INTERCONNECTION OF DIRECT-DRIVE WIND TURBINES
USING A SERIES CONNECTED DC GRID

by

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Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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This thesis presents the concept of a “distributed HVDC converter” for offshore wind farms. The proposed converter topology allows series interconnection of wind turbines obviating the necessity of transformers and an offshore platform. Each wind turbine is equipped with a 5MW permanent-magnet synchronous generator and an ac-dc-dc converter. The converter topology is a diode rectifier (ac-dc) cascaded with a single-switch step-down converter (dc-dc). The dc-dc stage allows the current to flow at all times in the dc link while regulating generator torque. The receiving end is equipped with a conventional thyristor-based HVDC converter. The inverter station is located onshore and it regulates the dc link current to be constant. Stability of the configuration and independent operation of the wind turbines are validated through simulations using the PSCAD/EMTDC software package. Protection for some key dc fault scenarios are discussed and a possible protection strategy is proposed.

Résumé

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Cette thèse présente le concept d'une distribution de convertisseurs à courant continu à haute tension pour un parc éolien installé en mer. La topologie du convertisseur proposée permet l'interconnexion en série des éoliennes éliminant ainsi le besoin de transformateurs et de plateformes en mer. Chaque éolienne est équipée d'un alternateur synchrone à aimants permanents de 5MW et d'un convertisseur ca-cc-cc. L'arrangement du convertisseur consiste en un pont redresseur à diodes (ca-cc) relié à un convertisseur abaisseur (cc-cc). Ce convertisseur cc-cc permet au courant de circuler à tout moment dans le lien cc tout en ajustant le couple de l'alternateur. À l'autre extrémité, la réception est conçue avec un convertisseur cc-ca conventionnel à thyristors. Cet onduleur est localisé sur un site terrestre et il maintient le courant du lien cc constant. La stabilité du système et le fonctionnement indépendant des éoliennes sont validés par des simulations effectuées avec le logiciel PSCAD/EMTDC. La protection pour quelques scénarios de fautes est discutée et une stratégie de protection est proposée.

À ma petite chérie, Annie.

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Chapter 1

Introduction

Recent national energy policies around the world are aiming to have 20% of electricity production from renewable energy [1]. Offshore wind power is expected to play a major role in meeting this target [2]. Large wind farms are composed of multi-megawatt wind turbines for an aggregate power potential that can go to hundreds of megawatts and beyond. The interconnection of these units represents a technical challenge because of both the location of the units and the stochastic nature of the produced power.

Existing offshore wind farms are located within 10km of the coast, but this distance is expected to increase significantly in future projects [3]. High-voltage direct current (HVDC) technology has proven its advantage for long distance transmission and also in submarine applications [4]. The use of HVDC transmission for distant offshore wind farms provides an economically viable solution [3, 5]. Presently, offshore wind farms with HVDC links install a rectifier station on a platform erected in the sea [6]. Figure 1.1(a) shows such an arrangement. Wind turbines are interconnected via a 33kV ac collector network with power supplied to a converter transformer and then to a rectifier station. An inverter station is located onshore and it is connected to the grid. As may be seen, electricity produced goes through many conversion stages, both via ac transformers and via ac/dc and dc/ac converters. Both from an initial cost and a system efficiency perspective it would be advantageous to have

Figure 1.1: Various offshore wind farm configuration suggested in the literature.

a configuration that minimizes the number of conversion stages. This has led to significant research activity in the area of dc collector grids.

A dc grid with parallel interconnection of wind turbines is shown in Figure 1.1(b). Various approaches have been studied in [7], [8] and [9]. The dc voltage must be boosted significantly above the generator's peak terminal voltage level in order to avoid large current at the collector. An optimal position for a single active bridge converter (step-up) has been studied in order to reduce losses [9]. It has been concluded that having one main (common) step-up converter is the best solution for long distance transmission, but this again requires the installation of a platform in the sea.

Another approach suggests series interconnection of wind turbines [10, 11]. Figure 1.1(c) shows the configuration suggested in [11] which uses current-source inverters (CSI). Each converter carries the same current while the voltage on the dc link is achieved by summation of the converter voltages. The cited approach regroups wind turbines into small clusters of

Table 1.1: Equipment needed per topology.

Figure	Power Electronics			3phase Transformers	Platform
	Diode	Thy	IGBT		
1.1(a)	-	12	12	3	1
1.1(b)	6	-	18	1	1
1.1(c)	12	-	12	1	1
1.2	7	6	1	1	0

Table 1.2: MWs of power electronics needed per MW produced.

Figure	Diode	Thy	IGBT	Total
1.1(a)	-	4	4	8
1.1(b)	2	-	6	8
1.1(c)	4	-	4	8
1.2	3	2	1	6

four units to counter the high cost of the CSI. The described method proposes an interesting approach to construct a multi-terminal dc grid. However, such a wind farm would not allow each wind turbine to operate independently, since turbines are grouped in clusters. Moreover, the failure of one converter would cause all four units in the cluster to go out of service. Thus a more modular approach is preferred over the formation of groups.

All configurations studied to date require several MWs of power electronic equipment to be installed for every one MW of installed capacity. Assuming variable speed synchronous generators with back-to-back converters are used, Table 1.1 compares the equipment needed to transmit the generated power to the ac grid for the arrangements of Figure 1.1. All three topologies require the construction of a platform at sea. Moreover, they all employ a minimum of 12 IGBTs, which are relatively high cost and, more importantly, high loss components. Table 1.2 compares topologies in terms of the approximate installed component power ratings. For example, if 1MW of power is processed by a voltage-source converter (VSC), roughly 2MWs of switch rating are required, since each of the 6 switches carries one third of the dc current but must support full rated dc voltage. Following this approximate approach, it is seen that, despite differing distributions, each design requires roughly 8MWs of switching components per MW produced. An economical solution should (i) avoid the

Figure 1.2: Proposed distributed HVDC configuration.

construction of a platform, (ii) reduce the number of expensive power electronics components and (iii) reduce the number of transformers.

1.1 Scope of the Thesis

This thesis suggests a new topology for series interconnection of wind turbines using a dc link as shown in Figure 1.2. This method uses dc-dc converters to create a “distributed HVDC converter” between wind turbines. The proposed topology eliminates all transformers at the sending end, and it requires no offshore platform for the rectifier station. Moreover, the converter has the minimum MWs of power electronic equipment, Table 1.2, in addition to the lowest number of components needed, Table 1.1. The proposed topology, therefore, offers the potential to reduce converter costs, reduce collector network costs, increase efficiency and avoid platform construction. The scope of this work is to explore the technical feasibility of the proposed HVDC system configuration for integrating power generation from offshore wind farms.

1.2 Objectives

The objectives of the thesis are:

- To propose a converter topology that allows series interconnection as well as independent operation of the wind turbine for peak power tracking.
- To select a suitable inverter topology and to design inverter controls adapted for this application.
- To model a complete wind farm composed of both the sending end and the receiving end.
- To introduce a possible protection scheme to address dc fault events.

1.3 Thesis Outline

Chapter 2 describes the wind turbine and the generator employed in this project. The wind turbine is chosen to be suitable for offshore application and a promising technology is selected for the generator design. Chapter 3 presents the distributed HVDC converter concept. An overview of the system is given and the dc-dc converter is detailed. Chapter 4 completes the wind turbine converter with the description of the ac-dc converter. Chapter 5 proposes the inverter station. In Chapter 6, the complete wind farm is modeled and simulated using the PSCAD/EMTDC software package. Chapter 7 introduces the system protection. Finally, a summary of the thesis and potential extensions of the project are presented in Chapter 8.

Chapter 2

Wind Turbine Characteristics and Generator Design

This chapter details two important components of a wind energy conversion system: the wind turbine and the generator.

Many aerodynamic and construction designs have been explored but nowadays almost all large wind turbines have the same profile. They are based on horizontal axis rotors with three blades, they operate at variable speed and the nacelle can rotate through yaw control to face the wind. Presently, one flourishing area of research in wind energy is the development of large generators suitable for offshore application. Manufacturers are now developing units with power capability up to 6MW. In the development of an offshore wind farm, the installation cost is significant: around one third of the total installed cost is associated with the wind turbine itself, the rest of the cost is attributed to foundation construction and electrical transmission equipment [12]. Thus, the greater power produced per installed structure, the more cost-effective is the solution. For this project a 5MW 3-bladed wind turbine will be considered.

For offshore application, robustness and high power density are two important requirements for the generator. Because of the location, mechanical failures are costly to repair. In

the direct-drive approach, the absence of a gearbox suggests an increase in reliability with the reduction of mechanical parts. Moreover, the direct-drive method has more potential for improved reliability over several years compared to other technologies [13]. As turbines are becoming more powerful, use of high power density generators can lead to major benefits in structural design. The permanent-magnet synchronous generator (PMSG) offers high power density and requires no additional equipment to supply field excitation. One drawback of this technology is the necessity of a fully rated back-to-back converter (ac-dc-ac). However, power electronics for high power applications are still developing, so cost is expected to decrease and components ratings are expected to improve. Thus, the direct-drive permanent-magnet synchronous generator is an attractive solution for future development of offshore wind farms and it is selected for this project.

Section 2.1 depicts the characteristics of the 5MW wind turbine selected for this project. It includes wind speed curves for peak power extraction, pitch control and mechanical dynamics. Section 2.2 details generator parameters used for the electromechanical conversion. The machine equivalent circuit model is derived as well as the machine equations.

2.1 Wind Turbine Characteristics

The 5MW wind turbine has a rated mechanical speed of 14.8RPM at a wind speed of 12m/s. Wind turbine parameters are based on [14] and they are detailed in Table 2.1.

2.1.1 Wind Speed Curves

Maximum power point tracking is an important aspect in wind turbine drives. It consists of adjusting the shaft speed so that the wind turbine operates at peak power. The shaft speed is regulated through torque control (current control) and the maximum power operating point depends on the wind speed. The output power of a wind turbine is expressed as [15]:

Table 2.1: Wind turbine parameters.

Wind Turbine Parameters	
Rated power [MW]	5
Rotor radius r [m]	58
Rated wind speed V_{wind} [m/s]	12
Rated mechanical speed w_m [RPM]	14.8
Rated torque [Nm]	3.226×10^6
Maximum aerodynamic efficiency C_P	48%
Optimum tip speed ratio λ_{opt}	7
Air mass density ρ_{air} [kg/m ³]	1.225
Cut-in wind speed [m/s]	3
Cut-out wind speed [m/s]	25
Hub height [m]	138
Rotor and turbine inertia J (2.55s) [kg m ²]	1.06×10^7

$$P = \frac{1}{2} \rho_{\text{air}} C_P(\lambda, \theta) \pi r^2 V_{\text{wind}}^3 \quad (2.1)$$

where ρ_{air} is the mass density of air, C_P is the aerodynamic efficiency function, r is the rotor radius and V_{wind} is the wind speed. The aerodynamic efficiency function, C_P , depends on the pitch angle θ and the tip speed ratio λ . The pitch angle, θ , is at its maximum value below the rated wind speed and varies above it. The tip speed ratio, λ , is calculated by dividing the tip speed by the wind speed.

In order to operate the generator at maximum power, it is essential to extract wind speed curves for a given unit. Such curves display the power and the torque of the wind turbine with respect to the hub speed for various wind speeds. Torque characteristic curves are shown in Figure 2.1(a) and power characteristic curves are shown in Figure 2.1(b). Details about the computation of those curves are given in Section A.1.1 of Appendix A. For each wind speed, the maximum power available is associated with a specific torque and hub speed. The optimal load torque, T_{opt} , is a curve identified as the dotted line in Figure 2.1(a).

Figure 2.1: Wind speed curves of 5MW turbine with rated wind speed of 12 m/s.

2.1.2 Pitch Control

Pitch control adjusts the aerodynamics of the blades so that the hub speed remains constant above the rated wind speed. Since pitch control dynamics are not a focus of this work, this feature is implemented by simply limiting the input wind speed to the rated value of 12m/s. By doing so, all wind speeds above 12m/s are set to the rated value and consequently the hub speed remains constant.

2.1.3 Mechanical Dynamics

The mechanical dynamics of the wind turbine are modeled using a single mass model of a stiff drive train. It is assumed that the switching of the proposed converters do not affect the average torque balance. Switching periods of the converters are in the millisecond range compared to seconds for the mechanical time constant. The impact of switching harmonics on the mechanical dynamics are thus neglected. Therefore, the first order equation is adequate and it is given as [16]:

$$J \frac{dw_m}{dt} = T_m - T_e \quad (2.2)$$

where J is the inertia of the drive train, w_m is the hub speed, T_m is the mechanical torque from the wind turbine and T_e is the electrical torque from the generator. The inertia constant J is listed in Table 2.1.

2.2 PMSG Parameters

The design of the radial flux PMSG is based on theory and equations described in [14, 17, 18]. The 5MW generator parameters are taken from [14] and it is shown in Table 2.2. Figure 2.3 illustrates a cross-section with dimensions of the PMSG. In the design process, the selection of the rated induced voltage depends on what type of converter is employed. The desired voltage is reached by selecting the number of turns per phase winding, N_s . In some cases (e.g. pairing PMSG with a diode rectifier), over-excitation is required, resulting in a higher number of turns. However, the number of turns also influences the synchronous inductance and the stator resistance. Therefore, a machine equivalent model in terms of the variable N_s is needed as shown in Figure 2.2. This model will be used to determine the number of turns required for each converter used in this project and it will be discussed in their respective sections.

Before obtaining the equivalent model, it is necessary to calculate the total number of poles and introduce constraints on the leakage ratio of the machine. The equivalent model will then be derived based on the physical construction of the machine, yielding the induced voltage, E_{PM} , the synchronous inductance, L_S , and the stator resistance, R_S . Finally, parameters and machine equations are transposed in the rotor reference frame.

Figure 2.2: Electrical diagram in terms of N_s .

2.2.1 Number of poles

The number of poles is not explicitly stated in [14] despite numerous details. However, dimensions of the generator are known as well as the pole dimensions. Therefore, it is possible to calculate the number of poles based on the circumference of the rotor and the pole pitch. The relation is shown below in Equation (2.3). Since data given in [14] have been truncated, the answer has to be rounded up to the closest even integer number. Following this approach the number of poles is 290 (145 pole-pairs).

$$P = \frac{2\pi (r_s - g)}{\tau_p} = 290 \quad (2.3)$$

2.2.2 Leakage ratio $k_{l/m}$

The value of the ratio of leakage inductance to magnetizing inductance, $k_{l/m}$, has to be larger than 1.27 to avoid any risk of demagnetization during a short circuit at the terminals [14]. On the other hand, large $k_{l/m}$ results in higher overall impedance of the machine which leads to more reactive power consumption. Based on the two arguments, $k_{l/m}$ is selected to be 1.5, as stated in Table 2.2.

Table 2.2: PM generator dimensions and characteristics.

Dimensions	
Stator radius r_s [m]	3.75
Stator length l_s [m]	1.5
Pole pitch τ_p [mm]	81.5
Stator slot height h_s [mm]	68.2
Stator slot width b_s [mm]	12.2
Stator tooth width b_d [mm]	14.9
Stator yoke height h_{ys} [mm]	17.1
Magnet height h_m [mm]	12.5
Magnet width b_m [mm]	56.8
Air gap g ($0.002r_s$) [mm]	7.5
Design Variables	
Number of slots per pole per phase q	1
Winding factor k_w	0.96
Carter factor k_c	1.02
L_{sl}/L_{sm} ratio $k_{l/m}$	1.5
Material Characteristics	
Slot filling factor k_{sfill}	0.55
Remanent flux density of the magnets B_{rm} [T]	1.2
Relative permeability of the magnets μ_{rm}	1.06
Resistivity of copper at $120^\circ C$ ρ_{Cu} [$\mu\Omega m$]	0.025
Physical Constant	
Permeability of vacuum μ_0 [H/m]	$4\pi \times 10^{-7}$

Figure 2.3: Cross-section of the PMSG.

2.2.3 Machine Equivalent Model

2.2.3.1 Induced Voltage

The induced voltage in a stator winding is given by Equation (2.4) [17, 19].

$$[E_{\text{PM}}]_{\text{LN}}^{\text{RMS}} = \sqrt{2}w_mk_w r_s l_s B_{g1} N_s = E_0 N_s \quad (2.4)$$

where w_m is the mechanical speed, k_w is the winding factor, r_s is the stator radius and l_s is the stator length. The flux density at the fundamental space harmonic, B_{g1} , has the form:

$$B_{g1} = B_{rm} \frac{h_m}{\mu_{rm} g_{\text{eff}}} \frac{4}{\pi} \sin\left(\frac{\pi b_m}{2\tau_p}\right) \quad (2.5)$$

where B_{rm} is the remanent flux density of the magnet, h_m is the magnet height, b_m is the magnet width, μ_{rm} is the relative permeability of the magnet, and τ_p is the pole pitch. The effective air gap, g_{eff} , is defined as:

$$g_{\text{eff}} = k_c \left(g + \frac{h_m}{\mu_{rm}} \right) \quad (2.6)$$

where k_c is the Carter factor and g is the air gap. From the values given in Table 2.2, E_0 of the equivalent model in Figure 2.2 is 9.63V/turn.

2.2.3.2 Resistance

The stator resistance is given by [17]:

$$R_s = \frac{\rho_{\text{Cu}}(2l_s + 4\tau_p)}{q k_{\text{sfill}} b_s h_s} \frac{2}{P} N_s^2 = R_{s0} N_s^2 \quad (2.7)$$

where ρ_{Cu} is the resistivity of copper, l_s is the stator length, τ_p is the pole pitch, q is the number of slots per pole per phase, k_{sfill} is the slot filling factor, b_s is the stator slot width, h_s is the stator slot height and P is the number of poles. From the values given in Table 2.2,

R_{s0} of the equivalent model in Figure 2.2 is $1.25\mu\Omega/\text{turn}^2$.

2.2.3.3 Inductance

The magnetizing inductance of the ac machine is calculated as [17]:

$$L_{sm} = \frac{6\mu_0 l_s r_s k_w^2}{g_{\text{eff}} \pi} \left(\frac{2}{P}\right)^2 N_s^2 \quad (2.8)$$

where μ_0 is the permeability of vacuum, l_s is the stator length, r_s is the stator radius, k_w is the winding factor, P is the number of poles and g_{eff} is the effective air gap given in Equation (2.6). The leakage inductance is based on the ratio $k_{l/m}$ determined earlier in Section 2.2.2. The leakage inductance is formulated as:

$$L_{sl} = k_{l/m} L_{sm} \quad (2.9)$$

Therefore, the total inductance, L_s , is the sum of the main inductance and the leakage inductance. By combining Equations (2.8) and (2.9), the machine resulting inductance is:

$$L_s = \left(1 + k_{l/m}\right) \frac{6\mu_0 l_s r_s (k_w N_s)^2}{p^2 g_{\text{eff}} \pi} = L_0 N_s^2 \quad (2.10)$$

By using the values given in Table 2.2, L_0 of the equivalent model in Figure 2.2 is $0.075\mu\text{H}/\text{turn}^2$.

2.2.4 General Equations

The permanent-magnet synchronous machine produces an emf proportional to its rotational speed. Since it is direct-drive, the rotational speed is the hub speed. The induced voltage in terms of the mechanical speed w_m and the stator field constant k_{PM} is given as:

$$[E_{\text{PM}}]_{\text{LN}}^{\text{RMS}} = k_{\text{PM}} w_m \quad (2.11)$$

As well, electrical and mechanical frequencies are related by the number of poles, P :

$$w_e = \frac{P}{2} w_m \quad (2.12)$$

The preceding equations relate the electrical diagram shown in Figure 2.2 and the mechanical dynamics described in Equation (2.2) via w_m .

2.2.5 dq0 Equations

In a machine drive system, it is common to use the dynamic dq0 model of the machine. Among the benefits, the reference frame makes the positive sequence of the fundamental component stationary. It offers the possibility to use a simple control technique such as Proportional-Integral (PI) control. For a synchronous machine, the reference frame is synchronized with the rotor position θ_r as shown in Figure 2.4(a). The transformation of a 3-phase variable from the time-varying abc-frame to the stationary dq0-frame is defined in Equation (2.13), followed by its inverse in expression (2.14) [20].

$$\begin{aligned} [x_{dq0}] &= [K] [x_{abc}] \\ \begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} &= \frac{2}{3} \begin{bmatrix} \cos(\theta_r) & \cos(\theta_r - 120^\circ) & \cos(\theta_r + 120^\circ) \\ \sin(\theta_r) & \sin(\theta_r - 120^\circ) & \sin(\theta_r + 120^\circ) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \end{aligned} \quad (2.13)$$

$$\begin{aligned} [x_{abc}] &= [K^{-1}] [x_{dq0}] \\ \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} &= \begin{bmatrix} \cos(\theta_r) & \sin(\theta_r) & 1 \\ \cos(\theta_r - 120^\circ) & \sin(\theta_r - 120^\circ) & 1 \\ \cos(\theta_r + 120^\circ) & \sin(\theta_r + 120^\circ) & 1 \end{bmatrix} \begin{bmatrix} x_d \\ x_q \\ x_0 \end{bmatrix} \end{aligned} \quad (2.14)$$

$$\omega_r = \frac{d}{dt} \theta_r \quad (2.15)$$

Figure 2.4: 3-phase PMSG.

The relationship between the rotor position θ_r and the rotor frequency ω_r is given in Equation (2.15). Current directions and voltage polarities for the dq0 model are shown in Figure 2.4(b). The machine equations based on the rotor reference frame are described below and variables are marked with the superscript 'r' [20].

$$V_q^r = \left(r_s + \frac{d}{dt} L_q \right) i_q^r + \omega_r L_d i_d^r + \omega_r \lambda_m'^r \quad (2.16)$$

$$V_d^r = \left(r_s + \frac{d}{dt} L_d \right) i_d^r - \omega_r L_q i_q^r \quad (2.17)$$

The variable r_s is the stator resistance and L_d , L_q are inductances. $\lambda_m'^r$ is the amplitude of the flux linkages of the permanent magnet. For non-salient poles, in which case $L_d = L_q = L_s$, the electrical torque is derived as:

$$T_e = \frac{3}{2} \frac{P}{2} \lambda_m'^r i_q^r \quad (2.18)$$

The implementation of Equations (2.16) and (2.17) in PSCAD/EMTDC software to model the generator is detailed in Section A.2.1 of Appendix A.

Chapter 3

Distributed HVDC Converter Concept

In this chapter, the distributed HVDC converter concept is described. It explains the configuration that creates the dc link voltage suitable for power transmission. The description highlights the role of each power electronic blocks in the system. Additionally, the practical issue of the insulation level is briefly discussed. The milestone of this project, the dc-dc converter, is introduced in this chapter. Series interconnection of wind turbines is possible by reason of the selected topology. Requirements for the dc-dc converter block are investigated in details. Finally, a simple example is shown to illustrate the behaviour and benefits of the proposed approach.

3.1 System Description

In Chapter 1, a brief overview of the series interconnection of wind turbines has been introduced without details about its composition. Figure 3.1 introduces different components of this new configuration. Firstly, this method uses dc-dc converters to create a “distributed HVDC converter” between wind turbines. The module ensures that a path always exists for conduction of the main dc link current. The voltage output of the module depends on

Figure 3.1: Proposed distributed HVDC configuration.

the injected power and the regulated link current. The wind farm is composed of a string of modules that build the dc transmission voltage. Secondly, the rectifier (ac-dc) stage is employed to convert power from the variable speed generator to an intermediate dc capacitor located between the ac-dc and dc-dc converters. The main function of the rectifier stage is to ensure that the wind turbine operates at maximum power extraction. In this project, this is accomplished through torque control based on the wind speed curves discussed in Section 2.1.1 of Chapter 2. Both the ac-dc and the dc-dc converters are located in the wind turbine nacelle. These are sometimes referred to as the ac-dc-dc converter of the wind turbine because they are enclosed together. Finally, the inverter station is located onshore and it injects the power into the ac grid. The role of the inverter station is to maintain constant current by performing current control. Moreover, it has to operate at various dc voltage levels depending on production. During a low wind day, the power generation is little, and consequently, the voltage is lower than its nominal value. Under those circumstances, the inverter station should also be able to adjust its reference current to maximize the transmission voltage.

3.2 Insulation Consideration

Figure 3.2: Insulation propositions.

A major practical consideration for the proposed distributed HVDC configuration is the insulation level of the equipment. The series interconnection implies that units are at a potential to ground higher than the voltage they actually develop themselves. For example, the last unit in the string might inject 5kV but the cumulative voltage for the dc link might be 100kV. In other words, a unit with equipment rated for 5kV is sitting at 95kV with respect to ground. Due to the metallic structure of the wind turbine, it is a major issue for components ratings and generator construction.

Though insulation coordination is out the scope of this work, challenges and possible solution approaches can be identified. It is possible to have a portion of the tower made with non-conducting material to provide insulation. This segment would allow the entire nacelle to float at potential. This is illustrated in Figure 3.2(a). Alternatively, a transformer can be installed as in the case of low power switch-mode power supplies. This approach is shown in

Figure 3.2(b). The converter side of the transformer would float above ground potential and the power electronics would need to be encapsulated to provide the necessary insulation.

To limit the scope of this work, insulation design will not be investigated further. Instead, focus is on the operation of a complete system using the developed converter topologies.

3.3 DC-DC Converter

As stated earlier, the key function of the dc-dc converter is to ensure continuity of the current in the dc link. Figure 3.3 illustrates the current path in both the on- and off-state of the dc-dc converter. The dc capacitor C_{dc} is located between the ac-dc and dc-dc converters. In the on-state, the voltage is introduced in the network as shown in Figure 3.3(a). In the off-state, shown in Figure 3.3(b), the current I_{link} by-passes the dc link capacitor. This approach satisfies the obligation for a continuous conduction path for the current.

The buck (step-down) converter is a topology that allows the output current to flow in both states. The one-quadrant chopper has a simple construction made of only one switch and one diode. The IGBT connects the capacitor voltage when it is conducting (on-state) and the diode allows the current to flow otherwise (off-state). Another advantage is in the event of an IGBT gating failure or switch failure, the link current would not be interrupted and it would simply continue to circulate through the diode. In addition, the buck converter

Figure 3.3: Current path.

Figure 3.4: DC-DC converter topology.

keeps the main storage element protected from the link by locating it behind an IGBT. DC link faults levels are therefore controllable. It is interesting to note that the step-down converter has not been selected for its property to lower the voltage but for its property to allow a continuous flow of the output current. The dc-dc converter can be upgraded to a two-quadrant chopper if energy reversal is required. By doing so, a unit could extract power for machine start up or auxiliary services. Nevertheless, this alternative is not explored and the buck converter is used as shown in Figure 3.4.

Recently, a dc-dc converter topology for series interconnection of photovoltaic module has been proposed in [21]. The suggested topology offers three modes of operation: buck, boost and pass-through. This approach is not valid in this high power application since the output capacitor offers only first order filtering which leads to insufficient filtering (small C) or excessive storage (large C), which is problematic during fault events.

Based on time-averaging assumptions, input-output relations of the step-down converter are [22]:

$$I_b = DI_X \quad (3.1)$$

$$V_X = DV_{dc} \quad (3.2)$$

Figure 3.5: Output filter circuit.

For the analysis done in this project, filter dynamics are neglected because they do not affect the low frequency behaviour of the system. Under this assumption, the current I_X equals the link current I_{link} and the output voltage V_O is equivalent to the average of voltage V_X . By applying those substitutions, the input current of the module I_{dc} may be related to the dc link current through the capacitor dynamics as stated in Equation (3.3).

$$C_{\text{dc}} \frac{dV_{\text{dc}}}{dt} = I_{\text{dc}} - DI_{\text{link}} \quad (3.3)$$

3.3.1 Output Filter

Equation (3.2) is the average output voltage over one switching period. However, the actual waveform of the output voltage of the buck converter is a pulsating waveform switching between the input voltage (on-state) and zero (off-state). It is essential to reduce those fluctuations by inserting an output filter as shown in Figure 3.4. Without filtering, major ripple would appear on the line voltage. For example, if all units are synchronized with the same on-off sequence, the total dc link voltage would oscillate between hundreds of kilovolts and zero which can potentially lead to instability of the network.

The general idea for the filter is to design a resistor-inductor-capacitor (RLC) branch

Table 3.1: DC-DC converter parameters.

DC-DC Converter Parameters	
Capacitor C_{dc} [mF]	3
Switching Frequency [kHz]	1
Filter Parameters	
L_1 [mH]	1
R_{L1} [m Ω]	20
L_2 [μ H]	50
R_{L2} [m Ω]	1
C_1 [μ F]	500
R_1 [Ω]	50

with high impedance at low frequency and very low impedance at high frequency. The filter structure is selected to be consistent with conventional HVDC dc side filters [23]. This means that the output voltage contains only low frequencies and, more importantly, a dc signal. The circuit of the second order highpass filter with a smoothing reactor is shown in Figure 3.5. The transfer function of the filter is given as:

$$\frac{V_o(s)}{V_x(s)} = \frac{L_2 R_1 C_1 s^2 + L_2 s + R_1}{L_1 L_2 C_1 s^3 + [L_2 R_1 C_1 + L_1 R_1 C_1] s^2 + L_2 s + R_1} \quad (3.4)$$

The smoothing reactor, L_1 , is used to enhance the filtering. The highpass filter has been tuned to the switching frequency of 1kHz. The values of the circuit components are given in Table 3.1. The inductor winding resistance is calculated using an R/L ratio of 50.

A simple simulation has been performed to validate the operation of the buck converter with the filter. The schematic shown in Figure 3.4 is implemented in the PSCAD/EMTDC software with the filter of Figure 3.5. The voltage V_{dc} is set to 5kV by a voltage source and the current I_{link} is fixed at 1kA using a current source. The duty cycle is 0.5 which is the operating point where the buck converter experiences its largest ripples [24]. Figure 3.6(a) shows both V_X and V_O . The voltage V_X is fluctuating from 0 to 5kV, but the filtered voltage is constant at 2.5kV with 4.8% ripple. The analysis of the harmonic spectrum, shown in Figure 3.6(b), demonstrates that the filter attenuates most of the high frequency component.

Figure 3.6: Output filter performance.

3.4 Concept Example

A simple example is described to illustrate the concept of the “distributed HVDC converter”. The system is composed of three units connected in series via the dc-dc modules and a current source models the inverter station performing current control. Each dc-dc module has a constant voltage source at its input with a specified power contribution for each of them. The circuit is shown in Figure 3.7.

Units 1 and 2 have the same dc voltage, 4kV, however, their power ratings are different: 2MW compared to 3MW. This results in a different operating duty cycle for the dc-dc converters. This comparison illustrates that two units with the same dc voltage but different generated power can be introduced in the same link.

The first and the third units have the same power, 2MW, but different dc voltages, 4kV compared to 5kV. Since they have the same power and they share the same link current, their output voltages should be the same based on the simple relationship $P_{dc} = V_{dc}I_{dc}$. This situation shows that the dc-dc converters have different duty cycles but that they both inject the same power, 2MW, at the same voltage level, 2kV.

Finally, the potential across the 1kA current source (inverter station) is the sum of all

three voltages for a total of 7kV. The current source is extracting 7MW of power which is the total power produced by the three units. This example demonstrates the flexibility that the dc-dc converter offers. Units with different powers and dc levels can be implemented in the same system. In theory, there is no limit regarding the number of units that can be connected in series. However, one practical limitation is the insulation level of the equipment that has been briefly discussed in Section 3.2.

Figure 3.7: Concept example.

Chapter 4

AC-DC Converter

In this chapter, the ac-dc stage is selected and is included with other parts of the wind turbine. The diode rectifier and the voltage-source converter have been surveyed to fulfill this task. The diode rectifier is selected for its robustness and its lowest cost, although, the voltage-source converter is considered as alternative in Appendix B. A control strategy is elaborated as well as a control diagram used for the controller design. Finally, the proper operation of the wind turbine is confirmed through simulation.

4.1 Diode Rectifier Topology

The diode rectifier has been widely used to convert electricity from ac to dc. In three-phase systems, a six-pulse topology is commonly employed because it is reliable and inexpensive. Two major drawbacks of this approach are the high harmonic content on the ac line currents and voltage ripples on the dc voltage [24]. When it is paired with a machine, those distortions on the ac side appear on the electrical torque of the apparatus. The impact of this uneven torque is neglected in this analysis because the large mechanical inertia of the turbine acts as a lowpass filter for the mechanical speed. However, the generator has to be built to sustain such operation. The ripple on the dc voltage is created from the sequence of conducting diodes. The sequence is divided into six equal intervals per line cycle. The period is $1/6$ of

Figure 4.1: Wind turbine converter topology using diode rectifier.

the line period [22]. The amplitude of this ripple can be minimized with a sufficiently large capacitor on the dc side.

The diode rectifier can operate in three modes:

- (i) discontinuous conduction mode (DCM), no commutation
- (ii) continuous conduction mode (CCM), current commutating from one diode to the next with a commutation angle less than 60°
- (iii) ac short circuit, commutation angle greater than 60°

Typically, the diode rectifier is operated in CCM. This mode implies that the output dc current is continuous. Generally, it is ensured by a large inductor at the output but it can also be assumed with any circuitry that can be modeled as a current source. The DCM takes place when the output dc current is discontinuous. In this mode, the rectifier is sometimes referred to as a peak-detector and the ac line current waveforms are narrow pulses [24].

Figure 4.1 shows the complete wind turbine converter equipped with the 3-phase electrical circuit of the generator from Figure 2.2 of Chapter 2, the diode rectifier and the dc-dc converter of Figure 3.4 in Chapter 3. In this project, the diode rectifier does not enter into

DCM because the dc-dc converter acts a current source from the rectifier point of view.

The analysis of the diode rectifier is made assuming CCM and a balanced three-phase ac source. The commutation process involved with the inductance L_s is considered but the small resistance R_s is neglected to simplify the analysis. The input-output relationships of the voltage and current for a diode rectifier are given as [4]:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} [E_{PM}]_{LL}^{RMS} - \frac{3}{\pi} w_e L_s I_{dc} \quad (4.1)$$

$$[I_t]_1^{RMS} = \frac{\sqrt{6}}{\pi} I_{dc} \quad (4.2)$$

4.2 Complete System Parameters

An equivalent circuit model of the generator has been derived in Chapter 2. The number of turns per phase winding, N_s , has not been defined because it depends on the application. From Figure 4.1, the voltage V_t is in phase with the current I_t because the diode rectifier imposes unity power factor at its terminal. Consequently, the back emf E_{PM} is not in phase with the current I_t because of the inductance L_s . Over-excitation of the generator is then required because the voltage magnitude at the terminal, V_t , is lower than at the back emf, E_{PM} [25].

4.2.1 N_s Value

The rated power of the machine is 5MW and the rated electrical angular frequency is 224.75rad/s (35.77Hz). The terminal voltage of the generator is selected to be 4kV_{LL}^{RMS}. Based on the unity power factor at the input of the ac-dc converter, the rated ac line current is calculated as:

$$[I_t]_1^{\text{RMS}} = \frac{P_e}{\sqrt{3}[V_t]_{\text{LL}}^{\text{RMS}}} = \frac{5 \times 10^6}{\sqrt{3} \times 4 \times 10^3} = 722\text{A} \quad (4.3)$$

The power at the back emf is given as:

$$P_e = 3[E_{\text{PM}}]_{\text{LN}}^{\text{RMS}}[I_t]_1^{\text{RMS}}\text{PF} \quad (4.4)$$

The power factor, PF, for a diode rectifier with the commutation process can be approximated as [4]:

$$\text{PF} = 1 - \frac{w_e L_s I_{\text{dc}}}{\sqrt{6}[E_{\text{PM}}]_{\text{LN}}^{\text{RMS}}} \quad (4.5)$$

The power factor can also be expressed in terms of I_t instead of I_{dc} using Equation (4.2). With those substitutions, Equation (4.4) results in Equation (4.6).

$$P_e = 3[E_{\text{PM}}]_{\text{LN}}^{\text{RMS}}[I_t]_1^{\text{RMS}} - \frac{\pi}{2}w_e L_s \left([I_t]_1^{\text{RMS}}\right)^2 \quad (4.6)$$

The induced voltage E_{PM} and the inductance L_s are parameters that depend on N_s . From Chapter 2, $[E_{\text{PM}}]_{\text{LN}}^{\text{RMS}} = E_0 N_s$ where $E_0 = 9.63\text{V/turn}$ and $L_s = L_0 N_s^2$ where $L_0 = 0.075\mu\text{H/turn}^2$. Equation (4.7) is obtained by substituting those variables into Equation (4.6). This second-order equation is solved to find N_s based on the values of P_e , w_e , I_t , E_0 and L_0 previously stated. The number of turns of per phase winding is calculated to be 300. Parameters of the system are summarized in Table 4.1.

$$\frac{\pi}{6} \left([I_t]_1^{\text{RMS}}\right)^2 w_e L_0 N_s^2 - [I_t]_1^{\text{RMS}} E_0 N_s + \frac{P_e}{3} = 0 \quad (4.7)$$

4.2.2 Commutation Angle

The performance of the diode rectifier depends on the commutation process. This process occurs during the transition between the turn off of the conducting diode and the turn on

Table 4.1: System parameters when using diode rectifier.

System Parameters	
Rated power [MW]	5
Rated frequency f_e [Hz]	35.77
Rated shaft speed w_m [rad/s]	1.55
Induced voltage E_{PM} [kV_{LN}^{RMS}]	2.89
Synchronous inductance L_s [mH]	6.77
Capacitor C_{dc} [mF]	3
Rotor and turbine inertia J [$kg\ m^2$]	1.06×10^7

of the next one in the sequence. It is the transfer of stored energy in the line inductance from the conducting phase to the next incoming one [4]. The angle is defined as the segment it takes for the conducting diode to completely turn off and the next one to conduct full current. The commutation angle can be calculated using Equation (4.8).

$$u = \cos^{-1} \left(1 - \frac{\sqrt{2}w_e L_s I_{dc}}{\sqrt{3}[E_{PM}]_{LN}^{RMS}} \right) \quad (4.8)$$

The operation can be problematic if the ac side is highly reactive because the commutation angle is high and commutation failure occurs if it reaches 60° . If this event happens, a short circuit is created on the ac side and it results in shorting the terminals of the generator.

The machine inductance of a PMSG tends to be generally high. Based on the parameters derived in Section 4.2.1, the commutation angle is calculated to be 53° under full load conditions. The angle is less than 60° but the safety margin is small. Improvement can be done through the construction of the PMSG with a much lower L_0/E_0 ratio. This ratio is influenced by many parameters of the generator design such as the $k_{l/m}$ ratio, the mechanical speed and the flux density of the magnets. It is interesting to note that the commutation angle does not depend on the number of turns per phase winding as this does not influence the L_0/E_0 ratio. In some lower power machine application, capacitor banks are connected at the terminals of the machine to reduce the overall impedance [18]. However, this solution might not be suitable for this application due to the nature of the project (high power, insulation consideration, distributed dc link). Therefore, for the purpose of this project a

commutation angle of 53 degrees will be accepted in order to avoid the addition of capacitive compensation.

4.3 Controller

The role of the ac-dc converter is to operate the wind turbine at maximum power extraction as discussed in Chapter 3. This task is performed by adjusting the electrical torque of the machine to operate on the optimal torque curve. In the case of the PMSG, the control strategy is to regulate the ac current. The diode rectifier does not fulfill this role since this topology provides control over neither the ac current, I_t , nor the output dc current I_{dc} . However, it has been discussed that the dc-dc converter can be used to control the rectifier current I_{dc} . Furthermore, Equation (4.2) has stated the correspondence between the dc current and the ac current. Therefore, the current I_{dc} is the signal regulated using the duty cycle of the dc-dc converter.

4.3.1 Optimal I_{dc} Curve and I_{link}

The optimal torque characteristic curve of the wind turbine has been extracted from Figure 2.1(a) of Chapter 2 and it is shown in Figure 4.2(a). This curve gives the optimal value of torque, T_e^{opt} , that should be demanded by the generator at a given measured hub speed. It is desired to derive an expression for the electrical torque in terms of the rectifier current I_{dc} . Using Equation (4.6), the electrical torque is defined as:

$$T_e = \frac{P_e}{w_m} = \frac{3[E_{PM}]_{LN}^{RMS}[I_t]_1^{RMS} - \frac{\pi}{2}w_e L_s \left([I_t]_1^{RMS}\right)^2}{w_m} \quad (4.9)$$

Using Equations (2.11) and (2.12) from Chapter 2 as well as Equation (4.2), the electrical torque in terms of I_{dc} has the form:

$$T_e = \frac{3\sqrt{6}}{\pi}k_{PM}I_{dc} - \frac{3}{\pi}\frac{P}{2}L_s I_{dc}^2 \quad (4.10)$$

Figure 4.2: Curves for maximum power point tracking.

A value of I_{dc} is associated with each optimal torque value of Figure 4.2(a) and it is calculated by solving Equation (4.10). Equation (4.11) expresses $I_{\text{dc}}^{\text{opt}}$ in terms of T_e^{opt} and Figure 4.2(b) shows the optimal I_{dc} curve. The curve gives the value of I_{dc} that should be demanded by the generator for a given measured hub speed.

$$I_{\text{dc}}^{\text{opt}} = \frac{\frac{3\sqrt{6}}{\pi} k_{\text{PM}} - \sqrt{\frac{54}{\pi^2} k_{\text{PM}}^2 - \frac{12}{\pi} \frac{P}{2} L_s T_e^{\text{opt}}}}{\frac{6}{\pi} \frac{P}{2} L_s} \quad (4.11)$$

The operating point $I_{\text{dc}}^{\text{opt}}$ is achieved by adjusting the duty cycle of the dc-dc converter. Since the duty cycle is limited to unity, I_{link} has to be larger than the maximum value of $I_{\text{dc}}^{\text{opt}}$. For the system under study, I_{link} is determined for a hub speed margin of 10%. In other words, I_{link} should be large enough such that a wind turbine operating at a hub speed 10% faster than the rated speed can be regulated. The incentive for this margin is in the event of a sudden acceleration of the hub speed, the wind turbine remains under control until the pitch controller would operate accordingly. By referring to Figure 4.2(b), the minimum link current for the desired margin is 1.16kA. As a result, the nominal value of the link current is selected to be 1.2kA.

4.3.2 Control Diagram

Figure 4.3: Control diagram.

Equation (4.12), taken from Section 3.3, express the dynamic relation between the rectifier current I_{dc} and the link current I_{link} via the duty cycle D . It is used with Equation (4.1) to derive Equation (4.13) which is used to construct the control diagram shown in Figure 4.3.

$$C_{dc} \frac{dV_{dc}}{dt} = I_{dc} - DI_{link} \quad (4.12)$$

$$C_{dc} \frac{d}{dt} \left[\frac{3\sqrt{2}}{\pi} [E_{PM}]_{LL}^{RMS} - \frac{3}{\pi} w_e L_s I_{dc} \right] = I_{dc} - DI_{link} \quad (4.13)$$

In this system, the E_{PM} branch is seen as a disturbance. The derivative sC_{dc} makes the disturbance zero if E_{PM} is constant. For model discrepancies or a ramping E_{PM} , the feedback control using a Proportional plus Integral (PI) controller is employed to ensure error tracking. The bandwidth of the controller is expected to be much higher than the slow mechanical dynamics dictating the induced voltage. The controller should respond in terms of milliseconds as opposed to seconds for the mechanical speed.

The open-loop transfer function of the uncontrolled system is described in Equation (4.14)

Figure 4.4: Bode plots.

Table 4.2: Controller and filter parameters.

Controller Parameters	
K_P	1.12×10^{-4}
a	60
Switching frequency [kHz]	1
Filter Parameters	
Natural frequency w_{filter} [rad/s]	224.7
Damping ratio ζ	0.707

and its frequency response is shown in Figure 4.4(a).

$$T_u(s) = \frac{I_{\text{dc}}}{I_{\text{dc}}^{\text{opt}}} = I_{\text{link}} P(s) H(s) \quad (4.14)$$

where

$$P(s) = \frac{1}{1 + \frac{3}{\pi} w_e L_s C_{\text{dc}} s}$$

$$H(s) = \frac{w_{\text{filter}}^2}{s^2 + 2\zeta w_{\text{filter}} s + w_{\text{filter}}^2}$$

Parameters of the lowpass filter and the controller are given in Table 4.2. The controller

has been designed to have an overdamped response to a unit-step response. Since the control model has been developed using equations based on approximations and averages, an overdamped design is a conservative approach to remain within the limitations of the model. The closed-loop transfer function of the compensated system is described in Equation (4.15) and its frequency response is shown in Figure 4.4(b).

$$T_c(s) = \frac{I_{dc}}{I_{dc}^{opt}} = \frac{C(s)I_{link}P(s)}{1 + H(s)C(s)I_{link}P(s)} \quad (4.15)$$

where

$$C(s) = K_P \frac{s + a}{s}$$

4.4 Simulations

Three simulations are performed in this chapter. The first simulation evaluates the model and the controller developed in Section 4.3.2. The second scenario confirms the capability of the machine drive to operate at the optimal torque. Finally, the system is analyzed at rated hub speed in steady-state.

4.4.1 Controller Performance

A unit step response has been simulated to validate the developed system model shown in Figure 4.3. The plant model has been derived based on the assumption that the capacitor C_{dc} combined with the parallel-connected dc-dc converter act as a current source. Based on this assumption, equations of the diode rectifier operating in continuous conduction mode have been employed. The simulation should confirm the validity of this assumption and the accuracy of the model.

The generator operates at a fix hub speed and a current source is connected at the output. Figure 4.5(a) depicts responses from both the circuit simulation and the model. The results

Figure 4.5: Controller performance and peak power tracking validation.

agree, which suggest an accurate model of the system even with the approximate nature of the equations involved. As expected, the response is overdamped and the settling time is approximately 0.6s.

4.4.2 Optimal Torque Operation

For the next simulation, the wind turbine experiences a gradual change in the wind speed from the cut-in wind speed (3m/s) to the rated wind speed (12m/s). The unit has to track the optimal I_{dc} curve shown in Figure 4.2(b). Figure 4.5(b) demonstrates that the wind turbine converter performs peak power tracking properly through the optimal torque control.

4.4.3 Rated Operation

This section simulates the wind turbine when it operates at rated hub speed. The ac current waveforms are shown in Figure 4.6. From this plot, the commutation angle is estimated to be 53.3° which agrees with the theoretical value of 53° computed in Section 4.2.2.

The waveforms of the capacitor voltage, V_{dc} , and the output voltage, V_o , are shown in

Figure 4.6: AC current waveforms for the wind turbine in steady-state at rated wind speed.

Figure 4.7(a). The capacitor voltage has an average of 5.47kV with 2.7% ripple. The output voltage varies between 4kV and 4.4kV with an average of 4.18kV. The switching period, t_{sw} , can be easily identified on the capacitor voltage waveform. The time between each minima is exactly 1ms which matches the switching frequency of 1kHz. It is expected that the capacitor voltage would have ripple with a period equals to 1/6 of the ac side signal. This duration is identified with t_{6th} on the plot. However, simulation shows that the ripple appears at the output voltage and not at the capacitor voltage. A harmonic spectrum analysis has been performed to validate this observation. Results, shown in Figure 4.7(b), confirm that the output voltage contains most of the 6th harmonic component of the rectification process. It would be problematic if this ripple was significant, but it represents only 1.6% of the output dc voltage. Total 6th harmonic ripple on the dc link will be far below 1.6% since each turbine does not operate synchronously. Therefore, this ripple is is not expected to alter the performance of the system.

Figure 4.7: Wind turbine operating in steady-state at rated wind speed.

Chapter 5

Inverter Station

In typical dc transmission systems under normal operation, the sending end controller performs current control and the receiving end controller performs voltage control (or extinction angle control). For thyristor-based HVDC systems, however, the receiving end controller can change to current control under certain circumstances [4]. In this project, the thyristor-based inverter is primarily operated in current control mode. Not only is the thyristor-based inverter more naturally suited to dc link current control than a VSC, but it is also the more economical solution. Indeed, drawbacks of thyristor technology are the need of a strong grid and ac filters at the output of the inverter.

The inverter station developed in this project is based on the CIGRE HVDC benchmark model implemented in PSCAD/EMTDC software package [26, 27]. The converter employs a 12-pulse configuration. The ac grid and its disturbances are not considered in this project. As a result, the ac bus is assumed to be a strong grid and no ac filters are designed. From the CIGRE benchmark model, ac filters and the ac system equivalent are simply removed and the primary side of the transformers are directly connected to the voltage source.

Section 5.1 details the size of the wind farm which establishes the nominal values of the transmission line. Section 5.2 depicts the inverter characteristics. In that section, parameters of the inverter and the control diagram are given. The behaviour of the wind farm is analyzed

Figure 5.1: Wind farm of 30 wind turbines with the transmission line and the inverter station.

in Section 5.4 in order to develop the current supervisor. The current supervisor used to maximize the transmission voltage is described in Section 5.5. Finally, the performance of the inverter controller is analyzed in Section 5.6. The system performance is also studied in that section.

5.1 Wind Farm and Transmission Line

The nominal value of the dc link voltage depends on the wind farm composition. In this project, the system under study is composed of 30 wind turbines rated at 5MW each.

Based on the rated link current of 1.2kA, a single unit is expected to inject 4.16kV assuming no power loss in the conversion process. Therefore, the cumulative voltage, V_{wf} , is expected to be $4.16\text{kV} \times 30 = 125\text{kV}$. The system is shown in Figure 5.1.

For the transmission line, the wind farm is located 25km from shore which leads to the need of 50km of conductor length. The most promising technology for submarine cable is cross-linked polyethylene (XLPE) [28]. Characteristics of the XLPE cable are taken from [29] and they are rated for a voltage of 132kV and a nominal current of 1.055kA. Those values

Table 5.1: Transmission line parameters.

Cable Properties	
Cable length [km]	50
Resistance R_{line} (48mΩ/km) [Ω]	2.4
Inductance L_{line} (0.34mH/km) [mH]	17
Capacitance C_{line} (230nF/km) [μF]	11.5

do not fit perfectly for this project (125kV and 1.2kA) but they are close enough to give an approximation. Transmission line parameters using the T-model are tabulated in Table 5.1.

5.2 Inverter Configuration

5.2.1 Transformers

The characteristics of the transformers used with a thyristor-based inverter have to be selected based on the power transmitted and the voltage level. The primary side of the transformer is connected to the ac grid which is rated at $250\text{kV}_{\text{LL}}^{\text{RMS}}$ at a frequency of 50Hz. The secondary side voltage is calculated using [26]:

$$[V_{\text{sec}}]_{\text{LL}}^{\text{RMS}} = \frac{\pi}{3\sqrt{2}} \frac{V_{\text{inv}}}{N_{\text{BR}}} \frac{1}{\cos(\gamma_{\text{min}}) - \frac{X_{\text{tr}}}{2}} \quad (5.1)$$

where V_{inv} is the dc nominal voltage at the inverter end and X_{tr} is the commutating reactance in per-unit. The number of 6-pulse bridges, N_{BR} , used in this system is 2. The minimum gamma angle, γ_{min} , is 20° and it is discussed in Section 5.3.3. The rated dc voltage of the wind farm is 125kV, however, the transformer is designed with a superior margin of 5%. The MVA ratings of the transformers are 97.055 using Equation (5.2) [26].

$$S_{\text{tr}} = \sqrt{3} [V_{\text{sec}}]_{\text{LL}}^{\text{RMS}} \left(\sqrt{\frac{2}{3}} I_{\text{link}} \right) \quad (5.2)$$

From the CIGRE benchmark, the transformers have a leakage inductance of 0.18pu which is used as the commutating reactance in Equation (5.1). The actual value of the leakage inductance can be calculated using S_{tr} , V_{sec} and f_e as the per-unit base. By doing so, an inductance of 0.18pu has the value of 19.3mH. All the parameters of the transformers are listed in Table 5.2.

Table 5.2: Transformer design and parameters.

Transformer Parameters	
Primary voltage V_{pri} [kV_{LL}^{RMS}]	230
Secondary voltage V_{sec} [kV_{LL}^{RMS}]	57.19
Transformer rating S_{tr} [MVA]	97.055
Network frequency f_e [Hz]	50
X_{tr} [pu/mH]	0.18 / 19.3
Inverter Characteristics	
Number of 6-pulses bridges N_{BR}	2
Rated voltage V_{inv} [kV_{dc}]	131.25
Rated current I_{inv} [kA]	1.2

Table 5.3: Base values for reactor impedance.

	CIGRE Benchmark [26, 27]	Project
Base Power [MW]	1000	150
Base Voltage [kV]	500	125
Base Frequency [Hz]	50	50
Base Impedance [Ω]	250	104
Reactor Impedance [pu/mH]	0.75 / 597	0.75 / 249

5.2.2 Reactor

The smoothing reactor, $L_{reactor}$, minimizes the variation of current on the dc link caused by disturbances on either side of the inverter [4]. It reduces the voltage and current distortions on the dc link and it decreases the risk of commutation failures. The value of the inductor is selected based on its relative value in the CIGRE benchmark using the per-unit system.

Table 5.3 details both the base values of the CIGRE benchmark and this project. The smoothing reactor L_{reactor} has a value of 249mH.

5.3 Inverter Controller Characteristics

The controller of the line-commutated converter (thyristor-based) is composed of three basic modes of operation: (i) $\alpha_{\min}$ control, (ii) $\gamma_{\min}$ control and (iii) current control. Each mode of operation is derived from the relationship given in Equation (5.3). The controller output is the angle β which is defined as $180^\circ - \alpha$, where α is the firing delay angle. In some cases, the angle β is set at a fix value ($\alpha_{\min}$ mode) or it can vary ($\gamma_{\min}$ mode and current control).

$$V_{\text{inv}} = \frac{3\sqrt{2}}{\pi} \left(N_{\text{BR}} \times [V_{\text{sec}}]_{\text{LL}}^{\text{RMS}} \right) \cos(\beta) + \frac{3}{\pi} w_e (N_{\text{BR}} \times X_{\text{tr}}) I_{\text{inv}} \quad (5.3)$$

The three modes of operation are described in the following subsections. Inverter voltage boundaries are set by the $\alpha_{\min}$ control for the minimum voltage and by the $\gamma_{\min}$ control for the maximum voltage. In the current control mode, the inverter voltage varies between these two limits. The analysis of HVDC transmission systems is often done using the static $V_{\text{inv}}-I_{\text{inv}}$ plot as shown in Figure 5.2(a). The benefit of this graphical representation is the possibility to identify operating points when both the sending end and the receiving end characteristics are plotted on the same graph. This section derives the profile of the receiving end converter and Section 5.4 extracts the characteristic for the wind farm (sending end converter). Sections 5.5 and 5.6 analyze the combined system by overlaying these two graphs.

5.3.1 $\alpha_{\min}$ Control

Assigning a minimum α value protects the inverter station from entering the rectifier mode of operation. Typically, the value of $\alpha_{\min}$ for an inverter is around 100-110 degrees [30]. For this project, $\alpha_{\min}$ is 90 degrees because it allows a wider range of operating voltage, especially

(a) Basic modes of operation of a thyristor-based inverter.

(b) Simulation results of the inverter controller.

Figure 5.2: V_{inv} - I_{inv} plots of the three modes of operation and simulation results of the inverter station.

useful under low power. The α_{min} control is sometimes referred as the β_{max} control where $\beta_{max} = 180^\circ - \alpha_{min}$. The V_{inv} - I_{inv} characteristic with $\alpha_{min}=90^\circ$ is expressed in Equation (5.4) and it is shown in Figure 5.2(a).

$$V_{inv} = \frac{3\sqrt{2}}{\pi} (N_{BR} \times [V_{sec}]_{LL}^{RMS}) + \frac{3}{\pi} w_e (N_{BR} \times X_{tr}) I_{inv} \quad (5.4)$$

5.3.2 Current Control

As stated earlier, the rectifier station typically operates in current control mode and the inverter station runs constant extinction angle control. The decisive element in those assignments is the reactive power consumption [4]. In general for an HVDC transmission system composed of two thyristor-based converters, the constant extinction angle at the receiving end results in lower reactive power consumption for the system. However, this project is not a conventional HVDC configuration and the role of the inverter station is to perform current control. In this mode, the angle α varies between 90 and 180 degrees to keep the

current constant (correspondingly, the angle β varies from 90 to 0 degrees). The current control characteristic is expressed in Equation (5.5) and it is shown in Figure 5.2(a). The link current, I_{link} , is the rated value of 1.2kA.

$$V_{\text{inv}} = \frac{3\sqrt{2}}{\pi} \left(N_{\text{BR}} \times [V_{\text{sec}}]_{\text{LL}}^{\text{RMS}} \right) \cos(\beta) + \frac{3}{\pi} w_e (N_{\text{BR}} \times X_{\text{tr}}) I_{\text{link}} \quad (5.5)$$

5.3.3 γ_{min} Control

The γ_{min} control is often referred to as the constant extinction angle control. The firing delay angle is adjusted to keep the extinction time constant.

In practice, the overlap angle u is difficult to measure and to predict. The angle γ is easier to measure - it begins when the thyristor is completely off and it ends when the voltage across the thyristor is no longer negative. In this mode, the controller adjusts the firing delay angle to keep the angle γ at a minimum value. Choosing a large γ_{min} ensures a safety margin for the commutation process occurs and risk of commutation failures is minimized [31]. On the other hand, a large value of γ_{min} results in higher reactive power consumption which is less desirable. Typically, γ_{min} therefore ranges between 15 and 20 degrees and for this project the value of 20 degrees is selected [4]. The control characteristic for $\gamma_{\text{min}}=20^\circ$ is expressed in Equation (5.6) and it is shown in Figure 5.2(a).

$$V_{\text{inv}} = \frac{3\sqrt{2}}{\pi} \left(N_{\text{BR}} \times [V_{\text{sec}}]_{\text{LL}}^{\text{RMS}} \right) \cos(\gamma_{\text{min}}) - \frac{3}{\pi} w_e (N_{\text{BR}} \times X_{\text{tr}}) I_{\text{inv}} \quad (5.6)$$

5.3.4 Controller Model

The controller is based on the CIGRE HVDC benchmark model. However, the basic characteristics are modified in the benchmark controller. Those changes reshape the $V_{\text{inv}}-I_{\text{inv}}$ characteristic curve such that the inverter operates properly when it is paired with a rectifier station [4, 30].

The control diagram implemented is shown in Figure 5.3. The inverter controller is

Figure 5.3: Inverter station controller.

Table 5.4: Controller parameters of the inverter station.

Current Control	
Input filter gain G	0.8333
Input filter time constant τ [s]	0.0012
Controller gain K_P	0.63
Controller time constant K_I [s]	0.1524
Controller output limits	$[35^\circ-90^\circ]$
Gamma Control	
Controller gain K_P	0.7506
Controller time constant K_I [s]	0.0544
Controller output limits	$[35^\circ-90^\circ]$

designed such that both the current control and the γ control have their own control branch. Each controller outputs an angle β and the largest of the two is the signal used. The largest β means the smallest α sent to the gate drivers of the thyristors. The α_{min} mode of operation is simply implemented by limiting the maximum value of beta to $\beta_{max} = 180 - \alpha_{min} = 90^\circ$ in both branches. The value of β_{min} is based on γ_{min} and the estimated overlap angle. The controllers have a minimum value of $\beta_{min} = \gamma_{min} + u_{est} = 35^\circ$.

The parameters of the PI-controllers are the same as in the benchmark. The gain of the input filters has been adjusted to per-unitize properly. The complete list of the parameters are in Table 5.4.

5.3.5 Simulation

The controller is designed such that at low power the inverter operates in the $\alpha_{\min}$ mode. As the sending end power increases, the voltage is kept low to create a large voltage difference between the sending end and the receiving end to build the current. Once the current reaches the reference current, the current control takes over. The current is maintained by increasing the voltage until the $\gamma_{\min}$ is reached. At this point, the inverter station enters in the minimum γ mode of operation and the current starts to increase again. This last mode of operation would normally never be entered.

The operation of the inverter has been simulated using a power source at the sending end. The results are shown in Figure 5.2(b). The inverter operates as expected in the three different modes of operation. The converter is stable and does not experience any commutation failures.

5.4 Wind Farm Plot

In order to analyze the operation of the complete system, it is necessary to put the sending end and the receiving end on the same V - I graph. The receiving end controller has been derived and validated in Figure 5.2.

For the sending end, some assumptions are made to simplify the analysis. Firstly, the wind farm is assumed to experience the same wind speed. Secondly, all units are assumed to operate at the optimal operating point. Finally, no loss is assumed in the conversion process at the wind turbine.

The peak power with respect to the wind speed is extracted from Figure 2.1(b) of Chapter 2 and it is shown for a wind farm of 30 units in Figure 5.4(a). For each wind speed, the value of the optimal power is used to plot the V_{wf} - I_{inv} characteristic using Equation (5.7).

$$V_{\text{wf}} = \frac{P^{\text{opt}}}{I_{\text{link}}} \quad (5.7)$$

Figure 5.4: Wind farm characteristics curves.

For a given wind speed, the optimal power values are used in Equation (5.7) to plot the curves in Figure 5.4(b). The triangle markers identify operating points where the duty cycle of the dc-dc converter is unity ($D=1$); at this point $I_{link} = I_{dc}^{opt}$. The duty cycle then decreases as I_{link} increases. At very small link current, the machine drive cannot extract enough power to remain in peak power tracking.

Figure 5.5 is used to illustrate the example of a wind farm with a wind speed of 10m/s. The optimal power of the wind farm is 87MW and the current I_{dc} required is 590A. As long as I_{link} is greater than I_{dc}^{opt} , the wind turbine is in optimal operation. However, when $I_{link} = I_{dc}^{opt} = 590A$, the duty cycle of the converter is unity. When I_{link} decreases below 590A, not enough electrical torque is developed by the machine drive to regulate the turbine at optimal operation. As a result, the wind turbine is no longer operating in peak power operation and the hub speed would be expected to accelerate.

In this project, wind turbines are not operated with $I_{link} < I_{dc}^{opt}$. For plotting purposes, it is merely assumed the turbine output voltage remains constant when I_{link} is below the optimal current. However, if operation in this region is anticipated, then the precise rise in output voltage due to acceleration of the turbine hub would need to be calculated. In the previous

Figure 5.5: Example to illustrate wind farm characteristic derivation.

example, the output voltage is assumed to remain at 147kV ($= P^{\text{opt}}/I_{\text{dc}}^{\text{opt}} = 8.7 \times 10^7/590$). The output voltage for each wind speed can be calculated using Equation (5.8). The wind farm characteristics with the clipped region are shown in Figure 5.6. The figure also depicts the inverter characteristic as required for the system analysis. The point A identifies the rated operating point which is the intersection of the rated wind speed (12m/s) curve and the inverter characteristic.

$$V_{\text{wf}} = \begin{cases} \frac{P^{\text{opt}}}{I_{\text{link}}}, & \text{for } I_{\text{link}} \geq I_{\text{dc}}^{\text{opt}} \text{ (optimal operation)} \\ \frac{P^{\text{opt}}}{I_{\text{dc}}^{\text{opt}}}, & \text{for } I_{\text{link}} < I_{\text{dc}}^{\text{opt}} \text{ (assumption for constant hub speed)} \end{cases} \quad (5.8)$$

Figure 5.6: $V_{\text{wf}}-I_{\text{link}}$ characteristics with hub speed limiter.

Figure 5.7: System characteristics with different reference currents.

5.5 Current Supervisor

From Figure 5.6, when the wind farm is experiencing a wind of 12m/s the operating voltage given a current control set at 1.2kA is 125kV. However, the voltage is very low during a low wind day with this high reference current. For example, if the wind is 7m/s, the dc link would be 25kV. In order to reduce the transmission losses, the link voltage should be optimized through a current supervisor that can reduce its reference current. Two cases are described to illustrate the operation and the benefits of a current supervisor.

The first situation is a wind of 10m/s. In the original system of Figure 5.6, the dc link voltage is 72kV. By operating the dc link with a current of 1kA, the voltage is now 87kV as identified with point B in Figure 5.7(a).

The second case is a wind of 7m/s. With a link current of 1.2kA, the voltage is 25kV. If the reference current is reduced to 300A, the voltage is 99kV as shown with point C in Figure 5.7(b).

Those two examples illustrate that reducing the reference current can maximize the transmission voltage. The transition has to be very slow to avoid any interaction with other

Figure 5.8: V - I characteristics with the current supervisor.

controllers in the system. In practice, the variation would occur over several minutes. For simulation purposes, the time constant for the current supervisor is estimated to be three times the mechanical time constant of the machine. Therefore, the time constant of the current supervisor is established to be 7.65s.

The current supervisor is designed to behave according to the dark line shown in Figure 5.8. Starting from the rated operating point, the current is kept at 1.2kA until the voltage drops to 100kV. From that point, the reference current is slowly reduced to maintain the dc link voltage at 100kV. The current is reduced until it reaches 300A. At this instant, the reference current is maintained at 300A and the voltage simply decreases.

The choice of 100kV for the link voltage is based on the probability analysis done in Appendix A. From the cumulative distribution, the wind turbine experiences a wind speed of at least 12m/s 25% of the time. The current is set to 1.2kA until the dc link voltage reaches 100kV. The wind speed associated with this point is approximately 11m/s. There is a 32% probability of operating above 100kV, as marked in Figure 5.8. Finally, the last

Table 5.5: Parameters of the current supervisor.

Current Supervisor	
Input filter gain G	0.008
Input filter time constant τ [s]	0.025
Integrator time constant T [s]	7.65
Integrator output limits	[0.25pu-1pu]

operating point at 100kV takes place at a wind of 7m/s. This point has a probability of 63%, as also marked in Figure 5.8. This probability analysis concludes that the dc link voltage is at least 100kV 63% of the time.

The current supervisor diagram consists of a simple integrator with the desired time constant of 7.65s. The integrator is limited with the maximum reference current which is the rated current of 1.2kA. The lower limit is the minimum reference current of 300A. The input of the integrator is the difference between the actual dc link voltage and 100kV. The current supervisor is implemented in per-unit since the inverter current controller is in per-unit. The current supervisor is shown in Figure 5.9(a) and parameters are listed in Table 5.5.

5.5.1 Simulation

A simulation is performed using a power source and the current supervisor. The simulation is similar to Section 5.3.5 but it is using the current supervisor instead of the fixed reference current. Figure 5.9(b) shows the simulation results which are very conclusive about the behaviour of the inverter station. It tracks the 100kV voltage reference and the current controller has the lower limit at 300A and the upper limit at 1.2kA. The simulation shows that the current goes beyond 1.2kA when the voltage reaches 131kV. This behaviour is normal since at that point the inverter station is no longer in the current control mode but enters the minimum gamma control mode of operation. It should be emphasized that, in the milliseconds time scale, the inverter is in current control for the range $300A < I_{inv} < 1200A$. On this short time scale, the inverter is not in voltage control mode as this would interfere

(a) Current supervisor.

(b) Simulation of the inverter station with the current supervisor.

Figure 5.9: Current supervisor and simulation results.

with operation of the sending end converters.

5.6 Inverter Station Performance

The PI-controllers from the CIGRE benchmark have not been changed, therefore, it is relevant to assess the response of the inverter station. The performance of the CIGRE benchmark current controller is evaluated using two step responses. Those two simulations will give insight on the bandwidth of the inverter station primary controls. The first test case is a step change in the reference current from 1kA to 1.2kA. The response is shown in Figure 5.10(a). The system reaches the steady-state within 40ms and the overshoot is within 5%. The second test is a step change in the sending end voltage from 100kV to 120kV. The current experiences a sudden increase until the controller adjusts the firing angle to return to the reference current of 1.2kA. The current overshoot is the same order as the voltage step, 17% compared to 20%. This response is expected since the immediate change in the sending end voltage automatically results in a larger voltage difference between the sending

Figure 5.10: Step responses of the current controller.

and receiving ends. As a consequence, the current increases almost as a step just like the voltage. The limiting factor of the current increase is the inductance of the transmission line. The interesting result in this test is the settling time which is less than 40ms. The system is capable of being regulated within 40ms after a step change of 20% in the reference current or in the sending end voltage.

The dynamic response of the system to an instantaneous change in wind speed is illustrated in Figure 5.11. Initially, the system operates at point A. The wind speed is 10m/s and the link current is regulated at 870A such that the dc link voltage is at 100kV. Then, the wind suddenly drops to 9m/s. The system moves from point A to point B in a time frame that depends on the mechanical inertia of the machine. The hub speed gradually slows down until the optimal operating point for a wind of 9m/s is reached. By design, this transition is considered 'fast' compared to the current supervisor response. At point B, the current supervisor starts to slowly reduce the reference current to increase the transmission voltage. The current is reduced until the voltage reaches 100kV and the new operating point is now point C.

Figure 5.11: Dynamic response of the system with the current supervisor.

Chapter 6

Complete System: Wind Farm

In this chapter, a complete wind farm is simulated. The system is composed of 30 wind turbines, a transmission line and an inverter station. The wind turbine model has been derived in Chapters 2, 3 and 4. The transmission line and the inverter station have been developed in Chapter 5. The aim of this chapter is to validate the operation of the complete system through simulation. The simulation software is PSCAD/EMTDC and circuit schematics can be found Appendix C.

6.1 25MW Unit

For simulation purposes, the 30 wind turbines are modeled using 6 units with a rated power equivalent to 5 turbines. Therefore, 6 units of 25MW are used to represent the wind farm of 30 units. Wind turbine parameters are scaled accordingly to maintain the same dynamics and they are listed in Table 6.1.

6.2 Wind Farm Simulation

Two scenarios are developed to validate the operation of the wind farm. The first case is a high wind day. All units are operating at rated wind speed and at different times,

Figure 6.1: Wind farm model.

Table 6.1: Wind turbine parameters.

	5MW unit	25MW unit
Wind Turbine Parameters		
Rated power [MW]	5	25
Rated wind speed V_{wind} [m/s]	12	12
Rated shaft speed w_m [rad/s]	1.55	1.55
Rated frequency f_e [Hz]	35.77	35.77
Rated torque [Nm]	3.226×10^6	1.613×10^7
Rotor and turbine inertia J (2.55s) [$kg\ m^2$]	1.06×10^7	5.03×10^7
Generator Parameters		
Induced voltage E_{PM} [kV_{LN}^{RMS}]	2.89	14.45
Synchronous inductance L_s [mH]	6.77	33.85
DC-DC Converter Parameters		
Capacitor C_{dc} [mF]	3	0.6
Switching frequency [kHz]	1	1
Output DC Filter Parameters		
L_1 [mH]	1	5
R_{L1} [m Ω]	20	100
L_2 [μ H]	50	250
R_{L2} [m Ω]	1	5
C_1 [μ F]	500	100
R_1 [Ω]	50	250
Controller Parameters		
K_P	1.12×10^{-4}	
a	60	
Controller Feedback Filter Parameters		
Natural frequency w_{filter} [rad/s]	224.7	
Damping ratio ζ	0.707	

Table 6.2: Simulation scenarios.

Wind Turbine Number	Wind Speed					
	Simulation 1			Simulation 2		
	Initial (m/s)	Final (m/s)	Ramping Time [$t_{\text{start}} - t_{\text{final}}$] (s)	Initial (m/s)	Final (m/s)	Transition Time [$t_{\text{start}} - t_{\text{final}}$] (s)
WT01	12	11.5	[20→23]	5	9	[5 ⁻ →5 ⁺]
WT02	12	11	[5→8]			
WT03	12	10	[15→18]			
WT04	12	12	-			
WT05	12	10.5	[10→13]			
WT06	12	9.5	[25→28]			

they individually experience a wind reduction. The system is expected to have a voltage drop. Then, the current supervisor should try to regulate the dc link voltage at 100kV by decreasing the current. When the system is back in steady-state, the operating point of each wind turbine is examined to validate peak power tracking.

The second scenario simulates a low wind day. The wind is 5m/s when it suddenly reaches 9m/s. In this simulation, all units have the same wind speed. The voltage is expected to increase until the reference current increases to keep the dc link voltage at 100kV. This simulation illustrates the behaviour of the system on a low wind day and an increase of wind as opposed to reduction. An overview of the simulation model is shown in Figure 6.1. The wind change scenarios are detailed in Table 6.2.

6.2.1 High Wind Day

The results of the first simulation are shown in Figure 6.2. Initially, all units inject the same voltage and the duty cycle is about the same for all converters. In the time frame between 5s and 25s, units experience their wind variations and the link current remains at 1.2kA. The duty cycle of the converter changes to maintain peak power tracking with the new wind speed. The dc link voltage drops because less power is injected. Eventually, the current supervisor engages in reducing the link current to increase the link voltage. Then, the duty cycle is readjusted slowly to keep optimal power operation. The angle α shows that the inverter station stays in current control mode since it drops (moving away from the $\gamma_{\min}$ control region) but does not reach the 90 degrees threshold to engage $\alpha_{\min}$ control. The V-I characteristic is shown in Figure 6.3(a) to illustrate the dynamic of the inverter station.

To demonstrate that peak power tracking is maintained, the rectifier output dc current, I_{dc} , of each unit is recorded when the system has reached steady-state. Figure 6.3(b) plots I_{dc} versus the wind speed at each turbine. The curve I_{dc}^{opt} is also shown. The operating points are located on the reference curve which confirms peak power tracking using the dc link.

Figure 6.2: Simulation 1: high wind day.

Figure 6.3: Simulation 1: V-I dynamic and steady-state operation.

6.2.2 Low Wind Day

The results of the second simulation are shown in Figure 6.4. For this simulation, all wind turbines experience the same wind speed throughout the simulation. All units are in steady-state with a wind a 5m/s when suddenly the wind changes to 9m/s. The duty cycle of the dc-dc converter quickly responds to the increasing generator speed. The link voltage changes from 30kV to 130kV in a few seconds. Then, the link current starts to increase. Initially, the current is at the minimum value of 300A. At the end, the dc link voltage is regulated at 100kV with a link current of 600A. The angle α shows that the inverter station enters in $\gamma_{\min}$ control when the angle is limited to 145 degrees. After a few seconds, the current control mode resumes. The V-I characteristic is shown in Figure 6.5 to illustrate the dynamic of the inverter station. The last portion of the curve (I_{inv} from 0.45kA to 0.6kA) suggests that the wind farm is following the relationship $V_{\text{wf}} = P^{\text{opt}}/I_{\text{link}}$ derived in Chapter 5.

The inverter responds as expected in both simulations. The system is able to operate at both low and high power. The simulations indicate that the wind farm is stable when it experiences a step change, either up or down, in the wind speed.

Figure 6.4: Simulation 2: low wind day.

Figure 6.5: Simulation 2: V-I dynamic.

Chapter 7

System Protection

In this chapter, a basic protection scheme for the new configuration is proposed. The purpose of the chapter is not to develop a comprehensive protection system, as this goes far beyond the scope of this thesis. However, some key fault scenarios are at least identified together with possible methods of dealing with such events. The system under study is the wind farm presented in Chapter 6. The first element discussed is the overspeed protection required to contain the hub speed. Then, different types of dc faults and their impact on the system are analyzed. As it is commonly done in protection studies, the analysis is performed via simulation. The protection scheme is detailed and the additional equipment required is identified.

Wind turbines operate in steady-state at rated wind speed when the faults are applied. Studied dc faults are all line-to-ground since the simulation model is unipolar. Similar behaviour is expected from a bipolar system since the power flow and the current direction are the same. AC faults on the generator side and on the ac grid are not addressed in this work. This chapter intends to grasp a general sense of the response of the system when it experiences disturbances on the dc link. The control scheme can serve as a foundation for deeper protection studies in future work.

Figure 7.1: Electromagnetic braking.

7.1 Overspeed Protection

In some situations, the wind turbine generator does not develop enough electrical torque to contain the hub speed. For example, this event can be caused by a malfunction of the dc-dc converter, a fault on the dc link or simply if the link current is not high enough to regulate that particular unit. As a result, the hub speed is expected to increase, possibly exceeding its nominal value.

As it speeds up, the induced voltage of the PMSG gets larger since it is directly proportional to the hub speed. The uncontrolled nature of the diode rectifier causes the dc link voltage to increase as well. Overspeed protection is performed through electromagnetic braking. It consists of a resistor and a switch connected in parallel with the capacitor as shown in Figure 7.1. When the capacitor voltage reaches a certain limit, the resistor is switched-in to extract more current. More electrical torque is thereby developed and the hub speed can be contained. Braking circuits are common in machine drives that are using diode rectifiers [22].

The value of the resistor is based on the rated capacitor voltage and the rated dc current. When the electromagnetic brake operates, the current flowing in the resistor has to be at least the rated dc current in order to contain the hub speed. A resistor of 25Ω is selected

Figure 7.2: Wind farm with different types of faults.

and the calculation is given in Equation (7.1). The capacitor voltage limit for the brake to operate has been set to 31kV, which is 15% above the rated value.

$$R_{bk} \leq \frac{V_{dc}^{rated}}{I_{dc}^{rated}} = \frac{2.7 \times 10^4}{924} = 29.22\Omega \quad (7.1)$$

7.2 DC Fault Analysis

The wind farm is shown in Figure 7.2 with the different types of faults studied in this project. The faults are divided into two categories: external (FLT1, FLT2) and internal (FLT3). Each fault can be either permanent or temporary, however, the protection scheme has to be able to detect the fault regardless of it being permanent or temporary. The system response to the different fault types is studied in this section.

Figure 7.3: Transmission line fault.

7.2.1 External Fault

An external fault is an event that occurred on the dc link. The fault can be located on the transmission line (FLT1) or on the cable between two wind turbines (FLT2). The location of the fault is a factor in the response of the system.

7.2.1.1 Transmission Line Fault (FLT1)

The wind farm of Figure 7.2 has been redrawn in Figure 7.3 to illustrate the power flow and current directions in this example. For the wind turbine, a fault on the transmission line is seen as a “downstream fault”, because of the power flow direction. The current flowing in the dc-dc converters is therefore called the “upstream current”, I_{link}^{up} , and the current from the inverter to the fault is the “downstream current”, I_{link}^{down} . In this project, the transmission line fault is located at 1/4 of the way for wind turbine WT01 to the inverter station.

From the inverter point of view, all faults take place upstream. During the fault, the voltage at the inverter decreases drastically and the controller decreases the firing angle. When it reaches 90° , no more inversion is performed keeping the current and the voltage at zero. As a result, I_{link}^{down} is not a factor in this analysis because no current is flowing from the inverter to the fault. The system response is shown in Figure 7.4(a) and it confirms the expected behaviour of the receiving end.

Figure 7.4: Transmission line fault response, no protection.

As expected, the sending end experiences a voltage drop, but also major current oscillations. Figure 7.4(b) shows the response of wind turbine WT02. Other turbines show a similar response. The wind turbine module output voltage collapses when a fault takes place downstream. The high frequency oscillations that appeared directly after the fault (between 0s and 0.04s) are due to the discharging of the output dc filter. The amplitude of the dc link current reaches 12kA because the units are attempting to inject constant power into the fault.

7.2.1.2 Midpoint Fault (FLT2)

Figure 7.5 illustrates a fault located between WT03 and WT04. For the units located upstream (WT04-06), the response is the same as for a transmission line fault. This is seen by inspecting the WT05 transients given in Figure 7.6(b).

However, the response of units located downstream (WT01-03) is different. From the perspective of these wind turbines, a permanent fault to ground is seen as a new reference point for the system. Disturbances are experienced but the units recover and they continue to operate at peak power output. A dc link voltage is sustained from this new ground point. Figure 7.6(a) shows that the link voltage recovers to half of the value prior to the

Figure 7.5: Midpoint fault.

fault. The inverter controller quickly responds to maintain its current at 1.2kA. The current supervisor will eventually attempt to bring the dc link voltage to 100kV but over a longer period of time. The fault may easily be identified from the transient, but after the fault transient, it is impossible for downstream units to know if the fault is still present or not. To allow automatic re-energization of the link, a communication channel is required such that upstream wind turbines (WT04-06) inform downstream units (WT01-03) whether the fault is temporary or permanent.

Figure 7.7 enlarges the current and voltage around the fault time. The currents of downstream units initially decrease contrary to the currents of upstream units which increase.

Figure 7.6: Midpoint fault response, no protection.

Figure 7.7: Responses of wind turbines WT02 and WT05 around fault time, no protection.

Also, the output voltage of downstream units face a slight increase as the dc-dc converter attempts to return to optimal power injection. This simulation serves as the base to compute threshold values for the detection methods because it allows us to differentiate between upstream and downstream converter waveforms.

7.2.2 Internal Fault (FLT3)

The internal dc fault occurs inside the wind turbine. For example, it can be produced by a flashover between a converter and a grounded nacelle or between a floating nacelle and ground. The internal fault can be easily detected by the faulty unit with differential protection. The difference between the current entering and the current leaving the nacelle has to stay within a tolerance margin, otherwise, an internal fault exists. For the other units in the system, this event is seen as a midpoint fault, as described earlier.

7.3 Protection Circuitry

Figure 7.8 details the converter topology with the protection equipment. The signals monitored through sensors for the protection are the output voltage, V_{prot} , and the currents entering, $I_{\text{prot-in}}$, and leaving, $I_{\text{prot-out}}$, the nacelle. The electromagnetic brake has been in-

Figure 7.8: Wind turbine converter topology with protection equipment.

troduced in Section 7.1. The second add-on is the thyristor T1 connected in parallel with the diode. The dc-dc converter can turn-off the IGBT switch during a fault but the link current continues to flow and it goes through the fast recovery diode. These components become expensive for high power ratings. Therefore, a thyristor is installed and it is activated only when the unit encounters a fault.

Switches are installed at the wind turbine output to bypass the unit, if required. Different concepts for dc circuit breakers have been proposed in [32]. Generally, they consist of power electronics configurations that can break dc current, however, these solutions represent significant additional costs. An affordable and practical solution has been identified for this project. Disconnect switches have been selected because they are reliable and available for this power rating. The main disadvantage of this device is its inability to break dc current. In order to disconnect, the system has to de-energize the link and to bring the dc link current to zero. In normal operation, SW1 and SW2 are closed and SW3 is opened. When the unit is bypassed, SW1 and SW2 are opened and SW3 is closed.

7.4 DC Fault Protection

The protection scheme is built on a sequence of events based on the work done in [33]. The first step is the fault detection. It has to be fast and must avoid any false detection. The time frame for detection has been established at 1ms for this project. Once the fault is detected, the dc link needs to be de-energized for the dc fault to extinguish. After a certain time, the system restarts and it evaluates whether the fault is permanent or not. In the case of a temporary fault, all units go back into service. Otherwise, the complete system shuts down. However, a permanent internal fault is a special case. The faulty unit can be permanently bypassed such that other units can operate normally. The protection strategy is shown in Figure 7.9.

7.4.1 Fault Detection

Various dc fault detection methods have been suggested for multi-terminal systems [33, 34]. As stated earlier, the detection has to be fast (within 1ms) and reliable (no false detection). Four approaches have been chosen to cover the different types of faults. More precisely, they are:

Current differential is used to detect internal faults. A difference between the currents of 10A causes fault identification.

High current and low voltage characterizes an external high impedance fault. The current increases but less drastically than a low impedance fault. Threshold values are 1.2kA for the current and 2kV for the voltage. Both conditions have to be true for a duration of 100 μ s to prevent false detection.

Current threshold prevents the power electronics from experiencing current beyond their maximum ratings. The limit has been set to 2pu of their nominal values. As seen in Section 7.2, the current increases rapidly during a low impedance fault. Fast detection

Figure 7.9: Protection strategy.

is required to limit the exposure of the components to high current. For this reason, this detection method does not have the duration condition.

Current derivative detects the early stage of an upstream fault. As shown in Figure 7.7, the upstream fault is characterized by the current starting with a negative slope. Values of the derivative of the current less than $-5 \times 10^6 \text{ A/sec}$ result in fault identification.

7.4.2 Controller Implementation

As is the case for traditional HVDC protection, the protection scheme is embedded within the controller of the converter [35]. For this project, the protection scheme has been developed using logic gates and it can be found in Appendix D.

7.5 Simulation

Two simulations are performed to observe the performance of the proposed protection strategy. The first is a permanent internal fault, leading to bypassing a unit. This tests both upstream/downstream fault identification as well as by-pass and re-energization process. The second is a temporary transmission line fault leading to complete system recovery.

7.5.1 Fault 1: Permanent Internal Fault in WT04

The first simulation is a permanent internal fault on unit WT04. This simulation evaluates the capability of the system to bypass one faulty unit and to continue to operate. The wind farm is operating at rated wind speed of 12m/s. Figure 7.10 shows that the system recovers after the fault and that it continues to operate. The voltage drops from 120kV to 100kV which represents the elimination of the faulty unit in the system. The inverter current is maintain at 1.2kV after the fault.

The output voltage waveforms of wind turbine 1 through 6, shown in Figure 7.11(a), can be divided into four sections. From -0.2s to 0s, the system is in steady-state with an

output voltage of 20kV. Between 0s and 0.4s, the fault occurs and it is detected. The protection take action and all units stop injecting power. During that period, WT04 detects the permanent internal fault and as a consequence, it activates this bypass switches. In order for the switches to operate, the link has to be completely discharged. Through the communication channel, the unit WT04 indicates that it experiences a permanent internal fault. At this point, the inverter shuts the system down temporarily to allow the bypass. Once the bypass is confirmed, the inverter restarts the system. From 0.4s to 1s, the units are then gradually energizing the dc link. At 1s, units are back in normal operation with WT04 is bypassed. Figure 7.11(b) shows that all units, except WT04, both upstream and downstream detect an external fault. For units other than WT04, the fault is interpreted as a temporary fault since they are able to resume operation. This simulation demonstrates the ability of the system to bypass a faulty unit and continue normal operation.

Figure 7.10: Fault 1: inverter station.

(a) Fault 1: output voltages.

(b) Fault 1: protection signals.

Figure 7.11: Fault 1: wind turbines.

7.5.2 Fault 2: Permanent Line Fault

The second simulation is a temporary fault on the line. This might occur due to a lightning strike of an overhead line. This simulation evaluates the ability of the system to detect a downstream fault and to recover quickly from a temporary fault. Additionally, this simulation observes that selected protection threshold values are valid for a lower power operating point because the wind farm is operating at a wind speed of 10m/s. Figure 7.12 shows that the system recovers from the fault but that the dc link voltage momentarily reaches 130kV. This rapid increase and high voltage value put the inverter station at risk of commutation failures. Nevertheless, the inverter returns to the same operating point as prior to the fault. The output voltage waveforms, shown in Figure 7.13(a), are similar to the previous case. However, a significant ripple is observed at the beginning of the reinsertion period and at the transition to normal operation. Figure 7.13(b) shows that all units properly detect a temporary external fault. Those results confirm proper line fault detection and adequate return to normal operation. A more elaborate controller schematic should be implemented to reduce the risk of commutation failures for the inverter and to minimize the ripple during the reinsertion stage.

Figure 7.12: Fault 2: inverter station.

(a) Fault 2: output voltages.

(b) Fault 2: protection signals.

Figure 7.13: Fault 2: wind turbines.

Chapter 8

Conclusions

Based on HVDC technology, this thesis introduces a new approach to collect and transmit power from offshore or remote wind farms. In place of a centralized converter, a series interconnection of distributed converter modules is proposed, where one module is located within each individual wind turbine. The series connection of modules builds the dc voltage for transmission purposes, hence it is referred to as a “distributed HVDC converter”.

To make the series interconnection viable, each series converter module must always provide a continuous condition path for the dc link current. The step-down (buck) converter is identified as a suitable low cost module meeting this criteria. Supply of power to the module can be accomplished using various approaches. In this project, wind turbine generators employing permanent-magnet synchronous machines are paired with diode rectifiers to supply the module.

At the receiving end, the inverter station is based on thyristor-based technology. The controller characteristics have been designed such that the inverter operates predominantly in current control. A supervisor regulates the current at a slow rate to optimize the dc link voltage. The reference current decreases under low power conditions to increase the voltage.

A 150MW wind farm is modeled in the PSCAD/EMTDC software package. To facilitate simulation, 6 scaled up wind turbine blocks, each representing the power of 5 units, are stud-

ied. The simulation demonstrates the viability of the proposed configuration. Modules share a common current while the dc link voltage is built up through the series interconnection. It is shown that the simple one-switch dc-dc converter modules offer sufficient control freedom to independently control each wind turbine and peak power operation of each turbine is demonstrated. Moreover, the inverter station fulfils its role of regulating the current. A current supervisor at the inverter station ensures that the dc link voltage remains near its nominal value.

A protection scheme for the system is presented. Three different types of dc faults are studied: transmission line fault, midpoint fault and internal module fault. A protection strategy is propose to ensure proper detection and actions. The protection scheme is implemented using logic gates.

Future research for this project would include:

- A laboratory experiment to verify system operation in light of practical implementation constraints (eg. controller latencies, sensor errors and offsets, unequal module parameters, etc).
- An advanced controller for the dc-dc converter in order to improve the power factor at the generator side could be considered similar to a power factor correction (PFC).
- An extensive protection study that would cover a wider range of faults, including ac faults, should be performed.
- The development of a communication channel between units that would influence controllers of the dc-dc converters. This would enhance the performance of the system and it would possibly result in the elimination of the output dc filter by permitting synchronous, but interleaved, switching of modules.
- Comparison of the performance of a system using diode rectifiers with one using voltage-source converters.

Appendix A

Wind Turbine and PMSG Parameters

A.1 Wind Turbine Parameters

A.1.1 Wind Speed Curves and PSCAD Model

The simulation software used in this project, PSCAD, has a wind turbine block included in its library. However, the component is not suitable for low-speed and high-torque units, most likely due to the absence of the maximum aerodynamic rotor efficiency coefficient as an input parameter. Consequently, the wind turbine block with medium-speed and medium-torque parameters is employed and per-unitized. Coefficients at the inputs and outputs have been introduced to match the nominal values of the desired wind turbine. Such an arrangement is shown in Figure A.1. Parameters of the medium-speed medium-torque unit are shown in Table A.1. From the modified model shown in Figure A.1, wind curves are extracted from simulations for different wind speeds. The simulation scenario consists of recording both output torque and power for a fixed input wind speed and a varying hub speed.

A.1.2 Wind Distribution

The stochastic nature of the wind makes the power production of a wind turbine unpredictable and irregular. However, a probability function has been derived from statistical

Table A.1: PSCAD wind turbine block parameters.

Wind Turbine Block Parameters	
Generator rated MVA	2MVA
Machine rated angular mechanical speed	2.453 rad/s
Rotor radius	35.33m
Rotor area	3921 m ²
Air density	1.225 m ²
Gear box efficiency	1pu
Gear box ratio	1
Equation for power coefficient	MOD 2

Figure A.1: Wind turbine model in PSCAD.

analysis of wind data. It has been shown that the Weibull function yields a good approximation to the wind distribution. The cumulative distribution function, Φ , is given in Equation (A.1) [15].

$$\Phi = 1 - e^{-\left(\frac{V_{\text{wind}}}{A}\right)^k} \quad (\text{A.1})$$

The scaling factor A is set to 7.9 based on [14]. The form parameter, k , is 2 in typical frequency distributions of many wind sites [15]. The Weibull function with a form parameter of 2 is often referred to as the Rayleigh distribution. The probability density function can be derived by differentiating the cumulative distribution function, Φ , by the random variable, V_{wind} . The probability density function, ϕ , is derived below.

$$\phi = e^{-\left(\frac{V_{\text{wind}}}{A}\right)^k} \frac{k}{A^k} V_{\text{wind}}^{k-1} \quad (\text{A.2})$$

Figure A.2: Weibull distribution.

This general probability function for wind sites has been derived from observations made over many years at different locations. The collection of data is typically made at a height of 10m. However, since the hub is considerably more elevated than 10m, this results in discrepancies in the analysis for the wind turbine. Since wind speed increases with altitude, it is necessary to calculate the wind speed at hub height. It is important to note that the scaling factor is not included in the computation of the probability functions (A.1) and (A.2). The coefficient is used only to map the wind speed from the reference point (10m) to the hub height. The scaling factor is described as, [15]:

$$V_{\text{wind}}^{\text{hub}} = V_{\text{wind}}^{10\text{m}} \left(\frac{h^{\text{hub}}}{h^{10\text{m}}} \right)^{\alpha} \quad (\text{A.3})$$

where h^{hub} and $h^{10\text{m}}$ are, respectively, hub and reference heights. The Hellmann's exponent, α , is 0.1 which gives an average wind of 9m/s. The cumulative distribution function for wind speeds at hub height is shown in Figure A.2(a) and the probability density function is shown in Figure A.2(b).

A.2 PMSG Parameters

A.2.1 PSCAD/EMTDC Model in dq0 frame

The generator model in the dq0 frame is implemented using current sources. Machine equations (2.16) and (2.17) from Chapter 2 are recalled. However, they are solved for currents and transformed in the s-domain. They are described in Equations (A.4) and (A.5). The rotor position for the Park transforms (K and K^{-1}) is calculated by integrating Equation (2.15) with respect to time. Using Laplace transform, it gives Equation (A.6). The diagram is shown in Figure A.3.

$$i_q = \left(V_q^r - \omega_r L_s i_d^r - \omega_r \lambda_m' \right) \left(\frac{1}{r_s + sL_s} \right) \quad (\text{A.4})$$

$$i_d = \left(V_d^r + \omega_r L_s i_q^r \right) \left(\frac{1}{r_s + sL_s} \right) \quad (\text{A.5})$$

$$\theta_r = \frac{1}{s} \omega_r \quad (\text{A.6})$$

Figure A.3: Block representation of the PSCAD circuit.

Appendix B

AC-DC Converter: Voltage-Source Converter

The voltage-source converter (VSC) can be used for the ac-dc stage instead of the diode rectifier. The main advantage is the control flexibility it offers. Peak power tracking can be performed at the rectification stage and a different control strategy for the dc-dc converter is developed.

The first section briefly introduces the converter topology. Then, the number of turns per phase winding, N_s , for the generator is defined for this new application. A control strategy is elaborated for both the ac-dc and the dc-dc converters. Finally, a simulation is performed to validate proper operation of series interconnected wind turbines equipped with VSCs.

B.1 Voltage-Source Converter

The VSC is composed of six Integrated Gate Bipolar Transistors (IGBTs) with their antiparallel diodes as shown in Figure B.1. The converter provides several control options because of the turn-on and turn-off capabilities of the components. In ac machine drive applications, the VSC is often employed because it offers high bandwidth control, low harmonic distortion in machine currents and it can supply/absorb reactive power.

Figure B.1: Wind turbine converter topology using VSC.

B.2 N_s Value and System Parameters

The generator does not have to be overexcited when it is paired with a VSC. All the reactive power consumed by the PMSG is supplied by the VSC. Therefore, the generator can be designed such that the back emf produced is at the selected terminal voltage of $4kV_{ll}^{RMS}$.

From Chapter 2, the number of turns per phase winding is calculated with Equation (B.1) where $E_0 = 9.63\text{V/turn}$. The value of N_s is 240 and based on this parameter, the machine inductance and resistance are found using equations described in Chapter 2. The amplitude of the flux linkages is computed with Equation (B.2) based on the rated induced voltage of 2.31kV and the rated rotor frequency of 224.7rad/s [20]. System parameters are listed in Table B.1.

$$[E_{PM}]_{LN}^{RMS} = \frac{4 \times 10^3}{\sqrt{3}} = N_s E_0 \quad (B.1)$$

$$[E_{PM}]_{LN}^{RMS} = \omega_r \lambda_m'^r \quad (B.2)$$

Table B.1: System parameters when using VSC.

Wind Turbine Parameters	
Rated power [MW]	5
Rated shaft speed w_m [rad/s]	1.55
Rotor and turbine inertia J [$kg\ m^2$]	1.06×10^7
Generator Parameters	
Rated frequency f_e [Hz]	35.77
Rated rotor frequency ω_r [rad/s]	224.75
Induced voltage E_{PM} [kV_{LN}^{RMS}]	2.31
Synchronous inductance $L_s (= L_d = L_q)$ [mH]	4.33
Stator resistance r_s [m Ω]	72.2
Flux linkages λ'_m [V·s]	1.454×10^4
System Parameter	
Capacitor C_{dc} [mF]	3

B.3 Optimal I_q

As in the case of the diode rectifier, the machine drive has to operate at optimal torque to perform peak power tracking. The machine electrical torque is directly proportional to the current i_q^r when the d-axis of the reference frame is aligned with the north pole of the rotor magnet. Equation (B.3), taken from Section 2.2.5 of Chapter 2, defines that relation. Since the electrical torque does not depend on current i_d^r , its reference current is set to zero to minimize the amplitude of the machine current [20].

$$T_e = \frac{3}{2} \frac{290}{2} \lambda'_m i_q^r \quad (B.3)$$

The optimal torque characteristic curve of the wind turbine has been extracted from Figure 2.1(a) of Chapter 2 and it is shown in Figure B.2(a). This curve gives the optimal value of torque, T_e^{opt} , that should be demanded by the generator at a given measured hub speed. Equation (B.4) gives the required q-axis reference current associated with optimal torque.

$$[i_q^r]^{\text{opt}} = \frac{2}{435 \lambda'_m} T_e^{\text{opt}} \quad (B.4)$$

Figure B.2(b) shows the $[i_q^r]^{\text{opt}}$ curve. The nominal values for i_q^r and i_d^r are, respectively,

Figure B.2: Curves for maximum power point tracking.

1020A and 0. According to the direction of the currents in Figure B.1, the current i_q^r has to be negative to generate power. Therefore, the $[i_q^r]^{\text{opt}}$ curve is multiplied by -1 when it is implemented as the reference signal for the current controller.

B.4 Controller

B.4.1 VSC Control Diagram

Machine equations in the dq-frame are recalled from Chapter 2 to develop the control model. The decoupled equations are used and they are shown in Equation (B.5). Decoupling is permitted because all the poles are located on the left half plane in the s-domain.

$$\frac{d}{dt} \begin{bmatrix} i_q^r \\ i_d^r \end{bmatrix} = \begin{bmatrix} \frac{-r_s}{L_s} & 0 \\ 0 & \frac{-r_s}{L_s} \end{bmatrix} \begin{bmatrix} i_q^r \\ i_d^r \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} u_q \\ u_d \end{bmatrix} \quad (\text{B.5})$$

where

$$u_q = -\omega_r L_s i_d^r + V_q^r - \omega_r \lambda_m'^r$$

Figure B.3: VSC control diagram.

$$u_d = \omega_r L_s i_d^r + V_q^r$$

Feedback control with a Proportional plus Integral (PI) controller is used for this converter. The control diagram of this system is shown in Figure B.3. The open-loop transfer function of the uncontrolled system is described in Equation (B.6) and its frequency response is shown in Figure B.4(a).

$$T_u(s) = \frac{i_{q,d}^r}{[i_{q,d}^r]^{\text{opt}}} = P(s)H(s) \quad (\text{B.6})$$

where

$$P(s) = \frac{1}{sL_s + r_s}$$

$$H(s) = \frac{w_{\text{filter}}^2}{s^2 + 2\zeta w_{\text{filter}} s + w_{\text{filter}}^2}$$

Figure B.4: Bode plots for VSC controller.

Parameters of the lowpass filter and the controller are given in Table B.2. Both i_q^r and i_d^r have the same controller design and the same lowpass filter characteristic. The closed-loop transfer function of the compensated system is described in Equation (B.7) and its frequency response is shown in Figure B.4(b).

$$T_u(s) = \frac{i_{q,d}^r}{[i_{q,d}^r]_{\text{opt}}} = \frac{C(s)P(s)}{1 + H(s)C(s)P(s)} \quad (\text{B.7})$$

where

$$C(s) = K_P \frac{s + a}{s}$$

B.4.2 DC-DC Converter Control Diagram

The VSC controller is using a sine-triangle pulse-width modulation (SPWM) to generate the gate driver signals for the IGBTs. The capacitor voltage has to be maintained at a certain level, otherwise, the VSC goes into overmodulation when the capacitor voltage is too low. This mode of operation is avoided with the dc-dc converter actions. The role of

Table B.2: VSC - Feedback filter and controller parameters.

Filter Parameters	
Natural frequency w_{filter} [rad/s]	3141.6
Damping ratio ζ	0.8
Controller Parameters	
K_P	3.8
a	16.67
Switching frequency [kHz]	1.5

Figure B.5: DC-DC converter control diagram.

the dc-dc converter is to maintain the dc voltage at a given level. By increasing its duty cycle, the current discharging the capacitor increases which results in a voltage reduction. Alternatively, the voltage increases when the duty cycle is reduced.

The reference value for the capacitor voltage is based on the nominal values of the system. $[V_q^r]^{\text{rated}}$ and $[V_d^r]^{\text{rated}}$ are calculated using (B.5) in steady-state. By doing so, the voltages are 3.194kV and 0.993kV respectively. The VSC does not enter in overmodulation provided we satisfy

$$\sqrt{(V_q^r)^2 + (V_d^r)^2} \leq k_{\text{inv}} V_c \quad (\text{B.8})$$

where $k_{\text{inv}} = \frac{1}{2}$ for sine-triangle pulse-width modulation (SPWM) and $k_{\text{inv}} = \frac{1}{\sqrt{3}}$ for space-vector modulation. In this work, SPWM is employed merely to simplify the simulation model. To permit a small control margin and to account for dc bus voltage ripple a dc reference voltage of 7.4kV is selected.

Table B.3: DC-DC converter - Feedback filter and controller parameters.

Filter Parameters	
Natural frequency w_{filter} [rad/s]	31.4
Damping ratio ζ	0.7
Controller Parameters	
K_P	6.5×10^{-5}
a	15
Switching frequency [kHz]	1

The dc-dc controller needs to adjust the duty cycle in order to maintain the capacitor voltage at 7.4kV. Equation (B.9), recalled from Chapter 3, is used to derive the control diagram.

$$C_{\text{dc}} \frac{dV_{\text{dc}}}{dt} = I_{\text{dc}} - DI_{\text{link}} \quad (\text{B.9})$$

The rectified power ($V_{\text{dc}}I_{\text{dc}}$) is assumed to be constant and it is identified as P_{dc}^* . Equation (B.9) in the s-domain with constant power has the form:

$$C_{\text{dc}}V_{\text{dc}}s = \frac{P_{\text{dc}}^*}{V_{\text{dc}}} - DI_{\text{link}} \quad (\text{B.10})$$

It can be rewritten as,

$$C_{\text{dc}}V_{\text{dc}}^2s + DI_{\text{link}}V_{\text{dc}} = P_{\text{dc}}^* \quad (\text{B.11})$$

This equation is linearized about an operating point to find the relation between V_{dc} and D . The model $G(s)$, described in Equation (B.12), is obtained from the linearization. The control diagram is shown in Figure B.5. Filter parameters are listed in Table B.3.

$$G(s) = \frac{\Delta V_{\text{dc}}}{\Delta D} = \frac{-I_{\text{link}}V_{\text{dc}0}}{2C_{\text{dc}}V_{\text{dc}0}s + D_0I_{\text{link}}} \quad (\text{B.12})$$

The operating point is at the rated values, where $P_{\text{dc}}^* = 5\text{MW}$, $V_{\text{dc}0} = 7.4\text{kV}$, $I_{\text{link}} = 1.2\text{kA}$ and $D_0 = I_{\text{dc}0}/I_{\text{link}} = 0.56$. The open-loop and closed-loop responses are shown in

Figure B.6: Bode plots for dc-dc converter controller.

Figure B.6.

B.5 Simulation

Figure B.7 shows the model used for the simulation in the PSCAD/EMTDC software package. The inverter station is modeled as a current source with a fixed current of $1.2kA$. The wind farm is composed of 30 units, for a potential total production of 150MW. Because of simulation limitations, the 30 unit wind farm is simulated using 6 blocks. Each block represents a wind turbine that has been scaled up to have the power of 5 units.

The simulation scenario is as follows. Initially, all turbines are operating in steady-state at rated wind speed. Rated power of 150MW is transmitted, 5MW per turbine (25MW per equivalent block in the simulation). Thereafter, in sequence each block of turbines is exposed to a different step reduction in wind speed. The output per turbine should stabilize at the maximum power available based on the new wind speed. The system response is shown in Figure B.8(a). Results show that the dc link operates stably throughout the disturbances

with minimal dynamic interaction between modules.

Figure B.8(b) plots the currents i_q^r and i_d^r at $t=25s$ versus the wind speed at the turbine. The optimal i_q^r curve is also shown to demonstrate independent peak power operation. As stated earlier, the optimal i_q^r curve has negative values in order to generate power. The ac-dc converter regulates i_d^r to zero as expected. The operating points are located on their reference curves which confirms proper operation of series interconnected wind turbines using a dc link.

Figure B.7: Simulation model for the proposed system.

(a) Simulation of the wind turbines experiencing different wind speeds.

(b) Steady-state operating point taken at $t=25\text{s}$.

Figure B.8: PSCAD simulation.

Appendix C

Wind Farm PSCAD/EMTDC Model

Figure C.1: Wind turbine control.

Appendix D

Protection Controller

PSCAD/EMTDC Schematic

Figure D.1: Wind turbine controller.

Figure D.2: Protection controller - Part 1.

Figure D.3: Protection controller - Part 2.

Figure D.4: Wind turbine block.

Figure D.5: Wind farm.

Figure D.6: Inverter controller.

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