy can be implemented using decoupling feed forward control method as mentioned and described in the previous section; which eliminates the effect of the coupling of control variables. Cosequently, vector control strategy is commonly used.

2.5 VSC- HVDC Configurations

The development of power electronics allows a VSC to be used in high power transmission. There are several factors that guide researchers to focus on this area due to instantaneous reversal power, good power quality, and independent active and reactive power control. In fact, in 1997, the operation and control of the first two-terminal VSC based system showed a possible trend to interconnect renewable energies and different AC systems with each other [23]. VSC-HVDC becomes the best option to transfer bulk power and to interconnect different AC systems with each other. Therefore, there are four configurations of VSC that can be implemented to get VSC-HVDC systems: symmetric monopole, asymmetric monopole, bipolar, and series bridge scheme (which is a multi series of asymmetric monopoles at the sending and receiving end) [24]. Choosing a configuration of VSC depends on its advantages; therefore, describing each configuration helps to determine the best configuration option.

2.5.1 An Asymmetric Monopole

An asymmetric monopolar topology contains of a conductor and either a metallic return or ground as depicted in Figure 2.10. This topology suffers from a high rate of corona loss and radio interference, although operating an asymmetric monopole at a negative polarity of DC voltage solves these problems [25]. Nonetheless, the main disadvantage of this topology is that when a fault occurs at a DC link, the system will immediately suffer an outage. It is clear that this topology is not reliable.

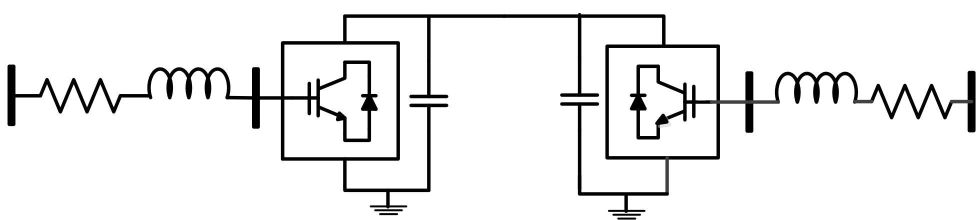


Figure 2.10 Asymmetric Monopolar VSC

2.5.2 A Bipolar

This topology type consists of four converters, so it will increase the cost. Therefore, a bipolar has two conductors, and both of them have a different voltage polarity. The connection point on the same side between converters could be grounded at both ends or at one as shown in Figure 2.11. The merit of both grounded ends allows for independent operation of the converters at the same ends [25]. In other words, during normal conditions there is no current flow through the ground path. In contrast, during a fault, one of the converters will suffer an outage and the second converter will use the ground as a path. This topology type has high rate of reliability, but it is more expensive.

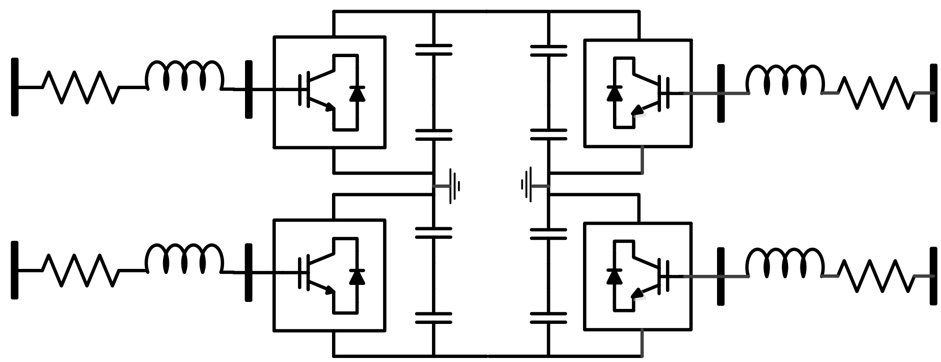


Figure 2.11 Bipolar VSC

2.5.3 Symmetric Monopole

A symmetric monopole has two conductors with different polarity as can be seen in Figure 2.12, and the DC side of this topology is divided into half for the two DC voltage levels [24]. The mid-point at the DC side is grounded, but there is no current flow during normal operation [12]. The main advantage of this topology is that when there is a fault between one of the conductors to the ground, the AC side cannot inject current into the DC side [26]. This topology is environmentally friendly due to the fact that there is no required special grounding. This type of VSC topology is widely and commonly used [24], [27]&[28]. As a result, this topology is more advantageous compared to other topologies, and it will be considered in this thesis.

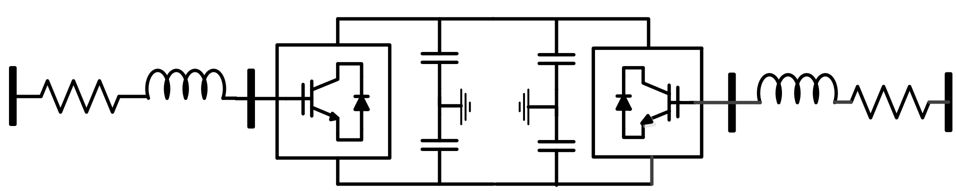


Figure 2.12 Symmetric Monopolar VSC

2.6 Control Design of VSC

A vector control concept provides the ability to control active and reactive power independently as discussed earlier in section 2.3.2. The controller of the VSC consists of two stages which are the inner and the outer controller as shown in Figure 2.13. The inner controller's inputs are fed from the outer controllers that are responsible to provide currents references based on the desired control employed such as the active and reactive power control. The duty of the inner control loops is to prevent overloading during electrical problems and to evaluate the voltage drop value at the AC side.

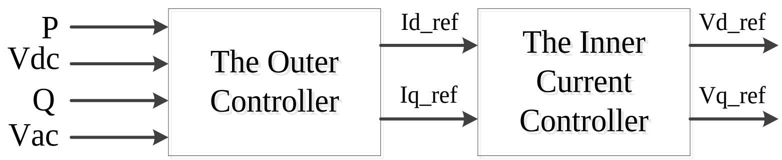


Figure 2.13 Control Structure of VSC

2.7 Mathematical Model of VSC

The vector control implementation of VSC requires developing a dynamic model in the d-q synchronous frame of the VSC converter. Applying KVL at the AC side in Figure 2.14 gives an equivalent differential equation of a voltage drop across the inductance and the resistance in terms of the *abc* coordinate system. On the other hand, the steady state operation of the DC side's power should be equal to the AC side without considering the losses.

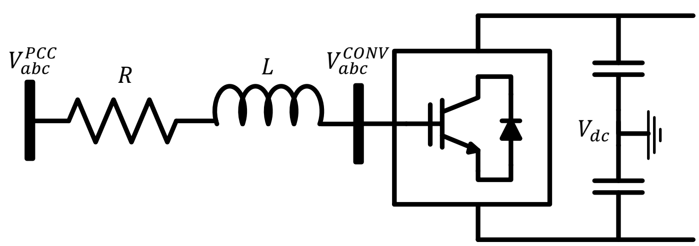


Figure 2.14 Schematic Single Line of VSC

$$\boldsymbol{V_{abc}^{PCC} - V_{abc}^{CONV} = R.\, i_{abc} + L\frac{di_{abc}}{dt}} \tag{2.9}$$

$$\boldsymbol{P_{abc}^{PCC} = P_{dc}} \tag{2.10}$$

Equation 2.9 is responsible for controlling the amount of the VSC's currents at the AC side. Therefore, it is necessary to transform equation 2.9 into the *d-q* synchronous frame in order to achieve a decoupled control of active and reactive power. Using direct Park transformation as follows will give equivalent equations of voltage drop across the AC side based on the *d-q* synchronous frame [29]. The general equation to transform from *abc* to *d-q* is:

$$X_{dq} = M \cdot X_{abc}$$

Where : X_{abc} is the three phase quantities whether voltages or currents.

: X_{dq} is park tansformation quantities.

$$M = \frac{2}{3} \cdot \begin{pmatrix} cos(\theta) & cos\left(\theta - \frac{2\pi}{3}\right) & cos\left(\theta + \frac{2\pi}{3}\right) \\ sin(\theta) & sin\left(\theta + \frac{2\pi}{3}\right) & sin\left(\theta + \frac{2\pi}{3}\right) \\ 0.5 & 0.5 & 0.5 \end{pmatrix} \quad (2.11)$$

Where: $M\ is$ matrix multiplication.

The first term of 2.9 is the AC voltages at point common coupling, so Park transformation can be calculated by rearranging as follows:

$$V_d^{PCC} = \frac{2}{3}\left[V_a^{PCC} cos(\theta) + V_b^{PCC} \cos\left(\theta - \frac{2\pi}{3}\right) + V_c^{PCC} \cos\left(\theta - \frac{2\pi}{3}\right)\right]$$
$$V_q^{PCC} = \frac{2}{3}\left[V_a^{PCC} sin(\theta) + V_b^{PCC} sin\left(\theta - \frac{2\pi}{3}\right) + V_c^{PCC} sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad (2.12)$$

The second term of 2.9 is the inverter's voltages; therefore, Park transformation is similar to 2.12

$$V_d^{CONV} = \frac{2}{3}\left[V_a^{CONV} cos(\theta) + V_b^{CONV} \cos\left(\theta - \frac{2\pi}{3}\right) + V_c^{CONV} \cos\left(\theta - \frac{2\pi}{3}\right)\right]$$
$$V_q^{CONV} = \frac{2}{3}\left[V_a^{CONV} sin(\theta) + V_b^{CONV} sin\left(\theta - \frac{2\pi}{3}\right) + V_c^{CONV} sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad (2.13)$$

The AC currents that are flowing through the resistances and the inductances are shown in 2.14.

$$i_d = \frac{2}{3}\left[i_a cos(\theta) + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta - \frac{2\pi}{3}\right)\right]$$
$$i_q = \frac{2}{3}\left[i_a sin(\theta) + i_b sin\left(\theta - \frac{2\pi}{3}\right) + i_c sin\left(\theta + \frac{2\pi}{3}\right)\right] \quad (2.14)$$

The last term of 2.9 is the inductors' voltages which contain the derivative of the AC current; therefore, transformation must be applied for each current separately [30]. The derivative of 2.14 gives the inductance voltages in the *dq* frame, but it is required to consider equation 2.15.

$$\frac{d\theta}{dt} = w \quad (2.15)$$

Where : w is the angular frequency

$$\frac{di_d}{dt} = \frac{2}{3}\left[\frac{di_a}{dt} cos(\theta) + \frac{di_b}{dt}\cos\left(\theta - \frac{2\pi}{3}\right) + \frac{di_c}{dt}\cos\left(\theta - \frac{2\pi}{3}\right)\right] - \left(\frac{2}{3}\cdot\omega\right)\left[i_a sin(\theta) + i_b\, sin\left(\theta - \frac{2\pi}{3}\right) + i_c\, sin\left(\theta - \frac{2\pi}{3}\right)\right]$$
$$\frac{di_q}{dt} = \frac{2}{3}\left[\frac{di_a}{dt} sin(\theta) + \frac{di_b}{dt} sin\left(\theta - \frac{2\pi}{3}\right) + \frac{di_c}{dt} sin\left(\theta - \frac{2\pi}{3}\right)\right] + \left(\frac{2}{3}\cdot\omega\right)\left[i_a cos(\theta) + i_b \cos\left(\theta - \frac{2\pi}{3}\right) + i_c \cos\left(\theta - \frac{2\pi}{3}\right)\right] \quad (2.16)$$

It is clear that equation 2.9 becomes in terms of the *dq* frame as written in 2.17, but it has a coupling term. The two parts of this equation are the main expressions that describe the AC side of the VSC's currents.

$$L\frac{di_d}{dt} = V_d^{PCC} - V_d^{CONV} - Ri_d - wLi_q$$
$$L\frac{di_q}{dt} = V_q^{PCC} - V_q^{CONV} - Ri_q - wLi_d \quad (2.17)$$

The apparent power of VSC and the DC side's power can be written in the *dq* frame as shown in equation 2.18:

$$S_{dq}^{PCC} = \frac{3}{2}\left((V_d^{PCC} \cdot \ I_d^{PCC}) - j\left(V_d^{PCC} \cdot \ I_q^{PCC}\right)\right) \Rightarrow \begin{cases} P_{dq}^{PCC} = \frac{3}{2}(V_d^{PCC} \cdot \ I_d^{PCC}) \\ Q_{dq}^{PCC} = -\frac{3}{2}\left(V_d^{PCC} \cdot \ I_q^{PCC}\right) \\ P_{dc} = (V_{dc} \cdot \ I_{dc}) \end{cases} \quad (2.18)$$

2.8 The Inner Controller of VSC

The inner controller of the VSC can be implemented based upon equation 2.9, so designing the inner current controller includes eliminating an inductance effect by a feed-forward crossing term in the controller loop. Involving PI controllers into equation 2.9 has an advantage, which is that the dominant poles of the VSC can be cancelled by the zeroes of the PI controllers. Thus the inner loops controller of the VSC is achieved from equation 2.9. The existence of the nonlinear term in equation 2.9 causes a static error at steady state, so using the PI controller with feedback of instantaneous value of i_d and i_q keeps both current vectors regulated. Thus, the nonlinear term can be achieved by tracking i_d^{ref} and i_q^{ref} in the inner control loops with instantaneous values of i_d and i_q as written in 2.19.

$$\begin{aligned} L\frac{di_d}{dt} &= \left(K_P + \frac{K_i}{s}\right) \cdot (i_d^{ref} - i_d) \\ L\frac{di_q}{dt} &= \left(K_P + \frac{K_i}{s}\right) \cdot (i_q^{ref} - i_q) \end{aligned} \quad (2.19)$$

Substituting 2.19 into 2.9 allows implementation of the inner current control loops of the VSC as depicted in Figure 2.15 and the main equations of VSC become:

$$\begin{aligned} \left(K_P + \frac{K_i}{s}\right) \cdot (i_d^{ref} - i_d) &= \ V_d^{PCC} - V_d^{CONV} - Ri_d - wLi_q \\ \left(K_P + \frac{K_i}{s}\right) \cdot (i_q^{ref} - i_q) &= \ V_q^{PCC} - V_q^{CONV} - Ri_q - wLi_d \end{aligned} \quad (2.20)$$

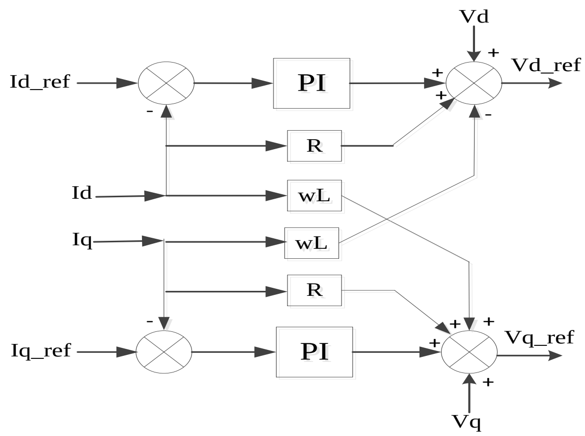


Figure 2.15 Block Diagram of Inner Current Control

2.9 The Outer Controller of VSC [31]

There are four types of the outer controllers' implemention of VSC: active power flow, AC voltage regulation at PCC, DC voltage regulation at DC bus, and reactive power control. However, in Figure 2.15, the Iq-ref of the inner controller is the output of the outer controller that should be either AC voltage regulation or reactive power control. On the other hand, the Id-ref in Figure 2.15 is the input of the inner controller that is fed from the output of the outer controller. The Id-ref might be either the DC voltage regulation or the active power control. Nevertheless, according to [32], it is possible to implement a multi-choice control for VSC. The four types of outer control are shown in Figure 2.16.

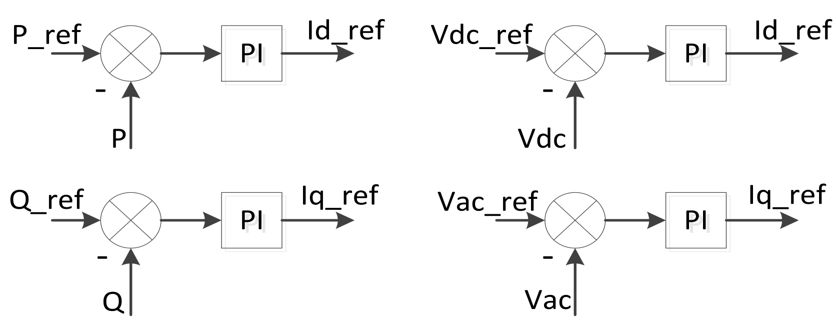


Figure 2.16 All Possible Outer Controls

2.10 Phase Locked Loop (PLL) [33]

A power factor of a VSC is more important to synchronize transfer power into an active AC system due to the fact that it might desire to get a unity power factor value. Moreover, synchronizing AC converter voltages with the active AC system leads to achieve a zero value of q-axis voltage vector, which is required in some cases such as in an active AC network. Using PLL will provide a displacement angle (*wt*) between the Clark and Park vectors. Therefore, a PLL circuit maintains the frequency of the AC converter voltages equal to the AC system frequency. Also, the displacement angle is required for matrix multiplication in order to transform the three phase voltage into the *dq* frame properly. In general, the PLL has three cascaded components which are voltage controlled oscillator, phase detector, and loop filter as shown in Figure 2.17.

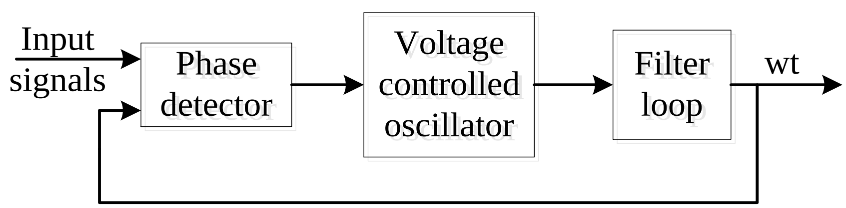


Figure 2.17 Block Diagram of Phase Locked Loop

2.11 Per Unit System

Controller design of power electronics is preferable to be implemented per unit because of the need of simple testing [34]. However, based on the literature in chapter two, designing the VSC depends on the peak value of the voltage. Determining per unit terms of the VSC based on the *dq* frame divides into AC side and DC side quantities as shown in table 2-2. Therefore all AC side quantities should be measured at PCC.

Table 2-2 VSC's Based Quantities

AC side quantities	
Power	$S_{base} = 3 \cdot V_{r.m.s} \cdot I_{r.m.s} = {}^{2}/_{3} \cdot V_{peak} \cdot I_{peak}$
Voltage	$V_{AC\,base} = \sqrt{{}^{2}/_{3}} \cdot V_{L-L}$
Current	$I_{AC\,base} = \frac{S_{base}}{V_{base}}$
Resistance	$R_{AC\,base} = \frac{V_{base}}{I_{base}}$
Capacitance	$C_{base} = \frac{1}{Z_{AC\,base} \cdot w_{base}}$
Inductance	$L_{base} = \frac{Z_{AC\,base}}{w_{base}}$
DC side quantities	
Voltage	$V_{DC_{base}} = 2 \cdot V_{AC_{base}}$
Current	$I_{DC_{base}} = \frac{S_{base}}{V_{DC\,base}}$
Resistance	$R_{DC_{base}} = \frac{V_{base}}{I_{DC\,base}}$

2.12 Multi-Terminal systems

A bulk power transmission through conventional AC systems has some limitations such as reactive power losses, voltage regulation limit, and current carrying capacity to meet the increase in electrical demand, so that using HVDC becomes a more preferable solution since it is more environmentally friendly. Therefore, successful operation and control of the VSC-HVDC link introduces a possible way to implement multi-terminal DC systems (MTDC). More than three terminals of converters interconnected with each other will give MTDC. Thus, the MTDC systems can be implemented with one of the configurations discussed previously. Numerous research studies have been done in the development of the VSC based MTDC system [35]. Using a VSC allows independent control of a reactive and an active power.

2.13 Power Sharing in MTDC Systems

Many MTDC projects and studies are underway to integrate offshore wind farms into an AC grid such as the European offshore wind farms [14]. There is a trend to implement MTDC into a distribution grid system in the future [36]. Meanwhile, power sharing among MTDC is a challenge and a critical issue for the stability of MTDC systems. There are different strategies of power sharing among MTDC systems based on previous research work that will be discussed revealing their drawbacks.

Sharing power among MTDC systems is a challenge due to the predefined or constant value of sharing, so the challenge for the operators is to determine the right values of converters' references to avoid the possibility of overloading for some terminals. Moreover, the stabilizing and balancing power in MTDC systems is achieved by DC voltage control [37]. The fixed power sharing among MTDC is difficult through DC voltage droop implementation due to the fact that sharing power among MTDC is determined by the DC voltage level. In the MTDC system, at least just one converter must control the DC voltage, while the other converters operate as a constant power control. In fact, delivering power into the MTDC system terminals is affected by DC voltage deviation [38]. Numerous studies have focused on power sharing in the MTDC system with diverse control strategies. As depicted in Figure 2.18, these studies can be categorized into four strategies, and they will be discussed briefly in the next subsections.

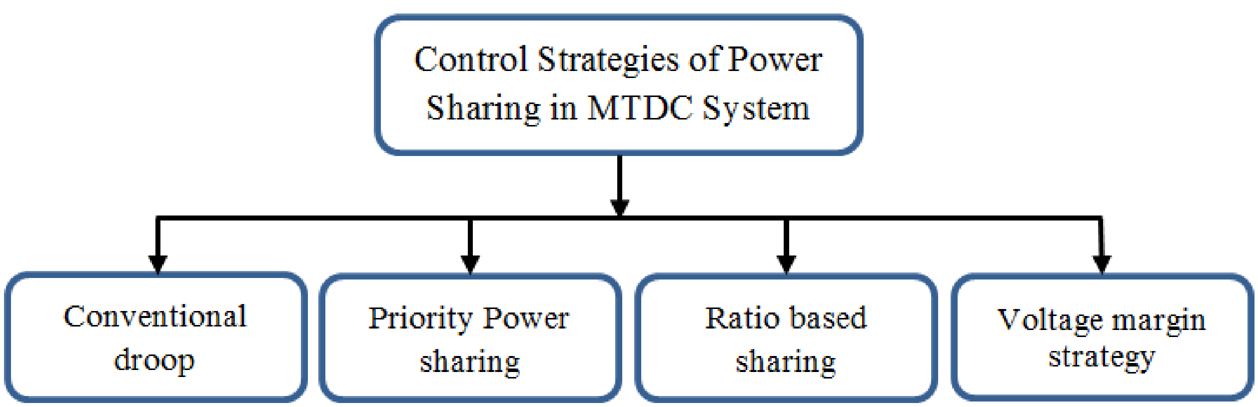


Figure 2.18 Power Sharing Strategies in MTDC System

2.13.1 Conventional Droop

Implementing a conventional droop strategy helps a converter to be adaptively controlled based on local measurements with no need for communication [39]. Thus, conventional droop strategy can be called a decentralized control. The concept for this strategy for AC or DC is similar. In an AC system, the droop characteristic depends on either active power versus the frequency or reactive power versus AC voltage [40], but in a DC system, the droop characteristic depends on either DC voltage versus active power [41] or DC current versus DC voltage [37]. In general, conventional droop can be simplified as shown in Figure 2.19. Conventional droop is to ensure balanced power sharing among inverter terminals based on constant or predefined values. Thus, there is no freedom to share available power above the constant or predefined values. It is obvious that using conventional droop will not supply extra power over the predefined value of power sharing (slope) due to the fact that implementing droop strategy must have limits. This disadvantage is clearly shown in equation 2.21

$$\mathrm{Vdc_{ref}} = \mathrm{Vdc_{meas}} - \frac{\Delta V}{\Delta P} * P_{meas} \quad where : \frac{\Delta V}{\Delta P}\ is\ the\ droop's\ slope \qquad (2.21)$$

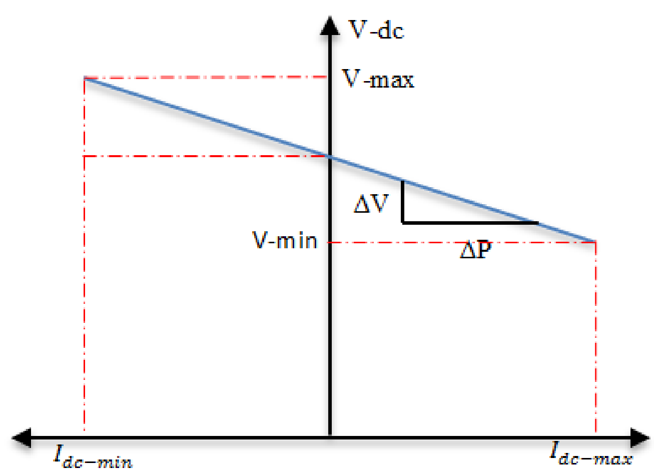


Figure 2.19 VDC verses IDC Droop Characteristics

According to [16], conventional droop does not consider either instantaneous loading or the available amount of power that can be absorbed. This control strategy was studied in depth in many research works [42],[43],&[44]. The drawback of the conventional droop strategy is that it lacks exact power flow control due the fact that maintaining the power flow constant reflects a bit of deviation in DC voltage.

2.13.2 Priority Sharing

This method gives priority to one terminal over the other, so it is clear that this method has a sequential pattern. Implementing this method for two grid side voltage source converters (GSVSCs) means the terminal that has priority will collect the total power from MTDC system until reaches its predefined limits. Then, the other GSVSC will start to collect the excess. As shown in Figure 2.20, the minimum voltage of the second terminal should be a bit higher compared to the maximum voltage of the terminal that has priority.

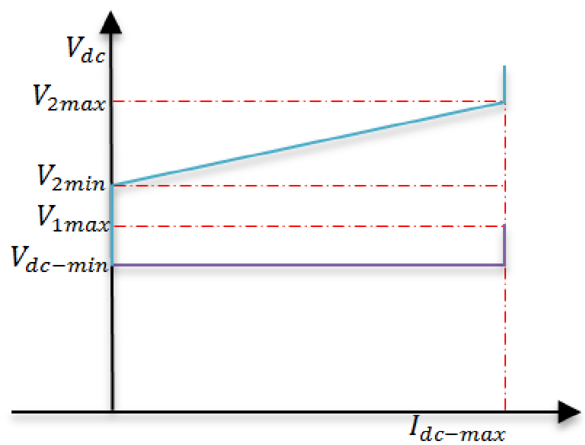


Figure 2.20 Priority Based of Power Sharing between Two GSVSCs

The advantage of this method is that it does not need communication [45], but it means that the switches of the terminal with less priority must have a higher voltage rating [46]. Moreover, the priority method is an interesting option for small MTDC systems due to the fact that it may put many terminals into idle mode [47].

2.13.3 Ratio Based Sharing

The substantial difference between the ratio based and the priority sharing methods is the need of communication. Using a ratio based strategy gives a priority for one terminal over the others [48],[49]&[50]. In other words, implementing ratio based sharing in MTDC systems might lead each terminal to have a surplus amount of power because of wind power variation. For an MTDC system that has two or more grid side VSCs (GSVSC), the delivering power into GSVSC terminals has a sequential pattern and both of them have a common DC voltage. Therefore, there is no power delivery to the second terminal until the first terminal achieves its limits or ratio. Figure 2.21 shows the ratio based mechanism.

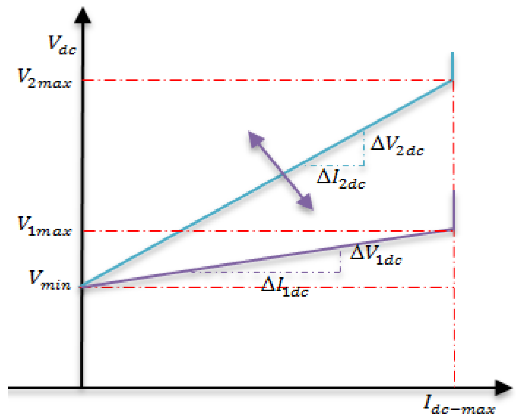


Figure 2.21 Ratio Based Power Sharing between Two GSVSCs.

The relationships of the two DC voltages are:

$$V_{ref1} = V_{min} + slope_1 \times I_{1dc} \quad (2.22)$$

$$V_{ref2} = V_{min} + slope_2 \times I_{2dc} \quad (2.23)$$

As shown in Figure 2.21, the droop characteristic of GSVSC #1 is fixed compared to GSVSC #2 which is dependently changeable based on the droop characteristic of GSVSC #1. Equations (2.22) & (2.23) are correlated; thus, the value of $slope_2$ can be written in terms of $slope_1$ after some simplifications the equation (2.23) becomes:

$$V_{ref2} = V_{min} + \frac{1}{\left(\frac{n}{slope_1}\right) + (n \times R_1) - R_2} \times I_{2dc} \quad (2.24)$$

In equation (2.24), the value of R_1 and R_2 are the resistance of DC lines, and the symbol n is the ratio of power sharing.

The ratio based strategy depends on the changing of the droop mechanism; therefore, changing the droop mechanism of just one terminal leads to a change in the ratio of power sharing [48]. This strategy needs communication [46], so the operators must know about the power being generated by offshore wind farms to adjust the slope of the droop characteristics [45].

2.13.4 Voltage Margin Strategy

The function of the voltage margin strategy (VMS) is to control active and reactive power, and DC voltage in an integrated manner. The direction of power flow affects the value of the voltage margin. For example, if the power is transferring from GSVSC #1 into GSVSC #2, the voltage margin is equal to V_{1dcref} minus V_{2dcref} [51]. Figure 2.22 shows the mechanism of VMS; therefore, the intersection node is the operating point for terminals.

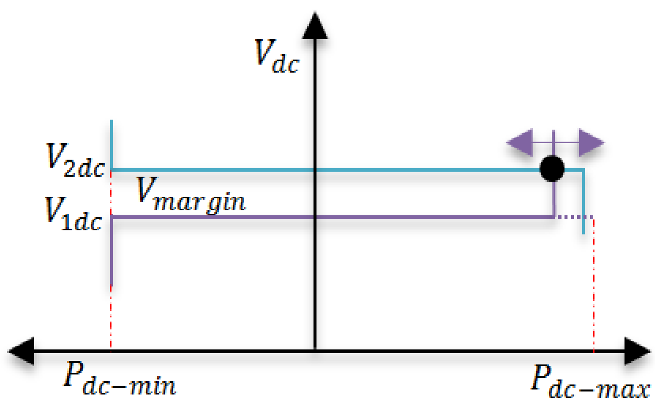


Figure 2.22 Voltage Margin Strategy of Two GSVSCs

It can be seen from Figure 2.22 that when terminal #2 reaches the limit, the DC voltage will drop, and terminal #2 will change from DC voltage control to a constant power control. This strategy does not require communication [47], and it is modified and implemented with different values for the voltage margin [52]. Nevertheless, the transient response of the VMS is quite high due to the fact that this scheme of control consists of two or more PI controllers [45].

2.13.4.1 Power Sharing Summary

Based on the literature, the main gap of power sharing among MTDC terminals is that there is no inclusion of available power that can be shared among all inverter terminals. Therefore, to clarify this strategy, equal power sharing between inverter terminals is considered in this thesis, but it can be different percentages based on a policy or arrangement. In other words, during the existence of communication between inverters it can be a specific percentage of power sharing such as 50% to 50 %. On the other hand, during communication failure, it can be different percentages (see appendix A).

2.14 Summary

This chapter discussed the power sharing issue among multi terminal HVDC system. Therefore, it is essentially to explain the concept and the operation of VSC in order to treat the power sharing issue. Controlling the power flow through the VSC has two strategies that can be used based on VSC's application. Furthermore, there are many topologies of VSC that can be implemented to get multi terminal HVDC systems. However, before choosing a topology of VSC one should consider the topology's advantages and disadvantages. Regardless of the amount of research conducted, there is no inclusion of available power that can be shared among MTDC systems. therefore, this issue has provided the incentive for this thesis.

Chapter 3
Proposed control and System

3.1 Introduction

A multi-terminal high voltage DC (MTDC) voltage source converter (VSC) based system becomes a viable solution to interconnect renewable resources into an AC grid due to fast power control with good power quality, and independent active and reactive power control. Much research has been done in the development and controling of the VSC based MTDC system showing the advantages of MTDC systems [49], [50], [52-56], and [61]. MTDC systems consist of multi-input converters or single and multi-output converters. Thus, controlling and operating MTDC systems pose many challenges due to their complexity. DC voltage droop control with a decentralized control is mostly used with MTDC systems [56]. Since the DC link in MTDC systems may have more than three connection nodes all having a common DC voltage value, using the DC voltage value as a common reference for all terminal control loops makes it possible to get a cooperative control performance [57].

This chapter proposes a cooperative autonomous control to share the active power among MTDCs. The main contribution in this proposed control is that it takes into account three different aspects which are: preventing the possibility of overloading for all terminals, sharing power based on an agreement and with different priority, and reducing energy generated from dispatchable units whenever there is available power at a rectifier terminal. To clarify and prove the advantages of the proposed control strategy of economical autonomous control to share the active power among MTDCs, the study investigates several different scenarios for an MTDC system with two configurations. The MTDC system in this thesis is based on a detailed switching VSC model, and it is simulated in a PSCAD/EMTDC environment. Still, it is necessary to introduce a brief review of cooperative control and the structure of an MTDC system in order to discuss the implementation of the proposed control algorithm.

3.2 Cooperative Control Concept

An intelligent control is an essential, economical way to operate an electrical system because it minimizes operating costs. Therefore, a live interaction between many controllers of a complex electrical system is important to achieve an economical operation. A cooperative control provides the intelligence to the systems' controllers and the interactions. Cooperative controls have been implemented in many practical power system applications such as a micro-grids, and shipboard power systems [58]. Several cooperative control strategies are introduced, so these strategies are used to control power sharing among MTDC systems such as autonomous control. This strategy allows the plug and play feature and hence when any terminal of MTDC system is in outage or curtailed, there is no need to reconfigure the MTDC system or reset new references for their controllers. Moreover, the cooperative control has several benefits such as high reliability [59], and minimizing the operation cost. In general, a complex system should be clustered into many subsystems, and it is not necessary for the cooperative control algorithm to communicate with all subsystems as shown in Figure 3.1.

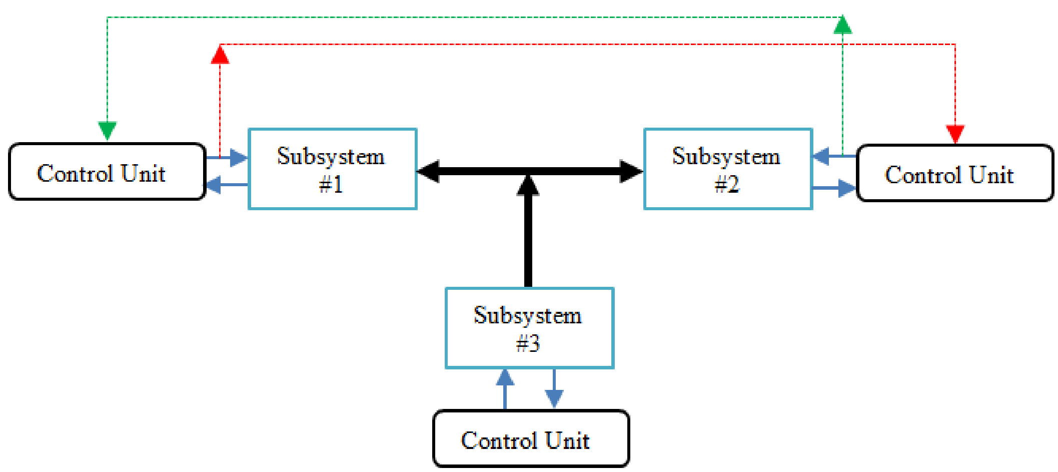


Figure 3.1 Representation of Cooperative Control Structure

Figure 3.1 explains the concept of a cooperative control that interacts with subsystems. The two subsystems #1 and #2 are considered to communicate with each other, but subsystem #3 will communicate with the other subsystems through its output. In other words, subsystems #1 and #2 inputs communicate to subsystem #3 in an indirect way.

3.3 Proposed Control Concept for MTDC Power Sharing

A cooperative control of power sharing among MTDC system has three goals. The first goal is that a local controller at each VSC terminal must protect its terminal from an overloading situation. This goal must be considered for all terminals using a current limiter in its outer control loop. The second goal is to consider the additional available power that can be shared among MTDC systems when one of the inverter terminals needs more power. Sharing power between inverters is based on an agreement weight when all inverters request more than the agreement at the same time is the third goal (50% to 50% is such an example that is considered in a case when an MTDC system has two terminals working in inversion mode and just one working in rectification mode). This agreement weight should be considered for all inverter terminals.

- The advantages of proposed cooperative control are:
  - Equal power sharing capability if the agreement weights are equal.
  - Preventing any possibility of overloading for all terminals especially at the rectifier terminal because it is controlling the DC voltage.
  - Sharing power based on an agreement in case of shortage.
  - Considering the additional available power that can be shared.
  - Reducing energy generated from dispatchable units whenever there is available power at the rectifier terminal.

The economical aspect of the proposed control is to minimize dispatchable unit generation when there is available power that can be received from the MTDC system. Since extracting more power from the dispatchable unit means increasing its operation cost, the main objective of system operators is to meet the demand from the MTDC system first when there is available power. Alternatively, when there is no power available except the permitted percentage, the dispatchable unit gets a command to increase its generation autonomously to cover the remaining value of the power demand. Thus, the proposed control strategy will decrease the operational cost as much as possible whenever there is available power at the rectifier terminal; otherwise, the proposed control supplies the terminal based on the agreement established among all inverters (ratio).

3.4 Proposed control Implementation of a MTDC System

The cooperative autonomous proposed control is depicted in Figure 3.2. Each inverter terminal has its local control unit based on Figure 3.2, which determines the required power that should be received into its system. Thus, the first objective of the local control unit is to receive the required power from the MTDC system if it is available; otherwise, the proposed control supplies the terminal based on the agreement weight between all inverters. This feature of the control is available whether there is communication among all the inverters or not. Therefore, it is clear that there is no possibility for the rectifier terminal to be overloaded because the sum of all inverters commands must be equal to the rated power of the rectifiers. As mentioned before, identical power sharing among MTDC systems is considered, so equations (3.1) and (3.2) show the dividing of power command that is determined by the local control unit.

$$\mathrm{P}_{\mathrm{received}}(MTDC) = \begin{cases} P_{available} - P_{required}, P_{supply} \geq 0 \implies \mathrm{P}_{\mathrm{received}}(MTDC) = P_{required} \\ P_{available} - P_{required}, P_{supply} < 0 \implies \mathrm{P}_{\mathrm{received}}(MTDC) = 0.5\, p.u \end{cases} \tag{3.1}$$

Each VSC working in inversion mode will collect power based on equation (3.1), so the first of the equation means that when the required amount of power is determined, and the difference between the available and the required power is greater or equal to zero the VSC will get its required power. However, when the difference between the available and the required power is less than zero the VSC will just get the allowed percentage of power sharing which is 50% in this case as shown in the second part of equation (3.1)

$$\mathrm{P}_{\mathrm{DG}} = \mathrm{P}_{\mathrm{received}}(MTDC) - \mathrm{P}_{\mathrm{DG}}min \tag{3.2}$$

Where $\mathrm{P}_{\mathrm{DG}}min$ is the minimum value of power to be supplied from a dispatchable unit [60].

Lack of available power at the rectifier terminal means that one of the inverters is consuming more than 50 % in order to decrease the contribution of its dispatchable unit. This feature provides the main advantage of the proposed method, which can supply additional power when the available power is not being consumed by the other inverter.

The control flow chart of the proposed control is shown in Figure 3.2. Initially, when the system starts working and the scheduled power is determined, the proposed control immediately checks whether the communication is active or not, so there are two paths of the proposed strategy for making decision. In case of communication is active, the schedule power will be compared with the rectifier's rated power. If the scheduled power is less or equal to the rectifier's rated power, then the terminal will collect its required scheduled power, and its dispatchable unit remains supplying its minimum power. On the other hand, when the scheduled power is greater than the rectifier's rated power, the inverter terminal will get the agreement value, and the shortage of the power required will be covered from the dispatchable unit. Moreover, the procedure in case of inactive communication is similar to the case when the scheduled power is greater than the rectifier's rated power.

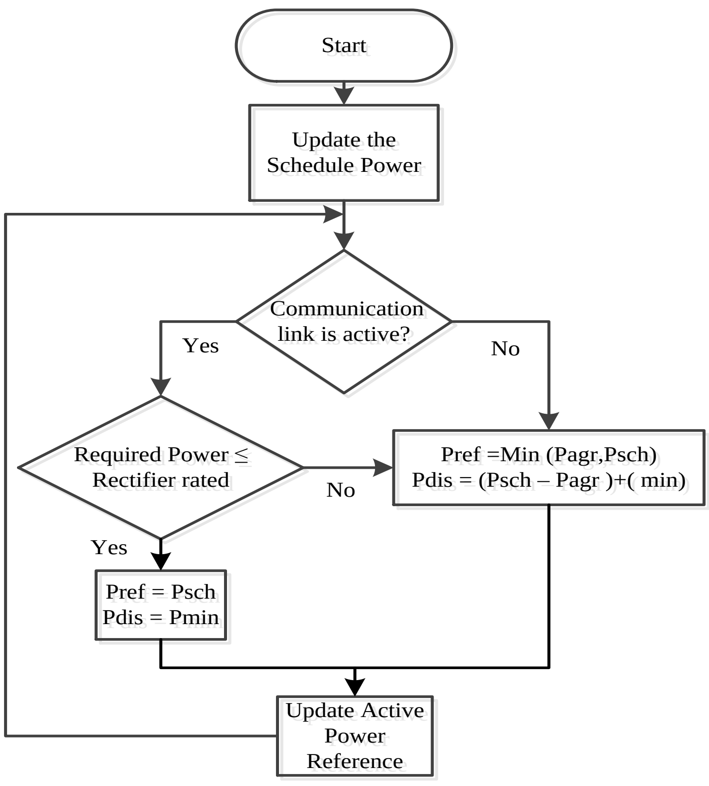


Figure 3.2 Flow Chart of a Cooperative Autonomous Control

When there is a communication failure, each inverter station will have just fifty percent of power available as considered in the study. In this case equation (3.1) will change during a communication failure to:

$$P_{\text{received}}(MTDC) = Min(0.5\,p.u., P_{required}) \tag{3.3}$$

It is clear that a communication failure only affects available power sharing when there is available power at the rectifier terminal, but still equal percentages of power sharing for both inverters is valid. The proposed control strategy can be flexible with different percentages of power sharing during communication or communication failure.

3.5 MTDC System

Cooperative proposed control is implemented on a specific configuration of an MTDC system that consists of one slack terminal. The reason for choosing this configuration is to prove the feasibility of proposed cooperative control based on real systems [61]. The configuration of the MTDC system consists of four terminals with one of those terminals linked to an offshore wind farm MTDC system. Nevertheless, studying this system configuration is useful to prove that the proposed cooperative algorithm works during abnormal configurations such as terminal outage.

3.5.1 Terminals MTDC System Configuration

As shown in Figure 3.3, the MTDC system in this case consists of four VSC terminals. The first VSC terminal is considered to be a wind farm to supply the active power to the MTDC system, so it is assigned to work as a constant AC voltage control to achieve maximum power tracking. Terminal #2 is assigned to be in constant DC voltage control, and it is called a slack terminal. On the other hand, terminal #3 and #4 are working in inversion mode, and they have a dispatchable thermal unit on their AC side. They are dedicated to control the active power flow from the wind farm terminal, the slack terminal, and the dispatchable unit.

All terminals in Figure 3.3 are connected to stiff systems except the wind farm terminal which is a weak system. Table 3.1 shows the MTDC system’s parameters.

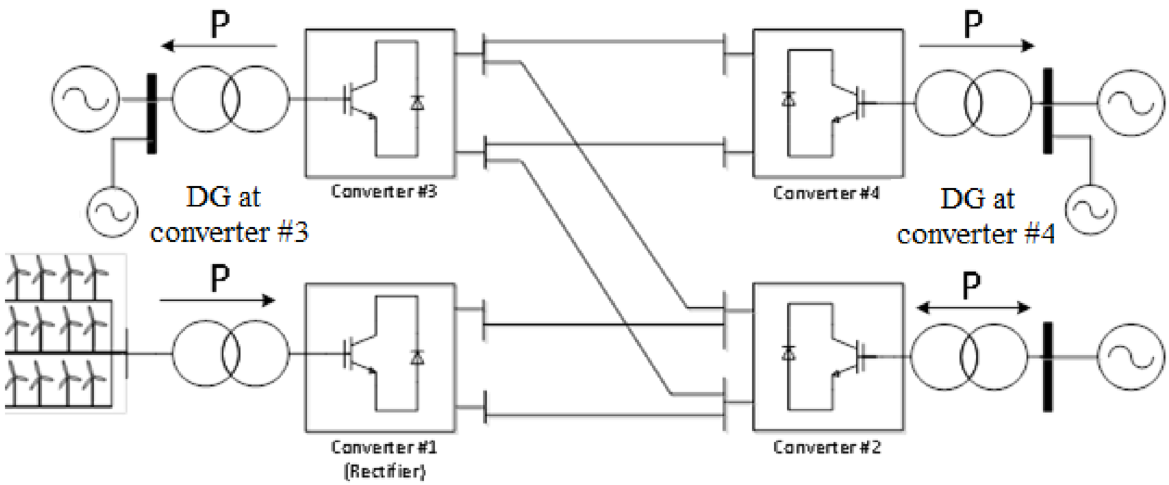


Figure 3.3 MTDC System for the Study

Table 3-1 MTDC System's Parameters

Quantity	Value
Converter Rated power	100 MVA
AC side resistance	0.15 Ω
AC side inductance	4.8 mH
DC side capacitance	320 µF
Switching frequency	1600 Hz
System frequency	60 Hz
Transformer rated power	100 MVA
DC voltage	60 kV

3.5.1.1 Dispatchable Thermal Generator Units

The operational cost of the dispatchable generator depends upon its parameters, and it can be collected from the plant (field). The objective of the proposed control strategy is to maximize the contribution of the rectifier's power to diminish the operational cost of the dispatchable generator unit. According to [60], the author provided the parameters of some dispatchable thermal generator units as shown in Table 3.2. Each converter works in inverter mode in Figure 3.7 and has a dispatchable unit. Table 3-2 shows the dispatchable units' parameters. Unit #3 in table 3-2 is considered in this study.

Table 3-2 Thermal Units' Parameters [55]

Unit	Pmin (MW)	Pmax (MW)	af $\frac{Mbtu}{MW^2h}$	bf $\frac{Mbtu}{MWh}$	cf $\frac{Mbtu}{h}$	Starting Up ($Mbtu$)
1	5	50	0.00812	18.1000	218.3350	20
2	30	70	0.00463	106940	142.7348	20
3	50	100	0.00143	10.6616	176.0575	150
4	30	120	0.00199	7.6121	313.9102	250

The heat requirement for a thermal generator to provide a certain amount of active power is donated by $H_i(P_i)$. The unit of $H_i(P_i)$ is MBTU which is a polynomial function of the active power. Thus, the heat requirement equation is:

$$H_i(P_i) = (af \times P_i^2) + (bf \times P_i) + cf \qquad 3.4$$

3.6 Summary

This chapter has explained the concept of cooperative control in order to clarify the use of the proposed control strategy to share the active power among MTDCs. Three different aspects of the proposed control strategy have been discussed, and the implementation of the proposed control was explained to be implemented on an MTDC system. Finally, The layout of the MTDC system is as shown with its parameters in Table 3-1.

Chapter 4
Simulation and Results

4.1 MTDC System with Multiple Slack Terminals

Once a MTDC system consists of multiple slack terminals it means that they are in DC voltage control mode. Thus using a conventional droop strategy introduces an issue that is unequal power sharing among slack terminals. Therefore, unequal power sharing issue can be solved using an adaptive droop control strategy. As shown in Figure 4.1, a MTDC system consists of three terminals and terminal #1 and #2 are assigned be slack terminals.

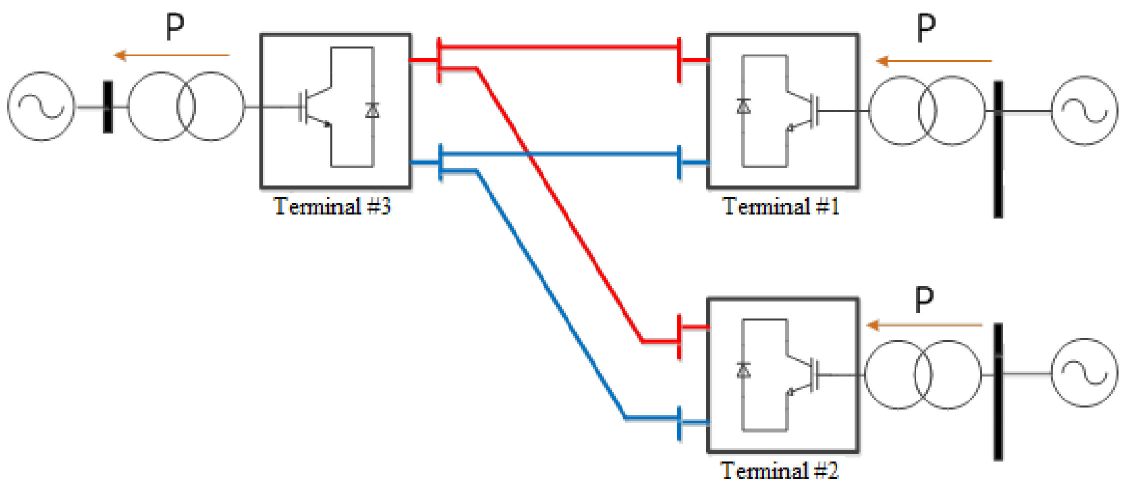


Figure 4.1 MTDC System with Multiple Slack Terminals

4.1.1 Droop Strategy Problem

Using conventional droop strategy will not ensure an equal or exact power sharing among MTDC system that has two slack teminals as shown in Figure 4.1. Using droop strategy is necessary to be used in case of DC control terminal outage. Figure 4.2 shows a droop strategy problem when an MTDC system has multiple slack terminals. It is clear that there is difference between the two slack terminals. The value of the difference is affected by the resistance length of the transmission. The power supplied by slack terminal #1, and #2 are not equal due to using conventional droop strategy as shown in Figure 4.2.

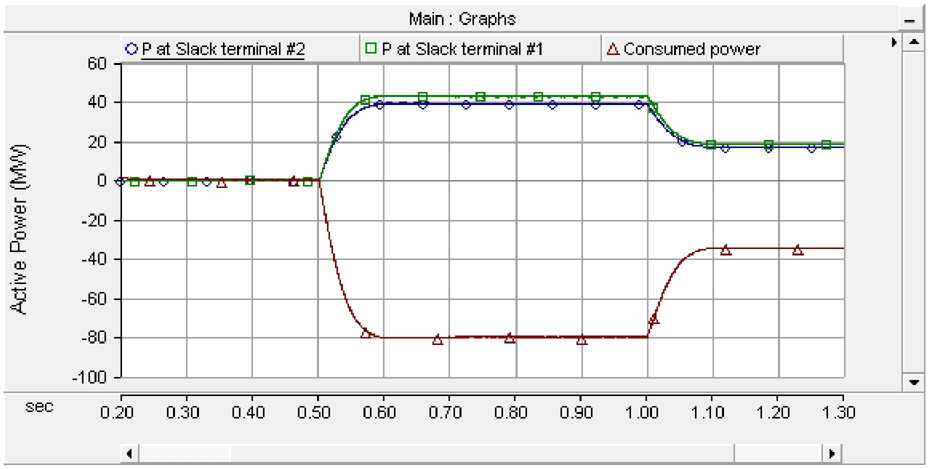


Figure 4.2 Unequal Power Sharing Using Conventional Droop

As shown in Figure 4.3 the DC voltage level is affected by droop value, so using a conventional strategy has a droop limit to keep the MTDC system stable.

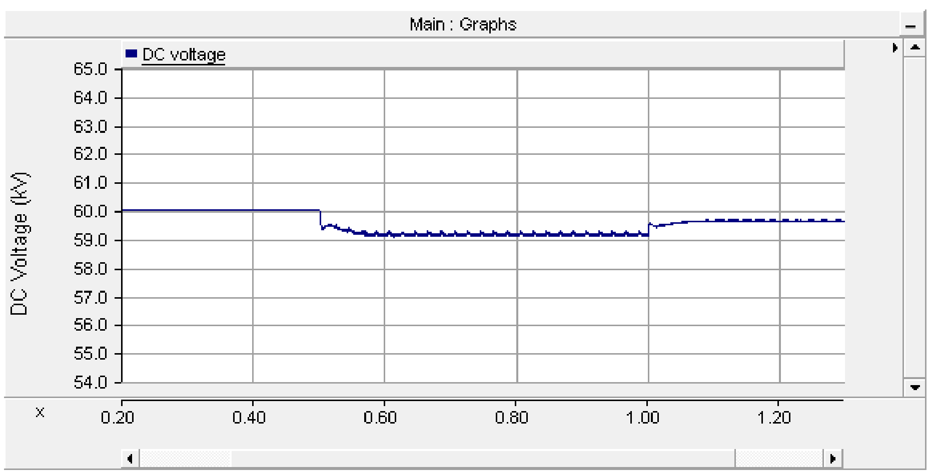


Figure 4.3 DC Voltage with Droop Strategy

4.1.2 Adaptive Droop Control

The equal power sharing problem can be solved using adaptive droop control, but it requires low bandwidth communication. Using adaptive droop control will allow terminals to share their power in an equal manner. The main advantage of equal power sharing among the MTDC system is to increase the utilitization of each terminal. Figure 4.4 shows the power flow case among the MTDC system when the adaptive droop control strategy is valid.

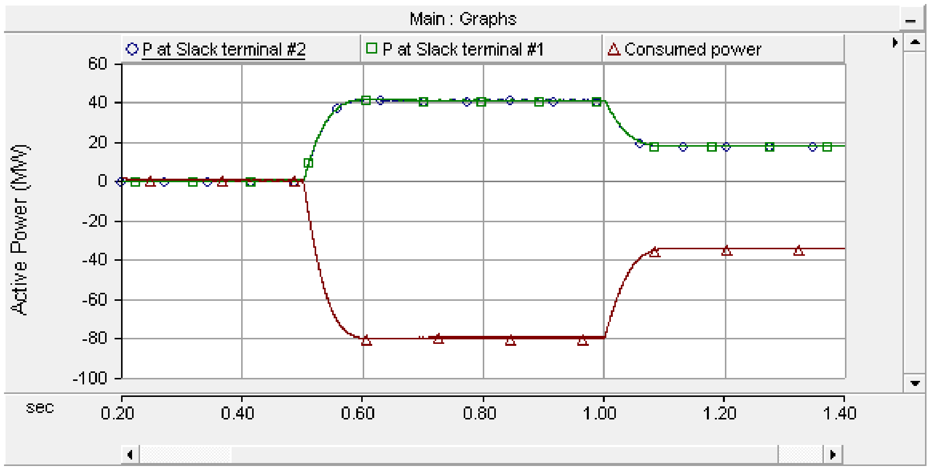


Figure 4.4 Equal Power Sharing Using Adaptive Droop Strategy

The adaptive droop strategy keeps the DC voltage level at a constant value as shown in Figure 4.5. Therefore, using this stragey diminishes MTDC line losses due to the fact that when the DC voltage is decreased, the DC current will increase and the line losses will increase.

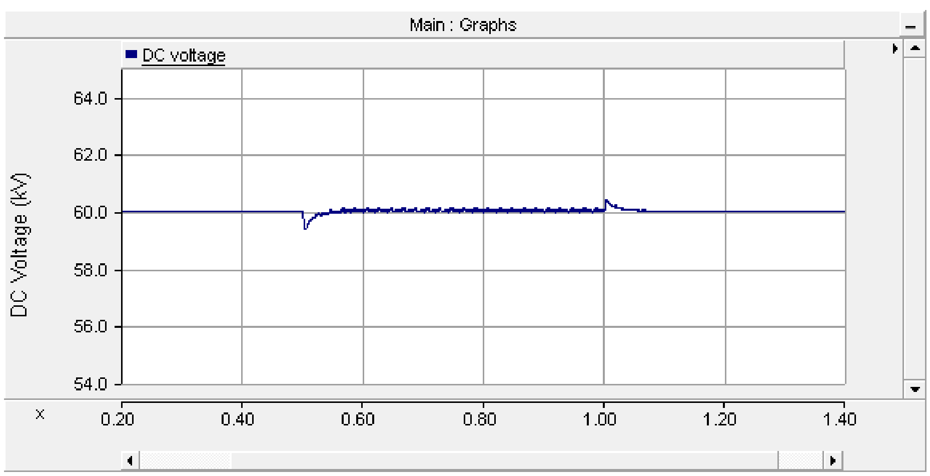


Figure 4.5 DC Voltage with Adaptive Droop Strategy

4.2 Verification of the Proposed Method

The MTDC system has four VSC terminals as depicted in Figure 3.3, and it is built in the PSCAD/EMTDC environment. All terminal stations are based on a detailed switching VSC model. The simulation investigates the proposed cooperative strategy feasibility during several cases which are: communication among inverters, communication failure and an outage of the inverter terminal. Furthermore, during all different scenarios the commands of required power that need to be delivered to the inverter stations are the same. Table 4-1 summarizes the actions of power commands that are applied in the simulation test; nevertheless, converter #2 is a slack terminal which is working in the rectification mode.

Table 4-1 Simulation actions

Wind Speed (m/sec)	Wind power (MW) at inverter #1	Time (sec)	Required power of Inverter #3 (MW)	Required power of Inverter #4 (MW)
7	58.3	0	0	0
		30	80	0
		45	80*	35
		60	50	35*
10	83.5	90	97	85
		110	25	85*
8	66.75	135	25*	30
		150	97	30*
		160	97*	97

Where * means the reference power's command does not change.

The system in these studies does not need a start up transient control to eliminate the dynamics because the proper tuning of the PI controllers based on the converter's transfer function shows a good transient dynamic response. Indeed, all tests concentrate on three important values, namely: DC voltage level, active power, and the power of the dispatchable units.

4.3 Unidirection Power Flow

4.3.1 Cooperative Case Study with Communication (case I)

Initially, each dispatchable unit is providing a minimum power into its load of 50MW as shown in Figure 4.6. The reason for this amount of power is that the dispatchable units should work based on economical operation which is decided by the unit commitment as mentioned in section 3.4.1.1.

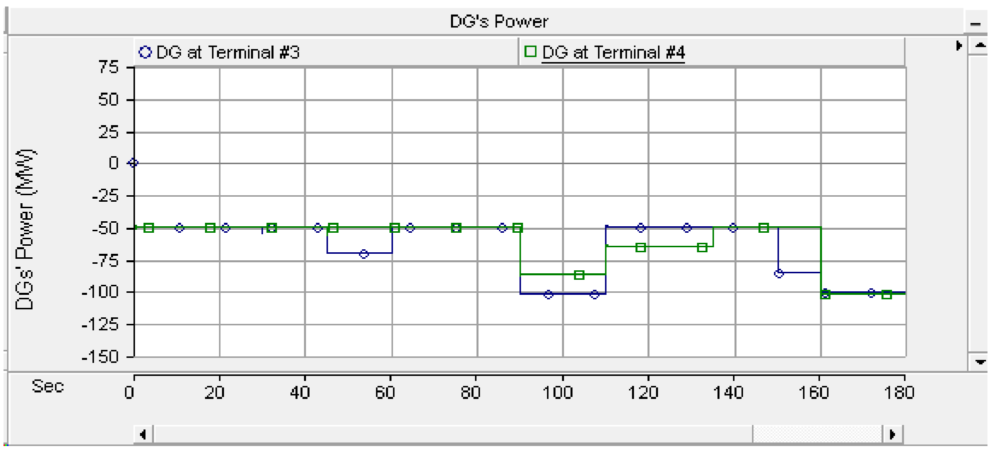


Figure 4.6 Dispatchable Unit's Power During the Absence of Communication (case I)

During the first 45 sec, both dispatchable units are supplying their minimum power based on an economical operation [55].

At t=45 sec inverter #3 requests 80 MW of active power which is not available at this time. Therefore the shortage of the required power will come from the dispatchable unit as shown in figure 4.6, and the last two columns in table 4-2 shows the power that is supplied by both dispatchable units.

The MTDC voltage level for this case is constant and stable as can be seen in Figure 4.7. The power sharing among the MTDC systems are shown in Figure 4.8, and Table 4-2 summarizes all scenarios of the cooperative case study with communication. The small amount of power loss reflects the requirement for line resistance and converter losses.

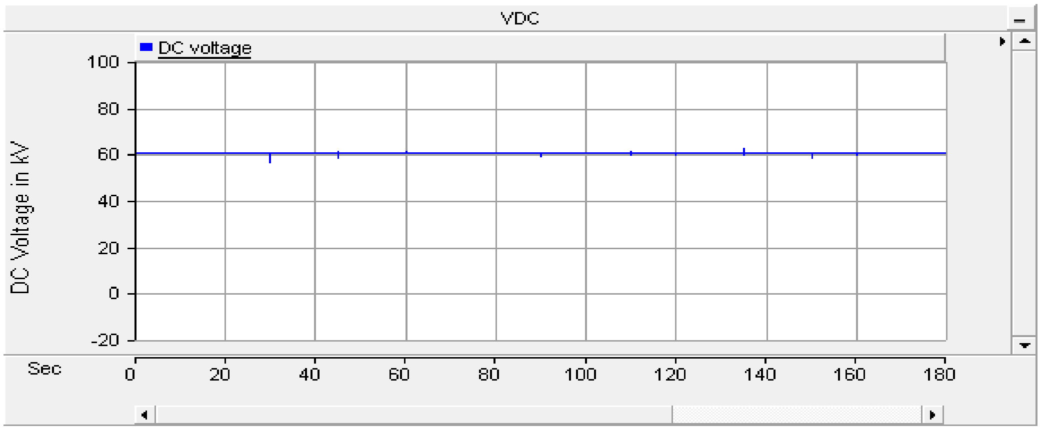


Figure 4.7 DC Voltage Level During Communication (case I)

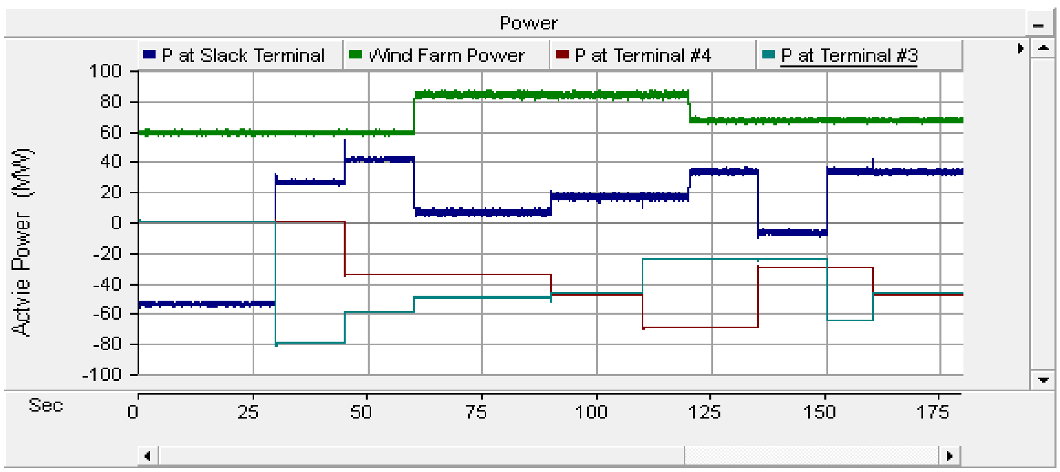


Figure 4.8 Power Sharing During Communication (case I)

Table 4-2 Summarizes all Scenarios of the Cooperative Case Study with Communication

Time	Wind Speed	Wind power terminal #1	Slack DC terminal #2	Required power of Inverter #3	delivered power into #3	Required power of Inverter #4	delivered power into #4	Unit #3	Unit #4
Sec	(m/sec)	(MW)		(MW)		(MW)			
0	7	58.27	-54.06	0	0.00	0	0.00	50	50
30	7	58.36	26.07	80	-80.00	0	0.00	50	50
45	7	58.31	41.18	80*	-60.00	35	-35.00	70	50
60	7	83.33	6.367	50	-50.00	35*	-35.00	50	50
90	10	83.29	16.62	97	-47.10	85	-47.90	99.9	87.1
110	10	83.38	16.30	25	-25.00	85*	-70.00	50	65
135	8	66.63	32.76	25*	-25.00	30	-70.00	50	50
150	8	66.58	-7.47	97	-25.00	30*	-30.00	50	50
160	8	66.62	33.07	97*	-65.00	97	-30.00	99.9	99.0

The criteria between both requests are the agreements and power management policy which is considered in this study as 47MW for both inverter stations. As shown in Figure 4.8, both inverters just achieved 47MW from the MTDC system; in contrast, dispatchable units are mismatching and compensating for the difference between the requests and the available power as shown in Figure 4.6.

During the first 60 sec, the wind farm speed is 7m/s that is supplying 58.3MW to the MTDC system. At t=0 sec, there are no power requests for both inverters; therefore, all wind power goes to the slack terminal that is inverter #2. The difference between wind power generation and the slack power terminal reflects power losses due to line resistances and converter losses. The positive values of power at the slack terminal mean that the terminal is supplying power to the MTDC system.

At t=30 sec, inverter #3 requests 80 MW of active power which is greater than the 50% of the agreement between the systems. Therefore, inverter #1 will achieve this request of power due to the fact that there is available power that can be consumed. This period of time shows the feature of proposed cooperative control to provide the total power that is allowed to be shared when it is available.

At t=45 sec, inverter #3 still requests 80 MW of active power, and inverter #4 starts to request 35 MW. At this time the power at inverter #3 will decrease until inverter #4 reaches its request demand because the power request of inverter #4 is less than the 50% of the power sharing agreement. Therefore, the shortage of power at inverter #3 will be compensated straightaway by its dispatchable unit. In particular, there is no surplus power that can be seen from the inverter side, because the dispatchable unit at inverter #3 compensates for the power difference between the requested and the delivered power, which is 20MW.

At t=60 sec, the requested power from inverter #3 becomes 50MW and inverter #4 still is requesting 35MW. This period of time, shows that the proposed cooperative strategy minimizes the contribution of dispatchable units` power generation to decrease the operational cost. In fact, the behavior of the MTDC system during this period proves the claim of an economical operation of the dispatchable units.

At t=90 sec, the wind power generation increased because the wind speed rose to 10 m/s meaning wind power generation became equal to 83.5 MW. Thus, the slack terminal during this period will have a small amount of power to be distributed among the MTDC terminals. At this time, inverter #3 and #4 request 97MW and 85MW respectively; however, the total allowed amount of power that can be shared is 95MW. In this case, the proposed cooperative strategy will allow equal power sharing between the two inverters. The shortage of power required will be compensated for by the dispatchable units instantaneously.

At t=110 sec, this period shows that when there is available power that can be shared, the dispatchable units will rapidly decrease their generation. At this time, the requested power from inverter #3 decreases from 97MW to 25MW; therefore, the delivered power to inverter #4 will increase due to the available power. In other words, it is clear that when inverter #3 does not request its full percentage, inverter #4 can benefit from the available power. Consequently, the proposed cooperative strategy will decrease the operational cost of the dispatchable units.

The other possible case is when both inverters request power less than 47 MW (50% of allowed power sharing) at t=135 sec. Both dispatchable units are working at their minimum power condition.

Finally, at t=160 sec, inverter #4 requests 97MW, while the request at inverter #3 is still equal to 97MW; thus, in this situation the proposed control strategy shares the active power between systems based on the agreement and power management policy that is considered to be fifty to fifty percent. However, the percentage of power sharing can be rearranged by systems operators.

4.3.2 Cooperative case Study with Communication Failure (case: II)

This case follows the same simulation actions that are considered in the case with communication. The DC voltage has a small dynamic response compared to the previous case during load changing as shown in Figure 4.9. The interpretation of this difference is based on the amount of power delivery from the rectifier terminal into the inverters. It can be noted that the dynamic of DC voltage is affected by the amount of power delivery as compared to the previous case.

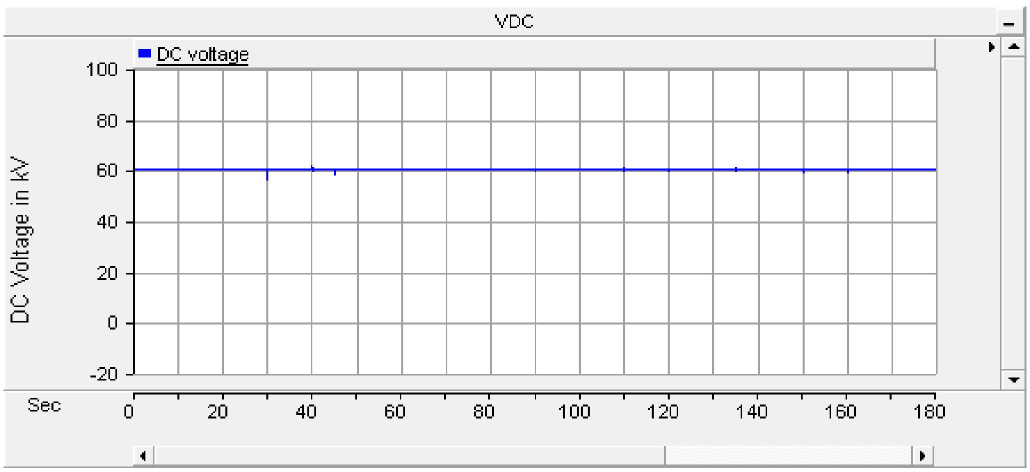


Figure 4.9 DC Voltage Level during the Absence of Communication (case II)

In the absence of communication, Figure 4.10 shows the power sharing among the MTDC. For instance, based on table 4-3, at t=40 sec, although inverter #3 requests 80MW which is available, it will only receive 47 MW due to a communication failure. In contrast, the remaining required power that is requested from inverter #3 will provide for dispatchable unit #3 to increase its power generation as shown in Figure 4.11. It is clear that in this case with no communication the operation cost will rise, but the proposed control strategy provides a robust protection from any possible overload.

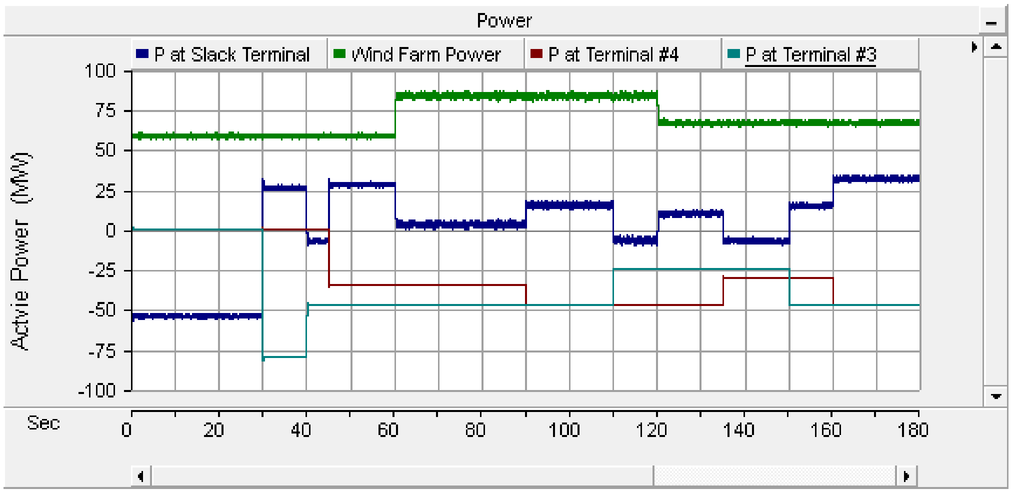


Figure 4.10 Power Sharing during the Absence of Communication (case II)

Table 4-3 Summarizes all Scenarios of the Cooperative Case Study with no Communication

Time	Wind Speed	Wind power terminal #1	Slack DC terminal #2	Required power of Inverter #3	Delivered power into #3	Required power of Inverter #4	Delivered power into #4	Unit #3	Unit #4
Sec	(m/sec)	(MW)		(MW)		(MW)			
0	7	58.3171	54.33878	0	-0	0	0	50	50
30	7	58.234	-26.0754	80	-80	0	0	50	50
40	7	58.36141	7.288063	80	-47	0	0	70	50
45	7	58.278	-27.8913	80	-47	35	-35	83	50
60	10	83.39217	-3.18771	50	-47	35	-35	53	50
90	10	83.33957	-15.226	97	-47	85	-47	100	88
110	10	84.55141	6.83529	25	-25	85	46.99	50	88
120	8	66.68904	-9.69081	25	-25	85	47	50	88
135	8	66.64157	7.300248	25	-25	30	30	50	50
150	8	67.47398	-14.7266	97	-47	30	30	100	50
160	8	66.77463	-31.7203	97	-47	97	47	100	100

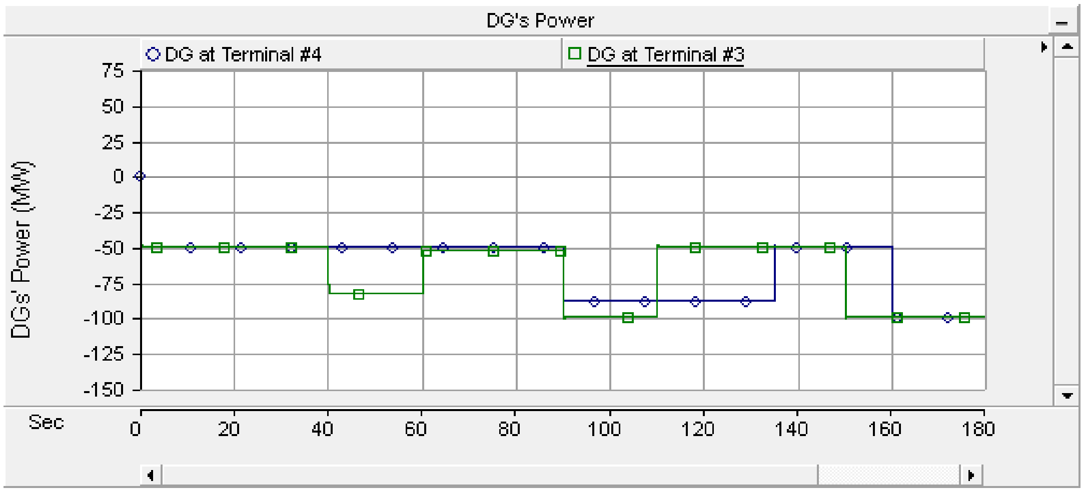


Figure 4.11 Dispatchable Units` Power during the Absence of Communication (case II)

It is important to notice that each inverter's terminal has a fifty percent freedom of a permitted power to be consumed. Nevertheless, the systems' operators can have a different percentage of power sharing during communication failure compared to the communication based on the agreement or dispatchable unit rated power or power management policy (see appendix A).

4.3.3 Cooperative Study during a Terminal Outage with Communication (case: III)

This case shows the behavior of the cooperative proposed strategy for power sharing among the MTDC system when one of the inverter terminals experiences an outage during the communication between inverters, so at t = 60 sec inverter #4 is disconnected from the DC side. As shown in Figure 4.12, at t = 90sec, the total allowed power that can be shared by both inverter terminals is consumed by inverter #3.

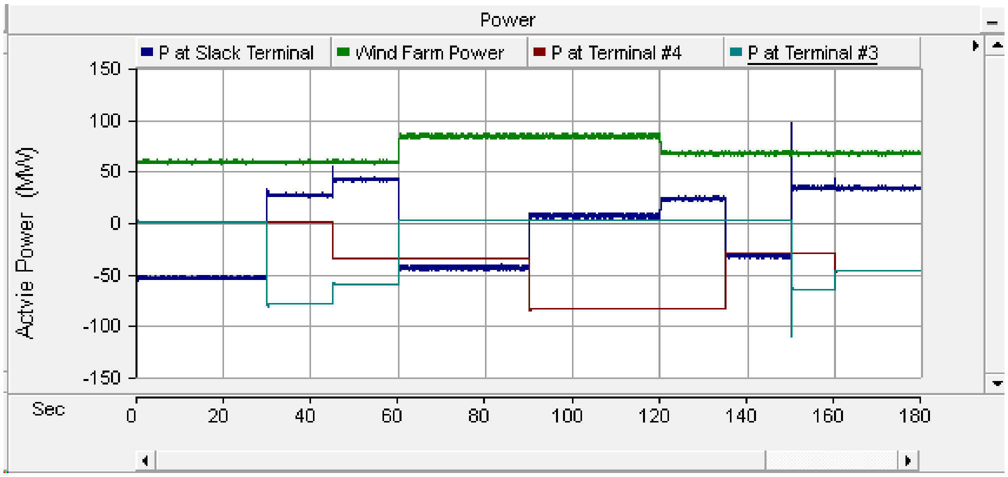


Figure 4.12 Power sharing during communication (case III)

In fact, the outage of any inverter terminal in the MTDC system means that there is no power consumed by that terminal, so the other inverter can benefit from this outage and minimize the contribution of its dispatchable unit. Figures 4.12 and 4.13 prove the benefit that is achieved by inverter #3 due to the outage of inverter #4. At t = 150 sec, inverter #4 is reconnected to the MTDC system, so at this instant, the power is shared between the inverter terminals based on the agreement of sharing. In other words, the outage of any terminal is shown by the cooperative strategy as zero power requested.

It is clear that the dispatchable unit at the AC side of inverter #4 worked at its minimum power, which is 50 MW according to [60]. Nonetheless, even though one of the inverters had an outage, the other inverter still benefited from this contingency situation. The power flow of this case is summarized in table 4-4. Therefore at t = 90 sec, the requested power from terminal #3 is equal to 97MW, but the available power that can be delivered from the dispatchable unit is 50MW. In this case, the operator must curtail a part of its load.

At t = 120 sec, the dispatchable unit is able to deliver the required power, so there is no need to curtail any part of the system load.

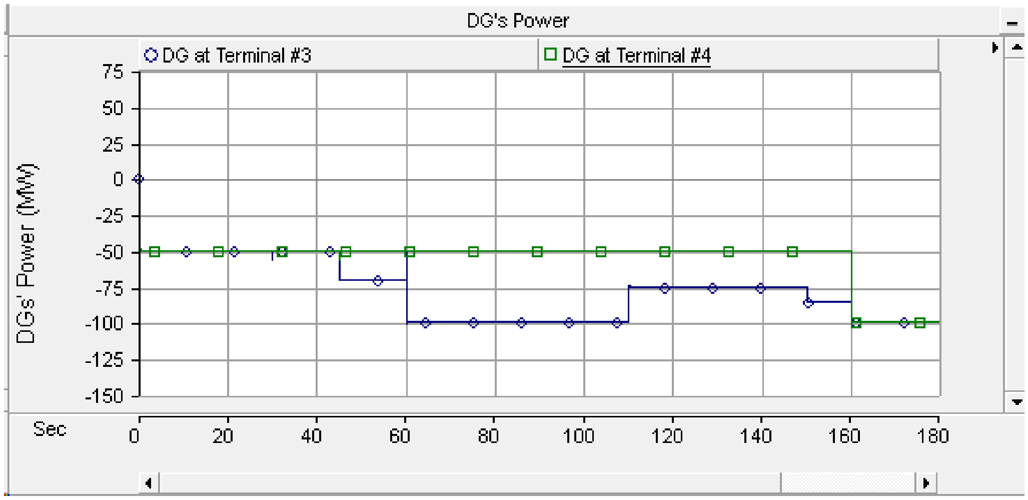


Figure 4.13 Dispatchable units` power during communication (case III)

Table 4-4 Summarizes all Scenarios of the Cooperative Study during a Terminal Outage with Communication

Time	Wind Speed	Wind power terminal #1	Slack DC terminal #2	Required power of Inverter #3	Delivered power into #3	Required power of Inverter #4	Delivered power into #4	Unit #3	Unit #4
Sec	(m/sec)	(MW)		(MW)		(MW)			
0	7	58.266	-55.71	0	0	0	0	-50	50
30	7	58.306	24.05	80	80	0	0	-50	50
45	7	58.277	38.97	80	60	-35	-35.00	-70	50
60	10	83.386	14.348	50	Terminal out	-35	-35.00	-100	50
90	10	83.457	-56.150	97	Terminal out	-85	-85.00	-100	50
110	10	66.535	-39.530	25	Terminal out	-85	-85.00	-75	50
120	8	66.603	31.086	25	Terminal out	-85	-85.00	-75	50
135	8	66.737	30.567	25	Terminal out	-30	-30.00	-75	50
150	8	66.743	30.428	97	-65	-30	-30.00	-82	50
160	8	58.266	-55.714	97	-47.00	-97	-47.00	-100	100

4.3.4 Cooperative Study during a Terminal Outage with no Communication (Case: IV)

In this case, terminal #3 is disconnected from the DC side at t = 60 sec, so it affects the DC voltage by slightly over voltage as shown in Figure 4.14. Therefore, the power that can be consumed by terminal #4 is limited because of the absence of communication, and it is clear that during this case, the slack bus just collected the remainder of the power that was generated by the wind farm terminal as shown in Figure 4.15.

At t =150 sec, the DC voltage is decreased due to the fact that terminal #3 is reconnected to the MTDC system. Moreover, the high transient in power curves in Figure 4.15 because the reconnecting of terminal #3 happened with a high request of power from the MTDC system.

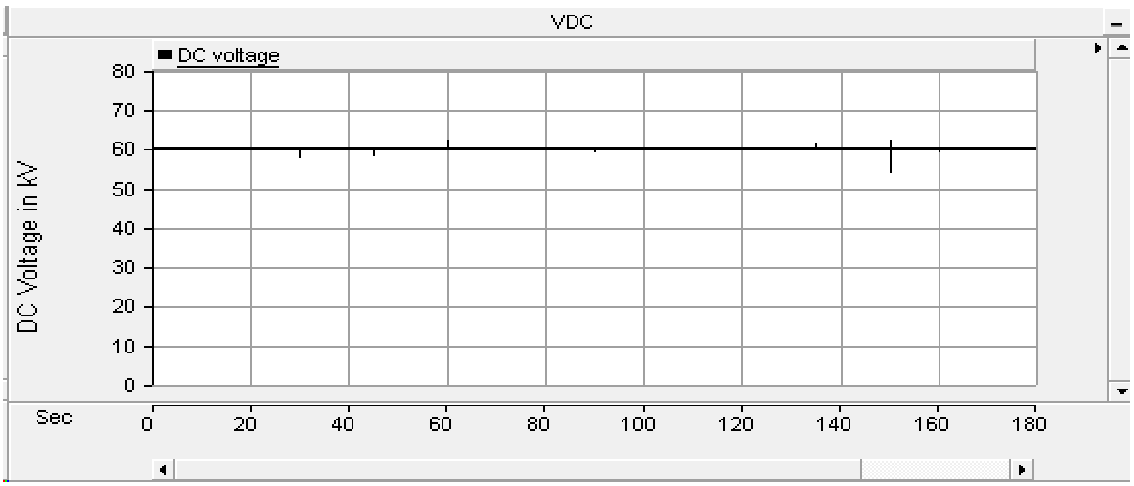


Figure 4.14 DC Voltage level during the absence of communication (case IV)

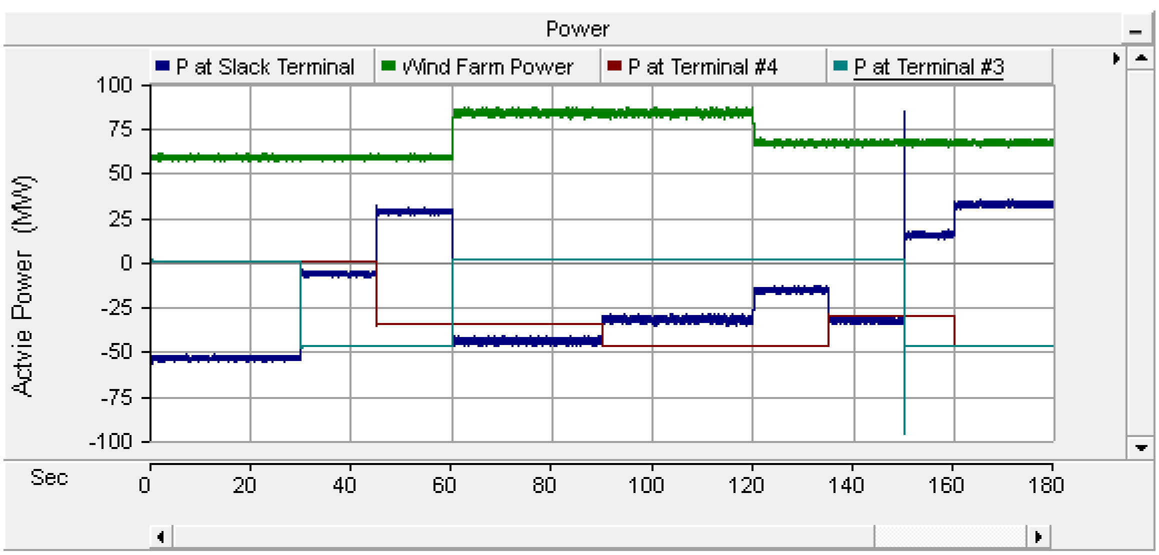


Figure 4.15 Power sharing during communication (case IV)

During the outage period, the dispatchable unit at the AC side of terminal #3 is working at its rated power as shown in Figure 4.16. However, at t = 90 sec, there is a shortage between the requested and the delivered power. Thus at this moment, it is necessary for the operator to curtail a part of the load or compensate by employing a standby generator such as a diesel generator.

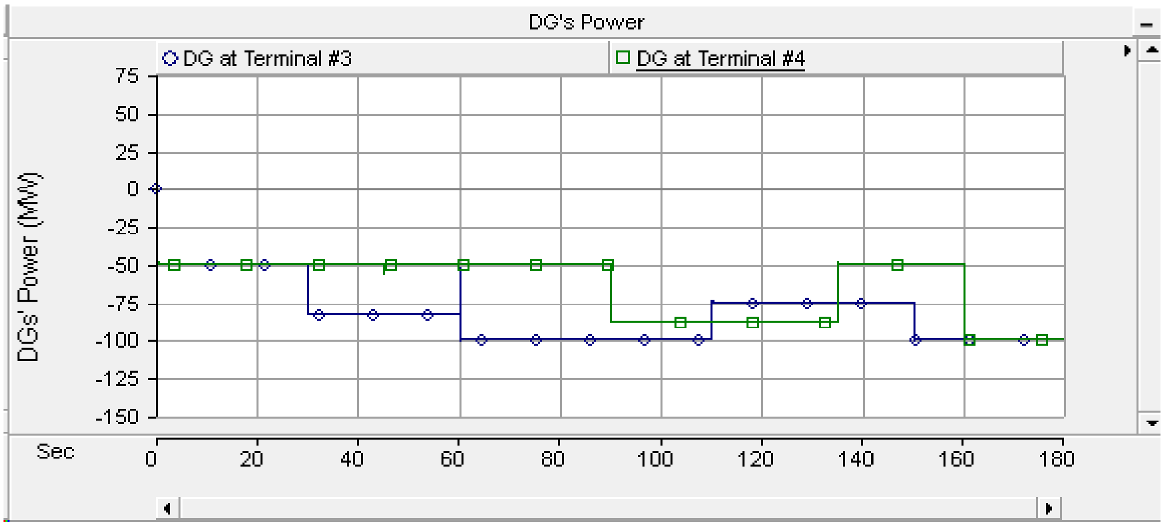


Figure 4.16 Dispatchable unit's power during communication (case IV)

It obvious that in this case the dispatchable unit of terminal #3 is providing its rated power most of the time to match the demand. Table 4-5 summarizes the power flow of the system.

Table 4-5 Summarizes all Scenarios of the Cooperative Study during a Terminal Outage with no Communication

Time	Wind Speed	Wind power terminal #1	Slack DC terminal #2	Required power of Inverter #3	Delivered power into #3	Required power of Inverter #4	Delivered power into #4	Unit #3	Unit #4
Sec	(m/sec)	(MW)		(MW)		(MW)			
0	7	58.30	-54.20	0	0	0	0	50	50
30	7	58.31	-7.12	80	-47.00	0	0	83	50
45	7	58.30	27.98	80	-47.00	35	-35.00	83	50
60	10	83.38	-44.42	50	Terminal out	35	-35.00	100	50
90	10	83.29	-32.38	97	Terminal out	85	-47.00	100*	85
110	10	83.29	-32.38	25	Terminal out	85	-47.00	75	85
120	8	66.62	-15.93	25	Terminal out	85	-47.00	75	85
135	8	66.65	-32.94	25	Terminal out	30	-30.00	75	50
150	8	66.65	14.89	97	-47	30	-30.00	100	50
160	8	66.74	32.06	97	-47	97	-47.00	100	100

4.4 Summary of the Unidirection Power Flow Study

The proposed control strategy is tested during four different cases. In the first case, when the communication between inverter #3 and #4 is active, the proposed control strategy worked properly, and it showed the merit of how the available power can be shared between the inverter terminals. Moreover, the power consumed from dispatchable units are decreased; which means a decrease in the operational cost of the dispatchable units.

In the second case, when the communication between inverter #3 and #4 is inactive, the proposed control strategy proved the feature of preventing the possibility of overloading for all terminals.

In the third case, when one of the terminals lost the connection with the MTDC system and the communication still is active, the proposed control strategy proved its feature to share all power to the the connected terminal.

The last case, when one of the terminals lost the connection with the MTDC system and the communication is inactive, the proposed control strategy showed that the total power that can be consumed is just the permitted percentage.

4.5 Bidirectional Power Flow

The proposed control algorithm works to share the power among MTDC systems in both directions. Moreover, in the bidirectional power flow study, the MTDC system has one more terminal that is working as a slack bus; therefore converter #2 and #5 are the slack terminals as shown in Figure 4.17.

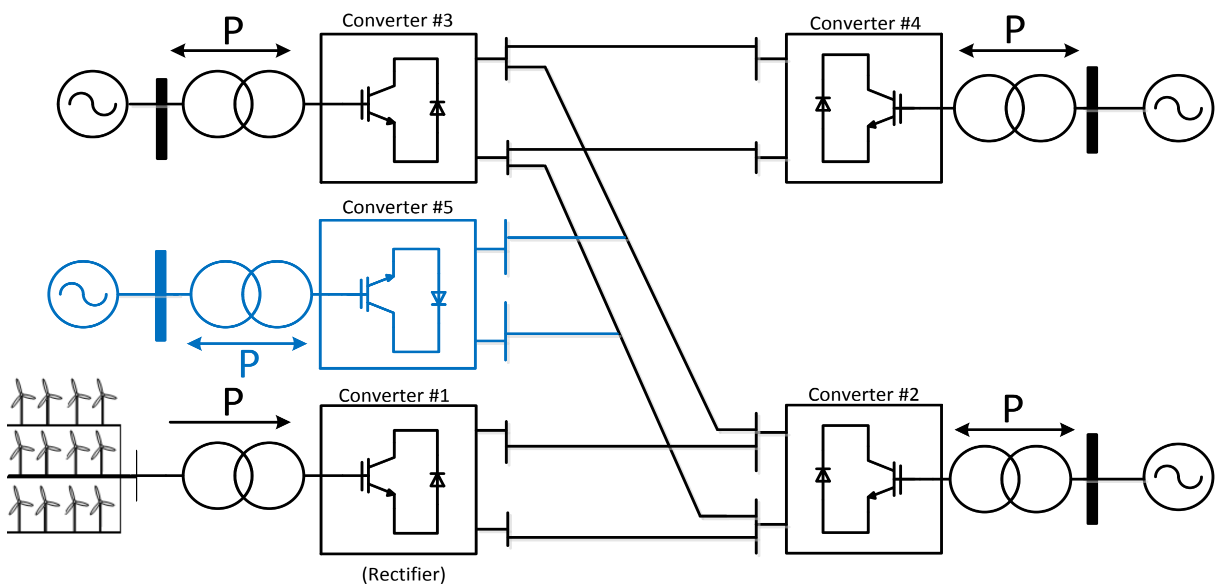


Figure 4.17 MTDC system with extra slack terminal

Table 4-6 Simulation actions

Wind Speed (m/sec)	Wind power (MW) at Inverter #1	Time (sec)	Required power of Inverter #3 (MW)	Required power of Inverter #4 (MW)
7	58.24	0	0	0
		0.5	0	80
10	83.37	1	35	80
		1.5	80	80
8	66.69	2	80	-70
		2.5	-55	-70
11	91.60	3	-55	-15
		3.5	-85	-15
10	83.32	4	0	0

The reason for adding a terminal is to show equal power sharing when the MTDC system contains multiple slack buses. In this case, table 4-6 summarizes the actions of power commands that are applied in the simulation test, and the total power that can be shared is equal to 100 MW.

4.5.1 Equal Power Sharing (case V)

In this case equal power sharing is achieved due to the existence of communication between the two slack buses. Figure 4.18 shows the power sharing in this case. At t=0 sec, all wind power goes to the slack terminals converter #2 and converter #5 because of no power requested for both inverters. During the first half second in Figure 4.18, the wind power is divided equally between two slack terminals because of the existence of the communication among the terminals. In other words, the adaptive droop control is valid, so the power curves are above each other.

At t = 0.5 sec, terminal #3 and #4 request more than fifty percent of the allowed power that can be consumed, so both of them just collect 50MW according to the arrangment as shown in the Figure.

Converter #4 is changed from absorbing to supplying power at t = 2 sec, at the same time converter #3 gets its requested power because of power availability.

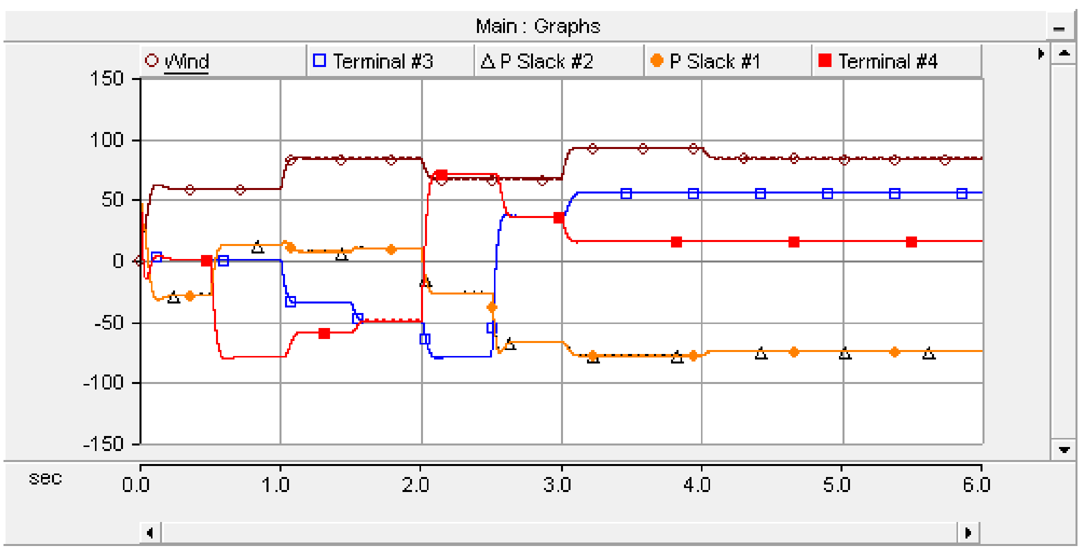


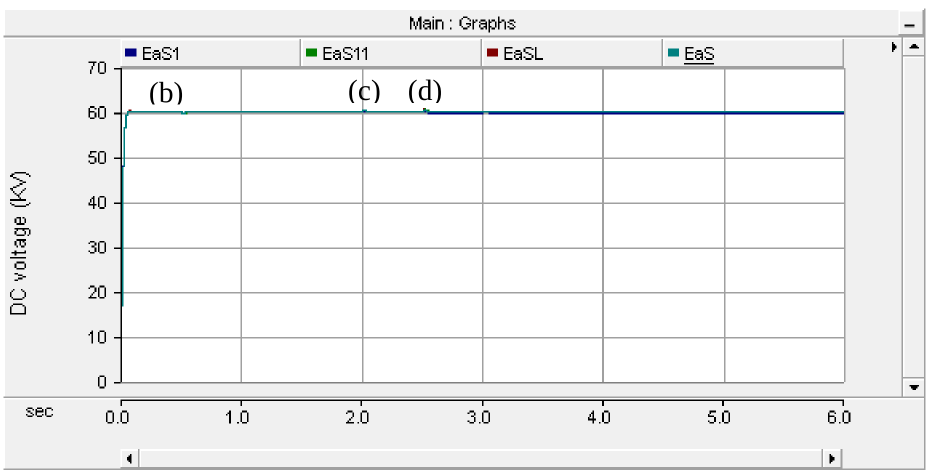
Figure 4.18 Equal Power Sharing (case V)

During supplying power to the slack terminals, the total power that is allowed to be supplied to the MTDC system is equal to 70 MW as shown in Figure 4.18 at t = 2 sec. The reason for this difference between absorbing and supplying power is to prove the flexibility of the proposed strategy.

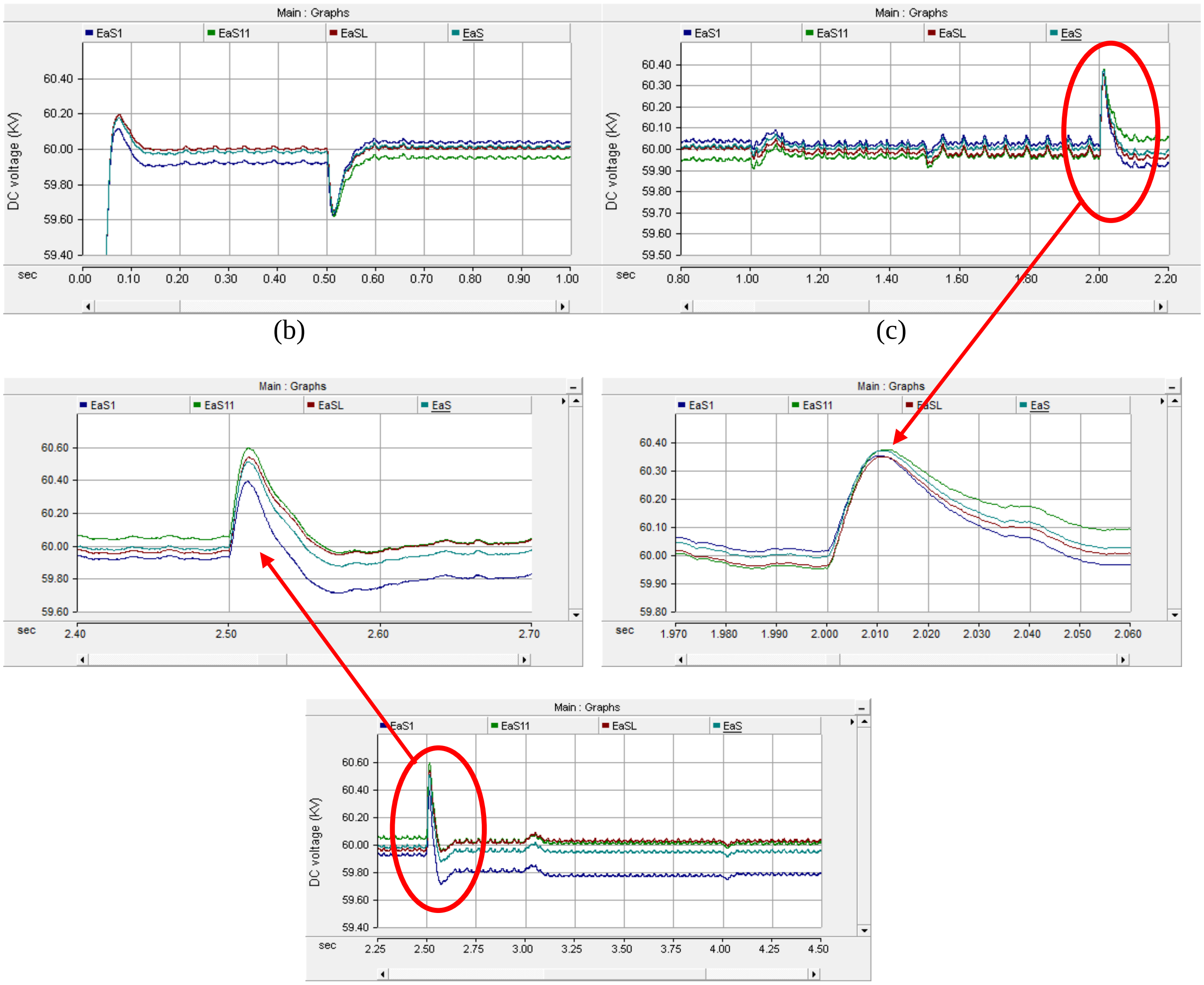
At t = 2 sec, terminal #4 is supplying the permitted amount of power into the MTDC system, but when terminal #3 is changed to supplying power into the MTDC system at t = 2.5 sec, the supplied power from terminal #4 will decrease until it reaches the limit of the power supply.

At t = 3 sec, the available power that can be supplied from terminal # 4 is decreased. Consequently, terminal #3 can supply more power into the MTDC system when it is available as shown in this period.

The stability of the MTDC system can be judged based on the DC voltage level, so when the DC voltage has a wide window of fluctuation that means the MTDC system is unstable. As a result, in this case, the MTDC system is stable as shown in Figure 4.19 (a), and the DC voltage is constant based on the amount of power sharing.



(a)



(d)

Figure 4.19 DC Voltage Level during the Existence of Adaptive Droop (case V)

4.5.2 Unequal Power Sharing between Slack Terminals (case VI)

As mentioned in the previous section using the adaptive droop control strategy ensures equal power sharing among the slack terminals in case of supplying or absorbing power. In fact, the reason for unequal power sharing between slack terminals using conventional droop is the DC line resistance.

In this case, the same actions of power commands as mentioned table 4-6 are applied. The slack terminals are controlling the DC voltage level of the MTDC system. Nevertheless, in this case, when communication is lost between the slack terminals, the DC voltage control will change immediately to the conventional droop. As shown in Figure 4.20, at t = 1.5 sec, the communication between the slack terminal is deactivated, and at t = 4.5 sec the communication is reactivated. It is clear that, the conventional droop strategy does not provide equal power sharing among terminals, but it is necessary to be valid during the absence of communication to keep the MTDC system stable during abnormal operating conditions.

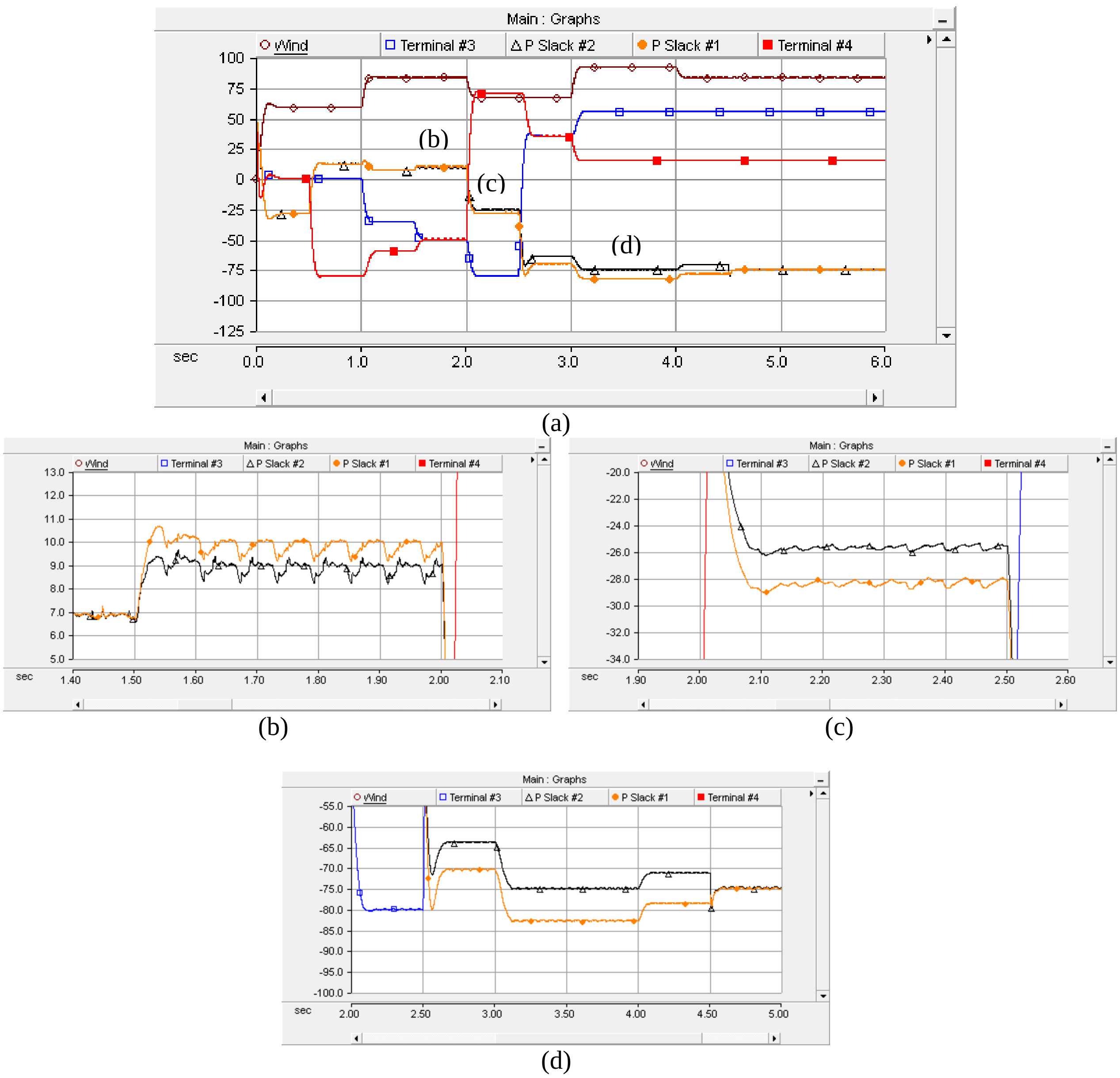


Figure 4.20 Unequal Power Sharing between Slack Terminals

As shown in Figure 4.20, the power difference between the slack terminals is affected by the amount of supplying or absorbing power. Still, the MTDC system in this case is stable because the DC voltage is constant as shown in Figure 4.21.

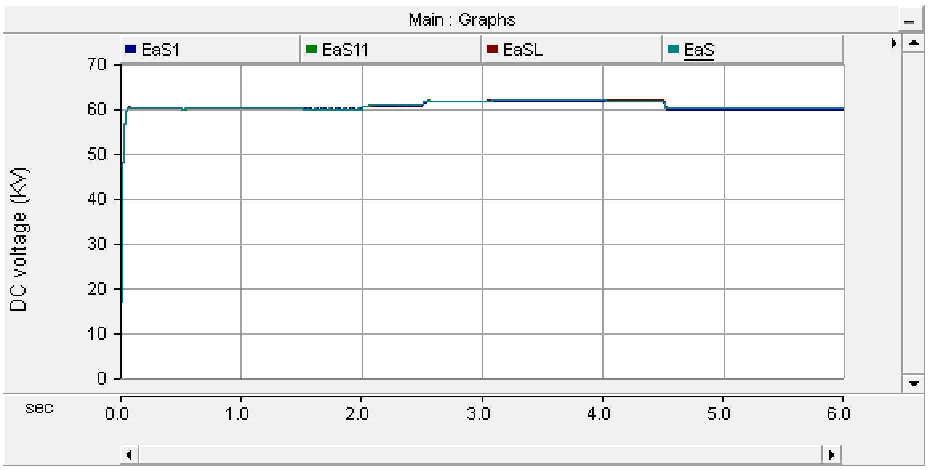


Figure 4.21 DC Voltage Level during Unequal Power Sharing between Slack Terminals

4.6 Summary of the Bidirectional Power Flow Study

In this study, the proposed control strategy is tested when the MTDC system in this study has two slack terminals, and the power flow among all terminals are bidirectional except the wind terminal. This study consists of two cases which are equal power sharing that is supplied by slack terminals and unequal power sharing between slack terminals.

In the case of equal power sharing between slack terminals, the proposed control strategy worked properly with the system that has multiple slack terminals. Moreover, the power was shared among the MTDC system in perfect manner, and the proposed control strategy had an establishment of different power-sharing percentages for supplying or consuming power among terminals.

In the case of unequal power sharing between slack terminals, the proposed control strategy demonstrated its capability to share power between the terminals that were worked in power control mode equally. Finally, when the communication between the slack terminals was lost, the conventional droop control strategy was valid immediately, so the MTDC system was stable.

4.7 Summary

This chapter studies a novel control strategy for active power sharing among MTDC system terminals. The simulation results prove that the proposed control strategy is a robust, reliable, and economical option for power sharing among MTDC systems. The simulation results also demonstrate the effectiveness of the proposed method for implementation with MTDC systems that interconnect a variety of onshore grids with offshore generation involving different loading peak times, such as European offshore wind farms. Significant benefits have been demonstrated with respect to decreasing operating costs and to rendering the system immune to the overloading of the terminals. The test system in this thesis, simulated using a PSCAD/EMTDC environment, consists of a detailed switching VSC terminals.

Chapter 5
Conclusion and Future Work

In this thesis, the proposed cooperative strategy is tested with different cases, and these cases are categorized based on communication availability. The first category is investigated when the communication between inverters was valid. The second category happens during the absence of communication between the inverters.

5.1 Conclusion

This thesis introduces a novel cooperative control strategy for active power sharing among MTDC system terminals. The simulation results of two intensive studies prove that the proposed cooperative control strategy is robust, reliable and an economical option for power sharing among MTDC systems. Moreover, the simulation results show the effectiveness of the proposed strategy to be implemented for MTDC systems that interconnect different onshore grids with a different loading peak time such as European offshore wind farms. Significant benefits such as preventing the possibility of overloading for all terminals, sharing power based on an agreement with (different or equal) percentages, and reducing energy generated from dispatchable units or AC systems whenever there is available power in the MTDC system. This has decreased operating costs and rendered the system immune to the overloading of the terminals. Nevertheless, the proposed control decreases the contribution of AC system power generation whenever there is avialable power that can be delivered from the MTDC system to decrease the operational cost, and this proposed strategy control allows different agreement ratios; therefore, it is not only equal power sharing. The test system in this thesis consists of four detailed switching VSC terminals and two dispatchable units with inverter terminals, and it is simulated through the PSCAD/EMTDC environment.

5.2 Future work

- The AC supply of MTDC system in this thesis is considered as a balanced AC source, but it is important to study the proposed cooperative strategy during unbalanced AC sources.

- The transmission lines in the DC side are considered as a resistance, but in the real system there are some capacitance and inductance contained in a DC filter. In other words, it is necessary to design either a DC overhead line or a DC cable .
- Fault analysis is the most important thing that must be considered and studied.

Appendix A
Different Percentage of Power Sharing

It is important to notice that each inverter's terminal has a fifty percent freedom of rectifier terminal rated to be consumed. Nevertheless, the systems' operators can have a different percentage of power sharing during communication failure compared to communication based on the agreement or dispatchable unit rated power or power management policy. It is easy to show the merit of different percentages during communication failure as shown in Figure A.1. This merit gives an advantage for the proposed cooperative strategy to be more reliable, economical, and practical. The percentage of power sharing among the inverters is changed from 50% to 65%, and 35% for inverter #1 and Inverter #2 respectively. At t=1sec in Figure A.1, the communication between inverters is lost.

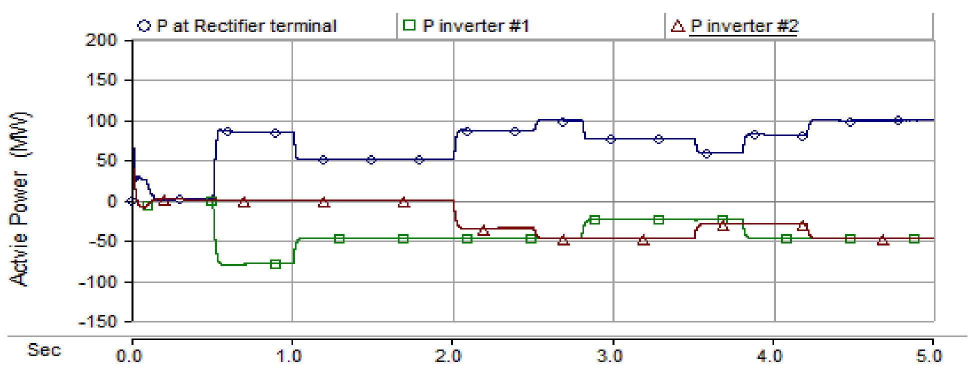


Figure A.1 Power sharing for cooperative case with no communication and 65%, and 35% for inverter #1 and Inverter #2 respectively.

The dispatchable units generate more power during communication failure as can be seen in Figure A.2. However, reducing the dispatchable units' power generation is solved by different percentages of power sharing during communication failure.

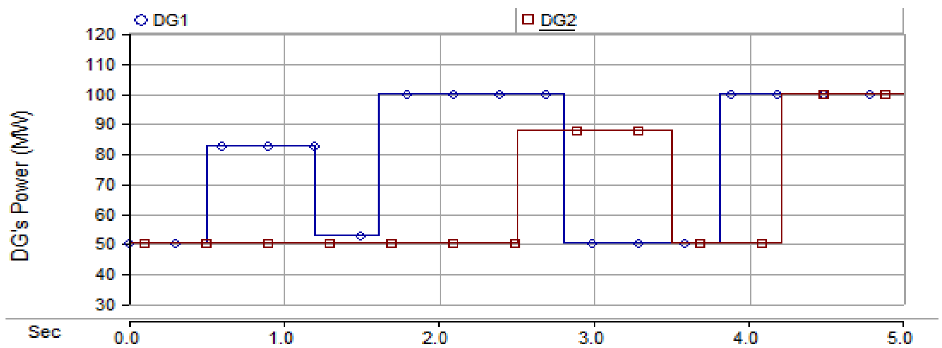


Figure A.2 Dispatchable units' power generation with no communication.

Considering different percentages of power sharing during communication failure affects dispatchable generators. In other words, the inverter terminal with a lower percentage of power consumption will obligate its dispatchable unit to generate more power as shown in Figure A.3 where the rated power for dispatchable units in this case is different compared to the previous case. The dispatchable units' parameter with the inverter that has 65% of power consumption is unit #2 in Table II and the other dispatchable thermal generator is unit #4 in Table II.

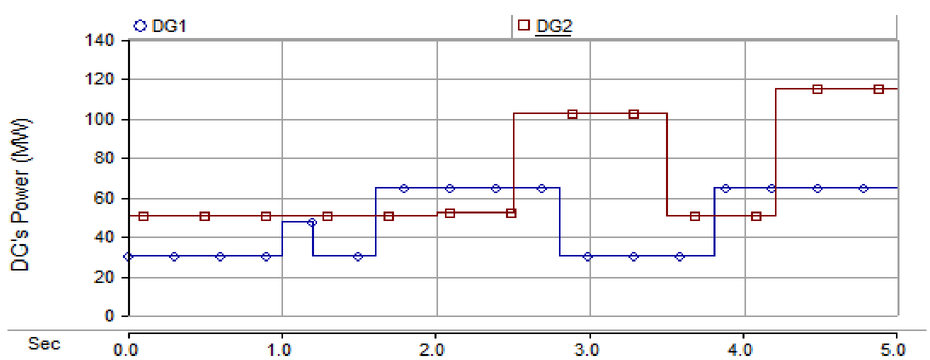


Figure A.3 Dispatchable units' power generation with no communication and 65%, and 35% for inverter #1 and Inverter #2 respectively.

In the case with different power sharing percentages, dispatchable unit #1 has not changed compared to #2, so the amount of its generated power is less than the case with an identical percentage. As a result, the proposed control minimizes the contribution of the dispatchable units` power generation to decrease the operational cost.

References

[1] eurobserv-er.org, “WIND ENERGY BAROMETER,” 2014. [Online]. Available: http://www.eurobserv-er.org/downloads.asp.

[2] E. E. Transmission, A. Behira, and A. Fertilizers, “High Voltage Direct Current Transmission A Review , Part I,” in *Energytech, 2012 IEEE*, 2012, pp. 1–7.

[3] B. R. Andersen, “VSC Transmission Tutorial held at the 2005 , CIGRE B4 meeting Bangalore , India,” India, 2005.

[4] V. Sood, *HVDC and Facts Controllers - Applications of Static Converters in Power Systems*. Kluwer Academic Publishers, 2004.

[5] V. G. Agelidis and N. Flourentzou, “Recent Advances in High-Voltage Direct-Current Power Transmission Systems Aconnections,” in *IEEE International Conference*, 2006, pp. 206–213.

[6] A. L. P. De Oliveira, C. E. Tibúrcio, M. N. Lemes, D. Retzmann, and M. Ieee, “Prospects of Voltage-Sourced Converters (VSC) applications in DC Transmission Systems,” in *Transmission and Distribution Conference and Exposition*, 2010, pp. 491–495.

[7] R. Mukhedkar, “Introduction to HVDC LCC & VSC - Comparison HVDC Converter Technology,” *South Asia Regional Initiative for Energy Integration*, 2010. [Online]. Available: www.sari-energy.org.

[8] N. Mohan, T. Undeland, and Robbins, *Power Electronics: Converters, Applications and Design*. John Wiley & Sons Inc, 2003.

[9] M. Larsson, “HVDC and HVDC Light An alternative power transmission system,” 2009. [Online]. Available: http://www.mit.edu/~ysharon/enrgysym/talks/larsson_talk.pdf.

[10] P. F. De Toledo, “Feasibility of HVDC for City Infeed,” Royal Institute of Technology Department, 2003.

[11] R. Rudervall, J. Charpentier, and R. Sharma, “High Voltage Direct Current (HVDC) Transmission Systems Technology Review Paper,” in *in Energy Week, Washington, D.C*, 2000, pp. 1–17.

[12] M. P. Bahrman and B. K. Johnson, “The ABCs of HVDC transmission technologies,” *IEEE Power Energy Mag.*, no. april, pp. 32–44, 2007.

[13] J. Zhu and C. Booth, “Future Multi-Terminal HVDC Transmission Systems using Voltage Source Converters,” in *Universities Power Engineering Conference (UPEC), 2010 45th International*, 2010, pp. 1–6.

[14] E. Prieto-araujo, F. D. Bianchi, A. Junyent-ferré, and O. Gomis-Bellmunt, “Methodology for Droop Control Dynamic Analysis of Multiterminal VSC-HVDC Grids for Offshore Wind Farms,” *IEEE Trans. POWER Deliv.*, vol. 26, no. 4, pp. 2476–2485, 2011.

[15] Canadian Wind Energy Association, “Wind Vision 2025,” 2014. [Online]. Available: http://canwea.ca/about-canwea/visionmission/.

[16] N. Chaudhuri and C. Balarko, “Adaptive Droop Control for Effective Power Sharing in Multi-Terminal DC (MTDC) Grids,” *IEEE Trans. Power Syst.*, vol. 28, no. 1, pp. 21–29, 2013.

[17] N. Mohan, T. Undeland, and william Robbins, *Mohan_Power_Electronics.pdf*. John Wiley & Son, 1995.

[18] Y. Amirnaser and I. Reza, *VOLTAGE-SOURCED CONVERTERS IN POWER SYSTEMS*. New York: Wiley, 2010.

[19] S. Khomfoi and L. M. Tolbert, *Multilevel Power Converters*, 2nd Editio. Elsevier Ltd, 2007.

[20] S. G. Johansson, G. Asplund, E. Jansson, and R. Roberto, “Power System Stability Benefits with VSC DC-Transmission Systems,” in *CIGRE Conference*, 2004, pp. 1–8.

[21] V. Sood, F. Ieee, H. Patel, and S. M. Ieee, “Comparison between Direct and Vector control Strategy for VSC-HVDC system in EMTP-RV,” in *Power Electronics, Drives and Energy Systems (PEDES)*, 2010, pp. 1–6.

[22] M. Riaz, “dq Transformations,” *University of Minnesota*, 2011. [Online]. Available: http://www.ece.umn.edu/users/riaz/animations/dqtranformeq.pdf.

[23] K. Eriksson, “HVDC Light ™ and development of Voltage Source Converters,” in *IEEE PES Transmission & Distribution*, 2003, pp. 1–5.

[24] R. Sellick and M. Åkerberg, “Comparison of HVDC Light (VSC) and HVDC Classic (LCC) Site Aspects, for a 500MW 400kV HVDC Transmission Scheme,” in *IET ACDC*, 2012, no. Lcc, pp. 1–6.

[25] J. R. Lucas, “High Voltage Direct Current Transmission,” in *High Voltage Engineering*, Faculty of Engineering, University of Moratuwa, 2001, pp. 1–204.

[26] E. Kontos, “Control and Protection of VSC-based Multi-terminal DC Networks,” Delft University of Technology, 2013.

[27] G. Tang, H. Zhiyuan, and H. Pang, “R&D and application of voltage sourced converter based high voltage direct current engineering technology in China,” *J. Mod. Power Syst. Clean Energy*, vol. 2, no. 1, pp. 1–15, Feb. 2014.

[28] D. Woodford, “Compact High Voltage Electric Power Transmission By,” 2014. [Online]. Available: http://www.electranix.com/.

[29] C.-M. Ong, *Dynamic Simulation of Electric Machinery using Matlab/Simulink*. Prentice Hall PTR, 1998, pp. 1–626.

[30] E. N. Abildgaard, “Exploring the Properties of a Modular Multilevel Converter Based HVDC Link,” Norwegian University of Science and Technology, 2012.

[31] T. M. Haileselassie, T. Undeland, and K. Uhlen, “Multiterminal HVDC for Offshore Windfarms – Control Strategy,” Helsinki, Finland, 2008.

[32] H. F. Latorre and M. Ghandhari, “Multichoice Control Strategy for VSC-HVdc Multichoice Control Strategy -MCS-,” 2007.

[33] N. R. Chaudhuri, R. Majumder, B. Chaudhuri, and J. Pan, “Stability Analysis of VSC MTDC Grids Connected to Multimachine AC Systems,” *IEEE Trans. Power Deliv.*, vol. 26, no. 4, pp. 2774–2784, Oct. 2011.

[34] A. Yazdani and R. Iravani, *VOLTAGE-SOURCED CONVERTERS IN POWER SYSTEMS*. Wiley, 2010, pp. 1–451.

[35] M. Hadjikypris and V. Terzija, “Transient fault studies in a multi-terminal VSC-HVDC grid utilizing protection means through DC circuit breakers,” in *PowerTech (POWERTECH), IEEE Grenoble*, pp. 1–6.

[36] M. Davies, M. Dommaschk, J. Dorn, J. Lang, D. Retzmann, and D. Soerangr, “HVDC PLUS – Basics and Principle of Operation,” 2008.

[37] C. Li, P. Zhan, J. Wen, M. Yao, N. Li, and W. Lee, “Offshore Wind Farms Integration and Frequency Support Control Utilizing Hybrid Multi-terminal HVDC Transmission,” in *Industry Applications Society Annual Meeting*, 2013, pp. 1–9.

[38] X. Zhao, Q. Song, H. Rao, X. Li, X. Li, and W. Liu, “Control of Multi-Terminal VSC-HVDC System to Integrate Large Offshore Wind Farms,” *Int. J. Comput. Electr. Eng.*, vol. 5, no. 2, pp. 201–206, 2013.

[39] J. M. Guerrero, L. GarciadeVicuna, J. Matas, M. Castilla, and J. Miret, “A Wireless Controller to Enhance Dynamic Performance of Parallel Inverters in Distributed Generation Systems,” *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1205–1213, Sep. 2004.

[40] K. De Brabandere, B. Bolsens, J. Van Den Keybus, A. Woyte, and J. Driesen, “A Voltage and Frequency Droop Control Method for Parallel Inverters,” *IEEE Trans. POWER Electron.*, vol. 22, no. 4, pp. 1107–1115, 2007.

[41] F. Luo, Y. M. Lai, K. H. Loo, C. K. Tse, and X. Ruan, “A generalized droop-control scheme for decentralized control of inverter-interfaced microgrids,” in *2013 IEEE International Symposium on Circuits and Systems (ISCAS2013)*, 2013, pp. 1320–1323.

[42] C. Li, P. Zhan, J. Wen, M. Yao, N. Li, and W.-J. Lee, “Offshore Wind Farms Integration and Frequency Support Control Utilizing Hybrid Multi-terminal HVDC Transmission,” *IEEE Trans. Ind. Appl.*, vol. pp, no. 99, pp. 1–1, 2014.

[43] J. Cao, W. Du, H. F. Wang, and S. Q. Bu, “Minimization of Transmission Loss in Meshed AC / DC Grids With VSC-MTDC Networks,” *Power Syst. IEEE Trans.*, vol. 28, no. 3, pp. 3047–3055, 2013.

[44] J. C. Vasquez, J. M. Guerrero, A. Luna, P. Rodríguez, and R. Teodorescu, “Adaptive Droop Control Applied to Voltage-Source Inverters Operating in Grid-Connected and Islanded Modes,” *Ind. Electron. IEEE Trans.*, vol. 56, no. 10, pp. 4088–4096, 2009.

[45] S. M. F. Rodrigues, “Dynamic Modeling and Control of VSC-based Multi-terminal DC Networks,” Instituto Superior Técnico, 2011.

[46] R. T. Pinto, S. F. Rodrigues, P.Bauer, and J. Pierik, “Comparison of Direct Voltage Control Methods of Multi-Terminal DC (MTDC) Networks through Modular Dynamic Models,” in *Power Electronics and Applications*, 2011, pp. 1–10.

[47] R. T. Pinto, P. Bauer, S. F. Rodrigues, E. J. Wiggelinkhuizen, J. Pierik, and B. Ferreira, “A Novel Distributed Direct-Voltage Control Strategy for Grid Integration of Offshore Wind Energy Systems Through MTDC Network,” *Ind. Electron. IEEE Trans.*, vol. 60, no. 6, pp. 2429–2441, 2013.

[48] L. Xu, B. W. Williams, and L. Yao, “Multi-Terminal DC Transmission Systems for Connecting Large Offshore Wind Farms,” in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,*, 2008, pp. 1–7.

[49] L. Xu, L. Yao, and M. Bazargan, "DC Grid Management of a Multi-Terminal HVDC Transmission System for Large Offshore Wind Farms," in *sustainable Power Generation and Supply*, 2009, pp. 1–7.

[50] O. A. Giddani, G. P. Adam, O. Anaya-Lara, and K. L. Lo, "GRID INTEGRATION OF OFFSHORE WIND FARMS USING MULTI-TERMINAL DC TRANSMISSION SYSTEMS (MTDC)," in *Power Electronics, Machines and Drives (PEMD 2010), 5th IET International Conference*, 2010, pp. 1–6.

[51] T. Nakajima and S. Irokawa, "Control System for HVDC Transmission by Voltage Sourced Converters," in *Power Engineering Society Summer Meeting*, 1999, pp. 1113–1119.

[52] W. Wang, S. Member, M. Barnes, and S. Member, "Power Flow Algorithms for Multi-Terminal VSC-HVDC With Droop Control," *Power Syst. IEEE Trans.*, vol. pp, no. 09, pp. 1–10, 2014.

[53] X. Lie and Y. Williams, B. W. Liangzhong, "Multi-terminal DC transmission systems for connecting large offshore wind farms," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1–7.

[54] S. Gonzalez-Hernandez, E. Moreno-Goytia, and O. Anaya-Lara, "Analysis of wide area integration of dispersed wind farms using multiple VSC-HVDC links," in *Power Electronics and Motion Control Conference, 2008. EPE-PEMC 2008. 13th*, 2008, pp. 1784–1789.

[55] D. Tao, Z. Chengxue, H. Zhijian, and D. Zhiyuan, "Coordinated control strategy for multi-terminal VSC-HVDC based wind farm interconnection," in *Sustainable Power Generation and Supply,*, 2009, pp. 1–6.

[56] X. Chen, H. Sun, J. Wen, W.-J. Lee, X. Yuan, N. Li, and L. Yao, "Integrating Wind Farm to the Grid Using Hybrid Multiterminal HVDC Technology," *IEEE Trans. Ind. Appl.*, vol. 47, no. 2, pp. 965–972, Mar. 2011.

[57] B.Berggren, R.Majumder, C. Sao, and K. Linden, "METHOD AND CONTROL DEVICE FOR CONTROLLING POWER FLOW WITHIN A DC POWER TRANSMISSION NETWORK," 2013.

[58] M. Pipattanasomporn, H. Feroze, and S. Rahman, "Multi-agent systems in a distributed smart grid: Design and implementation," in *2009 IEEE/PES Power Systems Conference and Exposition*, 2009, pp. 1–8.

[59] A. L. Dimeas, S. M. Ieee, N. D. Hatziargyriou, and S. M. Ieee, "Agent based control of Virtual Power Plants," in *Intelligent Systems Applications to Power Systems*, 2007, pp. 1–6.

[60] G. P. V. B. System, B. Lu, and M. Shahidehpour, "Short-Term Scheduling of Battery in a Grid-Connected PV/Battery System," *IEEE Trans. POWER Syst.*, vol. 20, no. 2, pp. 1053–1061, 2005.

[61] K. Rudion, a Orths, P. B. Eriksen, and Z. a Styczynski, "Toward a Benchmark test system for the offshore grid in the North Sea," *IEEE PES Gen. Meet.*, pp. 1–8, Jul. 2010.