

École polytechnique de Louvain

Dynamic Modelling and Control of a Hybrid Link in the Context of an Energy Island

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Abstract

In response to the environmental impact of conventional electricity power generation, and motivated by geopolitical and economic considerations, there is a shift towards renewable energy sources. To support the integration of future offshore wind farms along the Belgian coast, Elia, Belgium's electricity transmission system operator, is developing the Princess Elisabeth Island, the world's first artificial energy island, featuring a hybrid transmission system to the mainland, combining HVDC (High-Voltage Direct Current) and HVAC (High-Voltage Alternating Current) technologies. This hybrid configuration is both novel and technically complex, requiring detailed analysis to predict its behaviour and impact on the existing power grid.

This thesis presents a comprehensive modelling and simulation study of the island's electric system using *MATLAB Simulink*. First, the hybrid transmission link is analysed in detail. The HVDC system is modelled, including its control strategies and operational principles, while the HVAC connection is incorporated to represent the full hybrid topology. Afterwards, wind turbine technologies are covered, with a particular focus on Doubly-Fed Induction Generators (DFIG). A method for aggregating multiple wind turbines into a single equivalent wind turbine model is also presented. Finally, the overall electric system is simulated to evaluate the proper functioning of the developed model.

This work resulted in the detailed comprehension of the Princess Elisabeth Island grid and the development of a preliminary model in *MATLAB Simulink*. It can serve as a foundation for further studies on this system, such as analysing its robustness, stability, control optimization, and grid integration, contributing to the reliable and efficient deployment of large-scale offshore renewable energy.

The *MATLAB Simulink* model can be found in the following repository: https://github.com/GeoffroyDM/MasterThesis_PrincessElisabethIslandModel.git

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Contents

Abstract	i
Acknowledgments	iii
Contents	v
List of Acronyms	ix
List of Figures	xi
List of Tables	xiii
1 Introduction	1
1.1 Princess Elisabeth Island Project	2
1.1.1 DC Connection Cost	3
1.2 Research Objective	3
1.3 Main Contributions	4
1.4 Methodology	4
1.5 Thesis Structure	5
2 State of the Art	7
2.1 AC vs DC	7
2.1.1 Energy Trading	7
2.1.2 Hybrid Link (HVDC + HVAC)	9
2.2 Space Vector and Per Unit Theory	10
2.2.1 Space Vector	10
2.2.2 Per-Unit	11
2.3 Synchronization Techniques	12
2.4 Grid Strength	13
2.5 HVDC Technologies	14
2.5.1 HVDC Topologies	14
2.5.2 Voltage Source Converter	15
2.5.3 Global Overview of VSC-HVDC Link	16
2.5.4 AC Filter	17
2.5.5 Electrical Equations	18
2.5.6 Control of HVDC Link	19
2.6 Wind Turbine Technologies	25
2.6.1 Types of Wind Turbines	25

2.6.2	<i>Mechanical Aspect</i>	28
2.6.3	<i>Maximum Power Point Tracking (MPPT)</i>	29
2.6.4	<i>Typical Power Curve</i>	31
2.7	DFIG Wind Turbines	32
2.7.1	<i>Power Flow and Modes of Operation</i>	32
2.7.2	<i>Electrical Equations</i>	34
2.7.3	<i>Control of DFIG</i>	35
2.8	Aggregated Wind Park Model	39
2.8.1	<i>Detailed Model</i>	40
2.8.2	<i>Aggregated Models</i>	40
3	Dynamic Model of Separate Components	43
3.1	Cable Modelling	43
3.1.1	<i>DC Export Cable</i>	44
3.1.2	<i>AC Inner and Export Cables</i>	44
3.1.3	<i>Shunt Reactors</i>	45
3.2	HVDC Connection Model	46
3.2.1	<i>HVDC Control</i>	47
3.2.2	<i>DC Capacitor and Smoothing Reactor</i>	47
3.2.3	<i>AC Filter</i>	48
3.2.4	<i>Synchronization Technique</i>	48
3.3	HVDC Connection Model Validation	48
3.3.1	<i>Start-up Procedure</i>	49
3.3.2	<i>Active Power</i>	49
3.3.3	<i>Reactive Power Variations</i>	51
3.3.4	<i>AC Balanced Voltage Dip</i>	52
3.3.5	<i>AC Fault</i>	53
3.4	Wind Farm Model	55
3.4.1	<i>DFIG Wind Turbine Model</i>	55
3.4.2	<i>Control of DFIG</i>	57
3.4.3	<i>Wind Farm Aggregated Model</i>	57
3.5	Steady-State Analysis of the Wind Turbine Model	58
3.6	Wind Farm Model Validation	59
3.6.1	<i>2 MW Wind Turbine</i>	60
3.6.2	<i>300 MW Wind Farm</i>	62
3.6.3	<i>300 MW Wind Farm with 10 km AC Cable</i>	63
3.7	Power Dispatch	65
4	Complete Model : Simulations and Results	67
5	Conclusions and Outlooks	71
	Appendices	73
A	Simulink Screenshots	74

1.1	Wind Turbine	74
1.2	Complete Model	78
1.3	HVDC Link	78
B	PI Regulator Gains	84
2.1	DFIG Wind Turbine Controller	84
2.2	HVDC Link Controller	84
	References	87

List of Acronyms

AC	Alternating Current
AVM	Average-Value Model
DC	Direct Current
DCOPF	Direct Current Optimal Power Flow
DFIG	Doubly-Fed Induction Generator
FAM	Full Aggregated Model
GTO	Gate Turn-off Thyristor
HCS	Hill Climbing Search
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
H&I	Hybrid and Intelligent
IGBT	Insulated-Gate Bipolar Transistor
LF	Loop Filter
MMM	Multi Machine Model
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
OPF	Optimal Power Flow
OT	Optimal Torque
PCC	Point of Common Coupling
PD	Phase Detector

PI	Proportional-Integral
PLL	Phase-Locked Loop
PMSM	Permanent Magnet Synchronous Machine
PSF	Power Signal Feedback
PWM	Pulse-Width Modulation
P&O	Perturb and Observe
RMS	Root Mean Square
SAM	Semi Aggregated Model
SCR	Short-Circuit Ratio
TSO	Transmission System Operator
TSR	Tip-Speed Ratio
VCO	Voltage-Controlled Oscillator
VSC	Voltage Source Converter

List of Figures

1.1	Global model of the electrical system of the Princess Elisabeth Island. Taken from [5].	2
2.1	Simple three-node model and maximum power transfer $1 \rightarrow 3$ considering transmission limits	9
2.2	Simple PLL scheme. Taken from [13]	12
2.3	HVDC topologies. Taken from [5]	14
2.4	Three-phase two level Voltage Source Converter. Taken from [16]	15
2.5	Pulse-Width Modulation. Reproduced from [16]	16
2.6	Single line diagram of a VSC-HVDC link.	16
2.7	LCL filter. Taken from [20].	17
2.8	HVDC control principle. Taken from [22]	19
2.9	Single line diagram of a VSC. Taken from [21].	20
2.10	General block diagram of inner loop	20
2.11	Detailed block diagram of inner loop. Taken from [21]	21
2.12	Detailed block diagram of the DC voltage controller	22
2.13	Active power controller block diagram	23
2.14	Reactive power controller block diagram	23
2.15	AC voltage controller block diagram	24
2.16	Current limiting strategies.	25
2.17	Typical configuration of a Type 1 wind turbine generator. Taken from [25] . .	26
2.18	Typical Configuration of a Type 2 wind turbine generator. Taken from [25] . .	26
2.19	Typical Configuration of a Type 3 wind turbine generator. Taken from [27] . .	27
2.20	Typical Configuration of a Type 4 wind turbine generator. Taken from [26] . .	28
2.21	Mechanical torque (left) and Mechanical power (right) for different wind speeds	30
2.22	Typical power curve of a pitch regulated wind turbine. Taken from [32]	31
2.23	DFIG Power Flow. Adapted from [9]	33
2.24	Steady-state power in function of wind speed	33
2.25	Equivalent one-phase electric circuit of a DFIG. Taken from [9].	34
2.26	Equivalent one-phase electric circuit of a DFIG referred to the stator. Taken from [9].	35
2.27	Rotor-side current control. Taken from [9]	37
2.28	Outer control loop	38

2.29	Single line diagram of grid-side system	38
2.30	Grid side controller	39
2.31	Wind park example	40
2.32	FAM representation of Fig. 2.31	41
3.1	PI section model. Taken from [5]	44
3.2	PI section with notation convention. Taken from [5]	46
3.3	HVDC link model.	46
3.4	Active power and DC voltage during start-up	49
3.5	Transient response to active power variations	50
3.6	Transient response to active power variations	51
3.7	Transient response to reactive power variations	52
3.8	Transient response to a 20% voltage dip at AC Grid 1	53
3.9	Transient response to a three-phase short circuit at the PCC with AC Grid 2	54
3.10	Zoom on Fig. 3.9(a)	54
3.11	$C_p(\lambda)$	56
3.12	Aerodynamic model in <i>MATLAB Simulink</i>	56
3.13	MPPT algorithm in <i>MATLAB Simulink</i>	57
3.14	Steady-state power in function of wind speed (Theoretical + Simulink results)	58
3.15	DFIG model test procedure	59
3.17	From subsynchronous to hypersynchronous	60
3.16	<i>MATLAB Simulink</i> 2MW wind turbine test simulation	61
3.18	Quadrature component of the current at the grid-side converter	62
3.19	10 km AC connection	63
3.20	<i>MATLAB Simulink</i> 300MW wind turbine + 10km AC connection test simulation	64
3.21	Active power dispatch controller.	65
4.1	Single line diagram of the complete model	67
4.2	Simulation of the complete model : Wind park active power and voltage	68
4.3	Simulation of the complete model : Active power in hybrid link	69
4.4	Simulation of the complete model : Reactive power	70
A.3	Rotorside Control θ_r Computation	74
A.4	Rotorside Current Control Back Compensation and Coupling Terms Cancellation	74
A.1	Wind Turbine	75
A.2	Rotorside Control	76
A.5	Gridside Control	77
A.6	Gridside Control : Cancellation of Coupling Terms	78
A.8	Wind farm	78
A.7	Complete Model	79
A.9	AC1 link	80
A.10	HVDC link	81
A.11	HVDC link wind farm side control	82
A.12	HVDC link grid side control	83

List of Tables

2.1	Rotation speeds at synchronism for $p = 2$ and gearbox ratio $N = 100$. . .	29
2.2	Modes of operation	32
3.1	DC cable parameters for positive and negative polarity	44
3.2	66kV and 220kV cable parameters	45
3.3	Parameters of the HVDC test setup	47
3.4	Coefficient values for $C_p(\lambda, \beta)$ (Eq. 2.48)	55
3.5	Values for aerodynamical model	56
3.6	Parameters of the Induction Machine - 2 MW Wind Turbine	59

1

Introduction

In response to the environmental impact of conventional electrical power generation, there is a shift towards renewable energy sources. Wind power plants installation have been growing over the last years, generally in the form of wind parks connected directly to the high-voltage grid. Over the last 20 years, the total installed wind energy capacity in the world has increased drastically, from 100 GW in 2005 to over 1,000 GW in 2025 [1]. With the larger penetration in the grid of wind generation technologies which use different generator types than conventional generation units, the power system dynamics are being modified. This has led to increased interest in accurately modelling wind farms to better understand their behaviour and impact on power system dynamics. However, simulating large-scale wind parks with many individual turbines can be computationally intensive. To address this, wind farm aggregation techniques are used to reduce the computational burden while preserving the essential dynamic characteristics of the wind farm.

Wind farms are typically large-scale installations, often reaching capacities in the gigawatt (GW) range. To maximize efficiency, they are commonly located in remote areas where wind conditions are more favourable, such as offshore, where wind speeds are generally higher and more consistent. However, this distance from the main transmission grid presents technical challenges in terms of energy transport. In this context, High-Voltage Direct Current (HVDC) technology offers a promising solution, enabling efficient long-distance transmission with reduced losses and improved control capabilities compared to conventional High-Voltage Alternating Current (HVAC) systems.

Elia Group, as owner of two electricity transmission system operators, one in Belgium (Elia Transmission Belgium) and a second in Germany (50Hz Transmission), has a strategic presence in the North and Baltic Seas. Offshore wind projects are motivated by both environmental goals, with Europe's ambition to achieve net zero emissions by 2050, and the desire to improve energy independence amid ongoing geopolitical tensions. Wind power also shows economic advantage, as it will ultimately reduce the

price of electricity [2].

The role of Elia is also to plan ahead of time. Modifications to the electricity grid take time. The electricity demand in 2050 is projected to be twice today's demand. It is necessary to plan today how the grid should look like in 2050, making sure that the future power generation and grid infrastructure are sufficient.

With a similar goal, Elia together with IRM (Institut Royal Météorologique de Belgique), PropheSea and Geosphere Austria team up to develop a service combining advanced meteorological predictions and a novel Dynamic Line Rating. Nowadays, transmission system operators use Static Line Rating, which fixes constant transmission capability to the transmission lines. Dynamic Line Rating aims at using precise meteorological data to compute the transmission capability of overhead lines, which depends on temperature, wind, solar radiation, etc. This should enable the use of additional capacity ranging from 10 to 25% on the existing transmission lines. More precise meteorological data will also enhance the prediction models for renewable energy production, such as the production of offshore wind farms [3].

1.1 Princess Elisabeth Island Project

In the context of the development of a new 3.5 GW offshore wind farm, the Belgian Transmission System Operator (TSO) Elia plans to build the world's first artificial energy island located 45 km off the Belgian coast in the North Sea, featuring a hybrid transmission system to the mainland, combining HVDC and HVAC technologies. The hybrid link has a rated power of 2.1 GW in AC and 2 GW in DC. The Princess Elisabeth Island will serve two purposes [4] :

- * The island will connect the new 3.5 GW wind farm, that will be built in the Princess Elisabeth Zone, to the Belgian and European grid.
- * The island will also serve as an intermediate landing point for future interconnectors that link to other countries, such as the UK and Denmark.

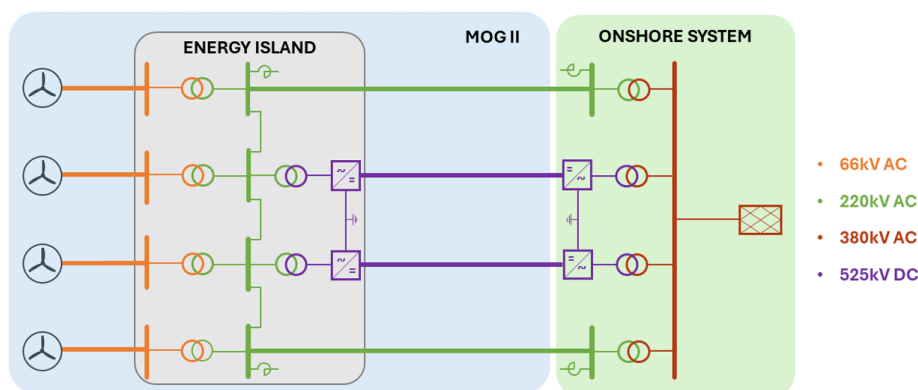


Figure 1.1 Global model of the electrical system of the Princess Elisabeth Island. Taken from [5].

The technical configuration of the studied electrical system, containing the wind farm, the energy island and the hybrid interconnection is shown on Fig. 1.1. This is the initial plan presented in 2023 by Elia [6]. The new 3.5 GW wind power plant consists of 4 wind parks (2 of 1050 MW and 2 of 700 MW) connected by 66kV cables to the energy island. On the island, the voltage is risen to 220 kV (AC). The connection to the mainland is done by 6 AC (220 kV) export cables of rated power 6x350 MW, as well as a bipolar ± 525 kV HVDC connection of rated power 2x1 GW. The AC/DC converters require a certain ratio between AC and DC voltage (Sec. 2.5.2). For this reason, step-up transformers are required before the AC/DC converters. Finally the hybrid link's output is connected on the mainland to the Belgian high-voltage grid at 380 kV.

1.1.1 DC Connection Cost

In 2021, Elia announced an initial budget of 2.2 billion euros. However, the announced price has since then skyrocketed reaching 8 billion euros in 2025. Reasons for this increase are mainly the DC parts. Due to the ongoing war in Ukraine, there is a strong push from Europe to become energetically independent of Russia. This sudden acceleration puts pressure on the supply chain for materials and components. The result is an increase in the price of the components. As a result, on 6 June 2025, the Belgian federal government decided to postpone the construction of the DC connection. They however are aware of the benefits the DC connection would bring. Whether or not the DC connection will be built in the future is for now uncertain [7], [8].

1.2 Research Objective

The main goal of this master's thesis is to develop a model of the global electrical grid of the Princess Elisabeth Island project. This system contains the wind farm, as well as the HVDC and HVAC connection referred to as a hybrid connection. The developed model should be able to test the system in different scenarios in order to analyse its dynamic response. Although the actual realization of the hybrid link for the Princess Elisabeth Island project is still uncertain, it remains relevant to study such a configuration, as it could be used in other future projects.

This thesis is a continuation of the master's thesis conducted in 2024 by Baptiste LAT-ERRE - *Technical Challenges Linked to the Grid Dynamics in the Context of Energy Islands* [5]. In his work, the Princess Elisabeth Island Project and the state of the art concerning HVDC technologies is presented in detail. His main contributions are the discussions concerning the development of an active power dispatch controller for the hybrid link, by analysing active power losses as well as the maximum active power transmissible on an AC cable, and the design of shunt reactors for compensating the reactive power of the AC export cables.

Topics that were already extensively discussed are not repeated in this thesis. Mandatory knowledge is however summarized, ensuring that this thesis is presented in a self-contained manner, making it accessible without reference to the previous thesis. Another master thesis, led by Mathieu DE JONGE, examines the same system, but with a specific focus on harmonics and power quality. To avoid overlapping topics, concepts related to the filtering requirements for this system are excluded from the scope of this thesis.

1.3 Main Contributions

This work consists at first in the detailed comprehension of the Princess Elisabeth Island electrical system, i.e. an offshore wind power plant and a hybrid (HVDC + HVAC) link. Each component is analysed and described based on scientific literature. This thesis enables the reader to understand and to model such a system.

Secondly, the major work resides in the development of a preliminary model in *MATLAB Simulink*. It can serve as a foundation for further studies on this system, such as analysing its robustness, stability, control optimization, and grid integration, contributing to the reliable and efficient deployment of large-scale offshore renewable energy.

The *MATLAB Simulink* model can be found in the following repository: https://github.com/GeoffroyDM/MasterThesis_PrincessElisabethIslandModel.git

1.4 Methodology

The methodology followed to develop the described model is a step-by-step approach. Each component (wind farm, HVDC link, HVAC link) was implemented and tested separately, before everything was brought together. Even in the development of each separate component the same step-by-step approach was implemented. For example, the Doubly-Fed Induction Generator (DFIG) was implemented by first implementing and validating the rotor-side controller with constant mechanical torque and speed reference. Afterwards, the aerodynamic model, the MPPT algorithm and the grid-side controller are added one by one.

This thesis follows the same approach. First, each component is described by the relevant theoretical background. Based on the theory, the model is developed. Each component is implemented and tested separately. Finally, all the components are combined to form the global electrical system of Princess Elisabeth Island.

The model was implemented in *MATLAB Simulink*, more specifically the Simscape library, which is designed to simulate electrical power systems. This software is used as it provides easy to use modelling tools, which are adapted for the preliminary implementation of a model. For the implementation of a more detailed model, the use of more advanced softwares would be required.

This thesis is written in English. AI tools, specifically ChatGPT, have been employed to assist in the academic formulation of our ideas. Additionally, ChatGPT was used to efficiently generate easy-to-read graphs based on the data acquired from simulations. However, it has not been utilized as a source of information for the technical content of this thesis.

The LaTeX template used for this master thesis is greatly inspired by the template created by P.-Y. Gousenbourger in 2019.

1.5 Thesis Structure

Chapter 1 - *Introduction* - introduces the topic of the master's thesis. It presents the studied system and the main goals, as well as the structure of this thesis.

Chapter 2 - *State of the Art* - is focused on presenting the different elements of the studied system. First, the use of a hybrid (HVDC + HVAC) connection is discussed. Space vector theory is briefly presented as it is used extensively throughout this work. The first component to be presented is the VSC based HVDC connection, followed by the DFIG wind turbine. For both components, the control principle is extensively discussed. Finally, some wind farm aggregation techniques are presented.

Chapter 3 - *Dynamic Model of Separate Components* - is dedicated to the implementation of the separate components in *MATLAB Simulink*. The numerical values used in the model are shared. First, the cable modelling is discussed, valid for the different cables present in the system, as well as the use of shunt reactors. Then the implementation of the HVDC model is explained, followed by the wind farm model. Both are simulated and validated separately.

Chapter 4 - *Complete Model : Simulations and Results* - combines the different components presented in Chapter 3 in order to form the complete system to be studied. A basic simulation is conducted to assess the proper functioning of the developed model.

Chapter 5 - *Conclusions and Outlooks* - summarizes the achievements of this work, as well as the results obtained by simulations. It also suggests future perspectives of work in order to improve the delivered products.

State of the Art

2.1 AC vs DC

When developing the electrical power system, alternating current (AC) has been preferred over direct current (DC). Reasons for this choice are that generation units can easily deliver AC by the use of rotating electrical machines. The AC voltage can also easily be adapted using transformers. With the emergence of power electronics, the use of DC becomes possible and also shows some advantages. [5] and [9] already established the main advantages of DC connections. They are summarized below.

- * In AC, the power transmission capacity is reduced as the length of the line increases, due to the skin effect and capacitive effect. Current for reactive power leads to power losses. In HVDC however, the amount of power that can be transferred is constant with distance. There is no reactive power, only Joule losses due to the resistivity of the conducting material.
- * It is not possible to connect directly two AC systems with different fundamental frequencies.
- * Since the electrical power systems works in AC, using an HVDC link requires converters. They cause installation costs as well as conversion losses. There is however a critical distance beyond which the use of HVDC is beneficial over AC. Typical values are 600–800 km for overhead lines and 25–50 km for undersea installations.
- * In HVDC, the converters offer active and reactive power control, which is very useful for energy trading and providing ancillary services.

2.1.1 Energy Trading

One advantage that was not analysed in detail in [5] is the enhancement of energy trading thanks to the ability to control the active power flowing through a HVDC link. This

can be shown in following example where the Direct Current Optimal Power Flow (DCOPF) is applied to a simple case. The concepts used are taken from the course LINMA2415 - *Quantitative Energy Economics* [10].

DCOPF Electricity market agents require tools to quickly compute the dispatch of generation units that minimizes the total cost of production. The most simple tool is the economic dispatch, which only takes into account the production cost and maximum capacity of the generators. The Optimal Power Flow (OPF) is a sophistication of the economic dispatch as it computes the power flowing in each line, in order to take into account the transmission limits. Starting from electrical equations, the mathematical expression of the OPF can be obtained.

Consider a N node system. The power S_{mn} exiting node m towards node n is given by :

$$S_{mn} = V_m \cdot I_{mn}^* = V_m \cdot Y_{mn}^* \cdot (V_m - V_n)^* = (V_m V_m^* - V_m V_n^*) \cdot (G_{mn} - iB_{mn}) \quad (2.1)$$

$$= \left[|V_m|^2 - |V_m||V_n|(\cos \theta_{mn} + i \sin \theta_{mn}) \right] \cdot (G_{mn} - iB_{mn}) \quad (2.2)$$

where θ_{mn} is the phase angle difference of voltages V_m and V_n and $Y_{mn} = Z_{mn}^{-1} = G_{mn} + iB_{mn}$ is the admittance of line (mn) with G the conductance and B the susceptance. The expression of conductance and susceptance based on the resistance R and reactance is as follows :

$$G = \frac{R}{R^2 + X^2} \quad B = \frac{-X}{R^2 + X^2} \quad (2.3)$$

Since lines are inductive ($X = \omega L$), they have therefore a negative susceptance B. Next, the OPF only considers the active power $P_{mn} = \mathcal{R}\{S_{mn}\}$. The reactive power Q is not taken into account.

$$P_{mn} = |V_m|^2 G_{mn} - |V_m||V_n| G_{mn} \cos \theta_{mn} - |V_m||V_n| B_{mn} \sin \theta_{mn} \quad (2.4)$$

Some approximations can be done to obtain the DCOPF, which is a linearization of the OPF.

- * Line resistance R is negligible : $Y_{mn} = iB_{mn} = \frac{-i}{X_{mn}}$
- * Phase angle differences are sufficiently small : $\sin(\theta_{mn}) \approx \theta_{mn}$ and $\cos(\theta_{mn}) \approx 1$
- * Voltage magnitude on each bus is nominal : $|V_m| \approx |V_n| \approx 1$

Finally the power flowing through line mn can be expressed by a very simple equation. Since the line resistance is neglected, there are no power losses on the line. The active power injected at one side of the line is equal to the power received at the other end of the line.

$$P_{mn} = -B_{mn}\theta_{mn} = \frac{\theta_{mn}}{X_{mn}} \quad (2.5)$$

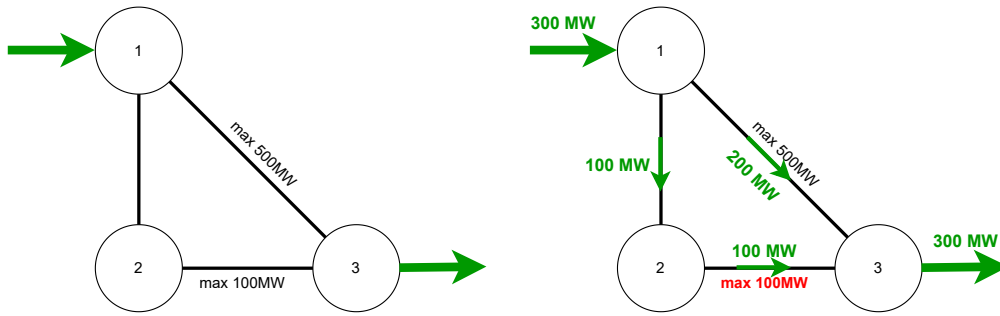


Figure 2.1 Simple three-node model and maximum power transfer $1 \rightarrow 3$ considering transmission limits

Three-node example Now consider a very simple electricity grid which can be represented by a three-node cyclic graph as shown on Fig. 2.1. We want to produce power at node 1 that will be consumed at node 3. We assume that each line has the same reactance X . Line $1 \rightarrow 3$ has a transmission capacity of 500 MW and line $2 \rightarrow 3$ 100 MW. Using Eq. 2.5 and power balance at each node it can be shown that for 1MW produced at node 1 and consumed at node 3, $2/3$ MW will flow through line $1 \rightarrow 3$ while $1/3$ MW will flow through lines $1 \rightarrow 2$ and $2 \rightarrow 3$. Intuitively, the reactance of line $1 \rightarrow 3$ is X while lines $1 \rightarrow 2$ and $2 \rightarrow 3$ in series have a reactance equal to $2X$. Therefore 2 times more power will flow through line $1 \rightarrow 3$.

In our example, the power transfer from node 1 to node 3 is limited to 300 MW because of the 100 MW transmission capacity of line $2 \rightarrow 3$ (see Fig. 2.1). This example shows that the AC electricity grid cannot be used at its maximum capacity. The reason is that the flow of electricity in an AC grid follows physical equations and it cannot be controlled manually.

Now consider that any one of these lines is a HVDC link for which the power flow can be controlled. It is then possible to have 500 MW flowing on line $1 \rightarrow 3$ and 100 MW on lines $1 \rightarrow 2$ and $2 \rightarrow 3$, increasing the transferred power to 600 MW. Through this example it is now clear that the use of a HVDC link can improve energy trading.

2.1.2 Hybrid Link (HVDC + HVAC)

In the case of the Princess Elisabeth Project, it has been chosen to combine HVDC and HVAC. The main reasons are summarized below [5] :

- * Grid-forming issues : Depending on the presence of a strong grid, the AC-DC converters are controlled in two very different ways. When a grid already exists, the converter works in grid-following mode. The controller uses the frequency of the grid to form the AC voltage at the converter terminal. If there is no grid, the converter must work in grid-forming mode. The controller sets the frequency, voltage amplitude and phase angle of the grid. It also assures the stability of the grid. This control strategy is more complex and also limits the active power transmit.

By using an AC connection, the grid of the energy island is already formed by the

continent. This simplifies the control of the converters of the wind turbines and of the HVDC link.

- * Distance : The distance of connection is 45 km, which corresponds roughly to the break-even distance. From a cost point-of-view, both technologies are relevant.
- * Power Quality : The HVDC link can support the HVAC link. In case of a fault on the HVAC link, the HVDC link can adjust the active power to recover stability. It can also control the reactive power at both ends, which can be used for AC voltage stability.

2.2 Space Vector and Per Unit Theory

2.2.1 Space Vector

Any three-phase voltage or current can be represented by a single space vector. Two conventions exist to express the Cartesian components (α, β) of the space vector : the Concordia and Clarke transform [11]. The general expression of a space vector also contains a homopolar component. However, this component will be considered equal to zero and will not be used throughout this thesis.

Concordia Transform

$$\begin{aligned} x_\alpha &= \sqrt{\frac{2}{3}} \cdot (1x_a - \frac{1}{2}x_b - \frac{1}{2}x_c) \\ x_\beta &= \sqrt{\frac{2}{3}} \cdot (0x_a + \sqrt{\frac{3}{2}}x_b - \sqrt{\frac{3}{2}}x_c) \end{aligned} \quad (2.6)$$

For a balanced three-phase system, the relation $x_\alpha = \sqrt{3/2}x_a$ is obtained. The amplitude of currents and voltages is scaled by a factor $\sqrt{3/2}$. The scaling is introduced to make this transformation power invariant :

$$p = \mathcal{R}\{3V_{ph}I_{ph}^*\} = v_a i_a + v_b i_b + v_c i_c = v_\alpha i_\alpha + v_\beta i_\beta \quad (2.7)$$

$$q = \mathcal{I}\{3V_{ph}I_{ph}^*\} = \frac{1}{\sqrt{3}} ((v_b - v_c)i_a + (v_c - v_a)i_b + (v_a - v_b)i_c) = v_\beta i_\alpha - v_\alpha i_\beta \quad (2.8)$$

Clarke Transform

$$\begin{aligned} x_\alpha &= \frac{2}{3} \cdot (1x_a - \frac{1}{2}x_b - \frac{1}{2}x_c) \\ x_\beta &= \frac{2}{3} \cdot (0x_a + \sqrt{\frac{3}{2}}x_b - \sqrt{\frac{3}{2}}x_c) \end{aligned} \quad (2.9)$$

For a balanced three-phase system, the relation $x_\alpha = x_a$ is obtained. The amplitude of currents and voltages is conserved. However, the amplitude of power must be scaled

by a factor $3/2$:

$$p = v_a i_a + v_b i_b + v_c i_c = \frac{3}{2}(v_\alpha i_\alpha + v_\beta i_\beta) \quad (2.10)$$

$$q = \frac{3}{2}(v_\beta i_\alpha - v_\alpha i_\beta) \quad (2.11)$$

Intuitively, the Concordia and Clarke transformations generate a two-winding representation of a three-phase (three-winding) system. Finally, it is generally useful to change the coordinate system in which the space vector is represented. This is done by the Park transformation.

Park Transform

$$\begin{aligned} x_d &= \cos(\theta)x_\alpha + \sin(\theta)x_\beta \\ x_q &= -\sin(\theta)x_\alpha + \cos(\theta)x_\beta \end{aligned} \quad (2.12)$$

These transformations are used for space vector control. For example, when controlling an electrical machine, the voltage and currents are represented in a rotating frame following the magnetic flux. Instead of working on sinusoidal signals, the controllers work on dq-components that are constant. This improves the quality of the control.

2.2.2 Per-Unit

When working with electrical systems it is common to work in per-unit values i.e. to replace physical quantities by its normalization to a reference. The reference is generally chosen as the rated value of the system. Starting from a base power S_B , phase voltage V_B (in rms value) and frequency ω_B , the other base values are computed. This however modifies the computation of power :

$$I_B = \frac{S_B}{3V_B} \rightarrow S_{pu} = V_{pu} I_{pu} \quad (2.13)$$

In *MATLAB Simulink*, the *Three-Phase VI Measurement Block* uses a different convention for p.u. computation. The base values for voltage and current are the nominal peak value, instead of the rms value.

$$V_B = \sqrt{2}V_{nom,rms} \quad I_B = \sqrt{2}\frac{S_B}{3V_{nom,rms}} \rightarrow S_{pu} = 2V_{pu}I_{pu} \quad (2.14)$$

Computing power using per-unit, based on peak value of nominal phase-to-ground voltage and current, combined to space vector expression, is done as follows :

Concordia Transform in Per Unit

$$p_{pu} = 2\mathcal{R}\{V_{pu}I_{pu}^*\} = \frac{2}{3}(v_a i_a + v_b i_b + v_c i_c) = \frac{2}{3}(v_\alpha i_\alpha + v_\beta i_\beta) \quad (2.15)$$

$$q_{pu} = 2\mathcal{I}\{V_{pu}I_{pu}^*\} = \frac{2}{3}(v_{\beta}i_{\alpha} - v_{\alpha}i_{\beta}) \quad (2.16)$$

Clarke Transform in Per Unit

$$p_{pu} = \frac{2}{3}(v_a i_a + v_b i_b + v_c i_c) = (v_{\alpha} i_{\alpha} + v_{\beta} i_{\beta}) \quad (2.17)$$

$$q_{pu} = (v_{\beta} i_{\alpha} - v_{\alpha} i_{\beta}) \quad (2.18)$$

The use of the Clarke transformation with such a p.u. convention shows to be very straightforward, as it does not modify the amplitude of voltage and current, and it is power invariant.

2.3 Synchronization Techniques

In Sec. 2.2, space vector transformations (Clarke, Concordia, Park) were introduced, which rely on a reference angle to project three-phase signals into stationary or rotating reference frames. This angle is determined by using a synchronization technique which is a device that computes the phase angle and/or frequency of an input voltage or current signal. Such a device is required for the control of the power electronics which is commonly performed in a dq rotating reference frame which synchronizes with the grid voltage. Many algorithms exist to generate a synchronized output signal. They can be regrouped under two main categories : open-loop synchronization techniques and closed-loop techniques [12].

In practice, most of the devices use closed-loop techniques, i.e. Phase-Locked Loop (PLL). They are known for their simplicity, robustness, and effectiveness . A simple representation of a PLL is shown on Fig. 2.2.

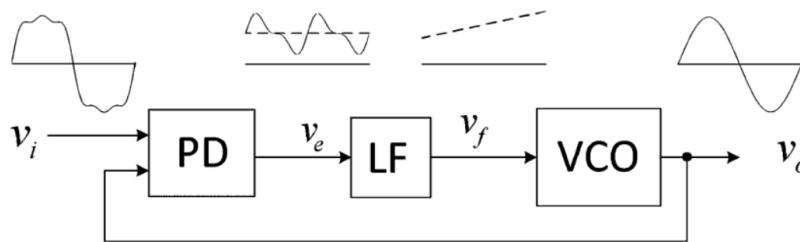


Figure 2.2 Simple PLL scheme. Taken from [13]

A PLL is composed of three building blocks. A phase detector (PD), a loop filter (LF) and a voltage-controlled oscillator (VCO). A VCO generates a periodic signal v_o with a frequency that is proportional to an applied input voltage v_f . The main difference between PLL's remain in the phase detector, which is the component that computes the angle of the input signal.

A very simple phase detector technique consists in computing the $\alpha\beta$ components of the voltage and using the atan2 function [12]. Using the Clarke Transform, the $\alpha\beta$ components of the space vector are computed. The angle is then computed as in Eq. 2.19.

$$\theta = \arctan\left(\frac{x_\beta}{x_\alpha}\right) \quad (2.19)$$

2.4 Grid Strength

The strength of the grid at a certain location is related to the changes of voltage a generator (or load) encounters on its terminals as the generator's current injection (load's current absorption) varies. It can be assessed by computing the three-phase short-circuit power S_{sc} or fault level at the studied location. It is defined as follows [14], [15] :

$$S_{sc} = \sqrt{3}U_n I_{sc} \quad (2.20)$$

with U_n the nominal line-to-line voltage and I_{sc} the three-phase short circuit current. It is equivalent to computing the Thévenin impedance (mainly inductive) of the grid as seen from the studied location. A higher short-circuit power corresponds to a smaller Thévenin impedance and a stronger grid.

Elia does not provide publicly available data concerning the short-circuit power, but it typically ranges around tens of GVAs for the high-voltage (380 kV) grid.

The impact of a generator or load on the grid can be assessed by the short-circuit ratio (SCR) defined as follows :

$$\text{SCR} = \frac{S_{sc}}{S_N} \quad (2.21)$$

with S_N the nominal power of the installation. A higher SCR means that the installation has a smaller impact on the grid. An installation with SCR below 3 has a noticeable impact on the voltage at the point of connection. Accordingly, the grid is said to be weak.

Due to its high power rating (4.1 GW), the hybrid link will have a big impact on the grid at its point of interconnection at the Belgian coast. This emphasizes the importance of studying this hybrid link.

Grid strength is required to assure voltage stability. It is also necessary for Phase-Locked Loops (PLL) to correctly synchronize with grid. This is mandatory for the control of VSCs working in a grid-following mode. These topics are developed in later sections.

2.5 HVDC Technologies

This section first outlines the overall structure of a HVDC link, follows by a detailed analysis of its individual components, and concludes with a discussion of its control system.

2.5.1 HVDC Topologies

As described in [5], there are different possible topologies for HVDC systems : monopolar, bipolar and homopolar (Fig. 2.3).

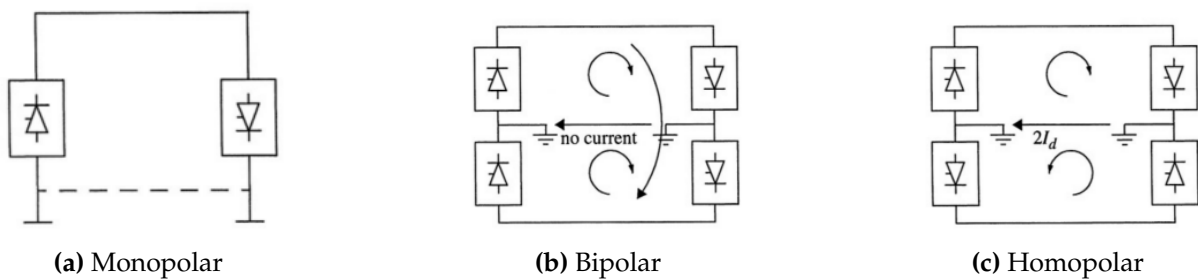


Figure 2.3 HVDC topologies. Taken from [5]

Monopolar topologies are composed of one active conductor and a return path via ground or a metallic return. Bipolar topologies use two converters per terminal and have two active conductors (one positive and one negative). This topology offers higher power transfer. Homopolar topologies use two converters arranged in a way such that both active conductors have the same polarity. This requires a ground return carrying twice the rated current, which considerably impacts the environment. In the case of the Princess Elisabeth Island, the bipolar topology has been chosen, even though it is more expensive than monopolar since it requires more converters and higher voltage ratings. The reasons for this choice are listed below :

- * Increased transmission capacity, as the voltage difference between the two poles allows higher power transfer.
- * Redundancy and robustness: if one pole or cable fails, the system can continue operating in monopolar mode, ensuring higher availability (meeting the N-1 criterion).
- * Reduced environmental impact: during normal operation, the same current flows through both poles in opposite directions, so no current flows through the ground.

Bipolar HVDC links can be made of either two two-level converters at each side or one three-level converter at each side.

2.5.2 Voltage Source Converter

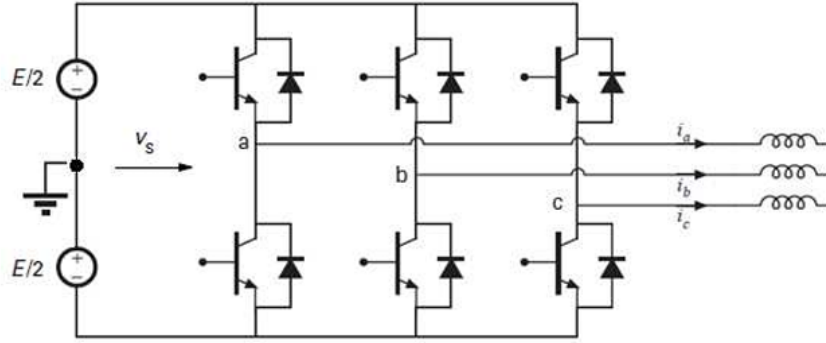


Figure 2.4 Three-phase two level Voltage Source Converter. Taken from [16]

The basic topology of a three-phase two-level six-pulse voltage source converter (VSC) is represented on Fig. 2.4. The main components are the switches, usually IGBT (Insulated-Gate Bipolar Transistor) or GTOs (Gate Turn-off Thyristor). These elements can be switched on and off at any time. They are controlled by the gate signal. Diodes are put in parallel to the IGBT's. This anti-parallel diode creates a path for the inductive current in order to discharge the IGBT, since the latter does not accept bi-directional flow. In practice, each valve group is composed of multiple IGBT-diode pairs put in series. The DC voltage is applied directly on the valve group. The minimum required number of IGBT's in series depends on the voltage ratings of a single IGBT. Each AC phase is connected through two valve groups to the positive and negative poles of the DC voltage. When one switch is closed, the other one is open. Consequently, the AC phase voltage can have two values: $+V_{DC}/2$ and $-V_{DC}/2$. This is the reason for the converter to be referred as two-level [17], [18].

It is now straightforward to find the maximum obtainable AC voltage :

$$v_{ph,peak}^{max} = V_{DC}/2 \quad u_{l,peak}^{max} = \sqrt{3}V_{DC}/2 \quad u_{l,rms}^{max} = \frac{\sqrt{3}}{\sqrt{2}}V_{DC}/2 \quad (2.22)$$

The reference AC voltage will be chosen lower than the maximum obtainable voltage. This in order to be able to generate an ac voltage higher (and lower) than the reference, which could be required to control the active and reactive power at the VSC. This factor is referred to as the modulation index m . One finally obtains :

$$u_{l,rms}^{ref} = \frac{\sqrt{3}}{\sqrt{2}} \frac{m}{2} V_{DC} \quad (2.23)$$

The switching can be done at very high frequency, so the gate signal is usually produced by pulse-width modulation (PWM) (see Fig. 2.5). The desired output voltage is achieved by comparing the desired reference waveform (modulating signal) with a high-frequency triangular 'carrier' wave. The output voltage on each phase has then a

rectangular shape, oscillating between $+V_{DC}/2$ and $-V_{DC}/2$. The line voltage is simply the subtraction of two phase voltages e.g. a-b [18].

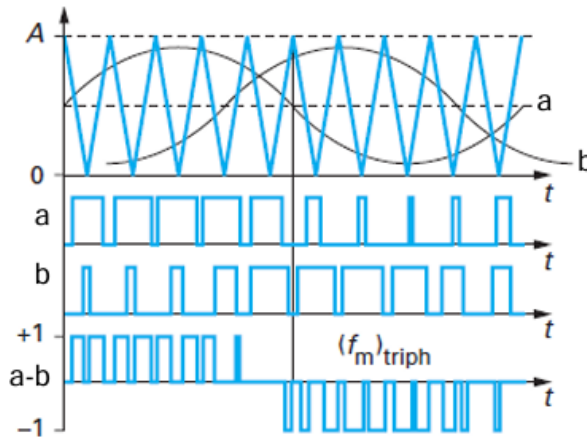


Figure 2.5 Pulse-Width Modulation. Reproduced from [16]

The switching of the valve groups happens at high frequency, set by the PWM carrier wave which has usually a frequency of some kHz. Simulating the effect of this switching in the VSC requires the use of a small step size of the solver, much smaller than the step size required for simulating electrical grids without power electronics. This complexifies the solving of the model. To simplify the solving, Average-Value Models (AVM) are being developed in order to neglect the switching and use the average value over a switching frequency instead. This concept is however not considered in this thesis.

2.5.3 Global Overview of VSC-HVDC Link

This section presents the different components of a VSC based bipolar HVDC link. The single line diagram of such a system is shown in Fig. 2.6.

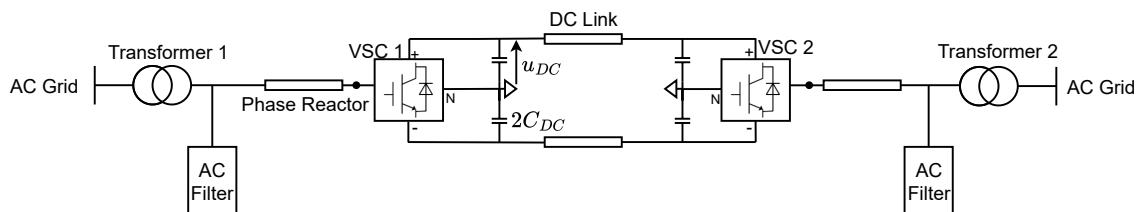


Figure 2.6 Single line diagram of a VSC-HVDC link.

Voltage Source Converter The VSCs implement the AC/DC conversion. Depending on the power flow, one VSC operates as a rectifier and the other one as an inverter.

Transformer The transformers are used to convert the AC voltage to a suitable value for the VSC [18]. They set the modulation index. They also serve as a reactance to filter the AC voltage.

Phase Reactor On the AC side, a VSC acts as a current source and therefore requires an inductor as an energy linking unit between the AC grid and the VSC [18]. It is also used to filter high frequency harmonics.

DC Capacitor On the DC side, a VSC acts as a voltage source thus requiring a capacitor as energy storage device [19]. The capacitors also help minimize voltage ripple caused by PWM switching. Since PWM introduces harmonic currents into the DC side, voltage ripple occurs, with its magnitude influenced by the capacitor size and switching frequency. As a result, the capacitor size is determined by the required energy storage at rated voltage and the allowable voltage ripple [17], [18].

AC Filter The purpose of these filters is to suppress high frequency harmonics on the AC side of the VSC. In Fig. 2.6 they are represented as a shunt element but the series inductance of the transformer and the phase reactor also take part in filtering.

2.5.4 AC Filter

AC/DC converters produce harmonics due to their high frequency switching and the rectangular-shaped output signals. They therefore require filters. This section details the design of LCL filters according to [20]. The filter is illustrated in Fig. 2.7.

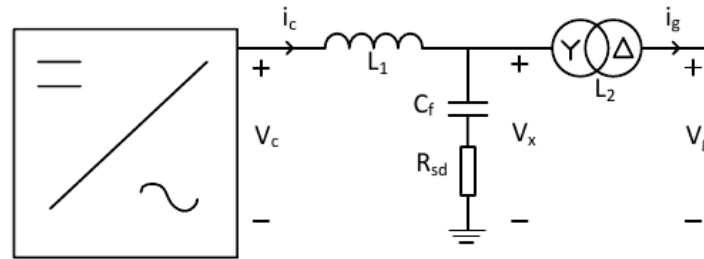


Figure 2.7 LCL filter. Taken from [20].

The inductance value of L_1 is selected such that it limits the current ripple to 10% of the rated current. It is computed as follows :

$$L_1 = \frac{u_{DC}}{16\Delta i_{imax,p-p}f_{sw}} \quad \Delta i_{imax,p-p} = 0.1\sqrt{2}I_{base} \quad (2.24)$$

where f_{sw} is the PWM switching frequency, $\Delta i_{imax,p-p}$ is the maximum peak-to-peak current ripple and u_{DC} is the DC side voltage. The capacitor is sized such that it pro-

vides 5% of the converter rated reactive power :

$$C_f = 0.05C_{base} \quad (2.25)$$

The converter harmonic current and the harmonic current injected into the grid are related by Eq. 2.26. It is used to determine the value of L_2 .

$$\frac{i_g(h)}{i_c(h_{sw})} = k_a = \frac{1}{|1 + x [1 - L_1 C_f \omega_{sw}^2]|} \quad x = \frac{L_2}{L_1} \quad (2.26)$$

The attenuation factor k_a is set to 20%. Note that the inductance of the transformer is considered as part of L_2 . A damping resistor is used to suppress oscillations around the resonance frequency. Its value is computed as :

$$R_{sd} = \frac{1}{3\omega_{res} C_f} \quad (2.27)$$

with the resonance frequency $f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C_f}}$.

2.5.5 Electrical Equations

The notations used in this section are the ones on the single line diagram of the HVDC link shown in Fig. 2.6 (Sec. 2.5.3).

The voltage over the phase reactor and transformer can be expressed using standard Kirchoff's voltage law :

$$v = L_v \frac{d}{dt} i_v + u + R_v i_v \quad (2.28)$$

where v is the grid voltage, R_v and L_v are the phase resistor and inductance respectively, i_v is the current flowing through the phase reactor and u is the voltage at the point of common coupling (PCC).

With the Clarke-Park transform, Eq. 2.28 can be written in the dq reference frame.

$$v_d = L_v \frac{d}{dt} i_d - \omega L_v i_q + u_d + R_v i_d \quad (2.29)$$

$$v_q = L_v \frac{d}{dt} i_q + \omega L_v i_d + u_q + R_v i_q \quad (2.30)$$

where ω is the frequency of the rotating reference frame in rad/s. The exchanged active and reactive powers, using the Clarke-Park transform with *MATLAB Simulink* p.u. conventions, are :

$$P = v_d i_d + v_q i_q \quad (2.31)$$

$$Q = v_q i_d - v_d i_q \quad (2.32)$$

2.5.6 Control of HVDC Link

Control Principle

The HVDC link's VSCs can be controlled via power-angle control or vector control. Power-angle control is based on the following equations :

$$P = \frac{uv \sin \theta}{X_v}$$

$$Q = \frac{v^2 - vu \cos \theta}{X_v}$$

where θ is the phase-angle difference between both sides of the phase reactor. The active power is mainly associated to the phase-angle while the reactive power is associated to the voltage magnitude difference [19]. This type of control is not used as it doesn't allow to limit the current in the VSC.

Vector control, on the other hand, is based on the control of active and reactive AC currents independently of each other. It involves the representation of three-phase quantities in the synchronously rotating reference frame. This means that in steady state, the dq-components of AC currents and voltages are seen as constant. This allows the use of PI controllers to eliminate static errors [21]. The vector control principle is shown in Fig. 2.8.

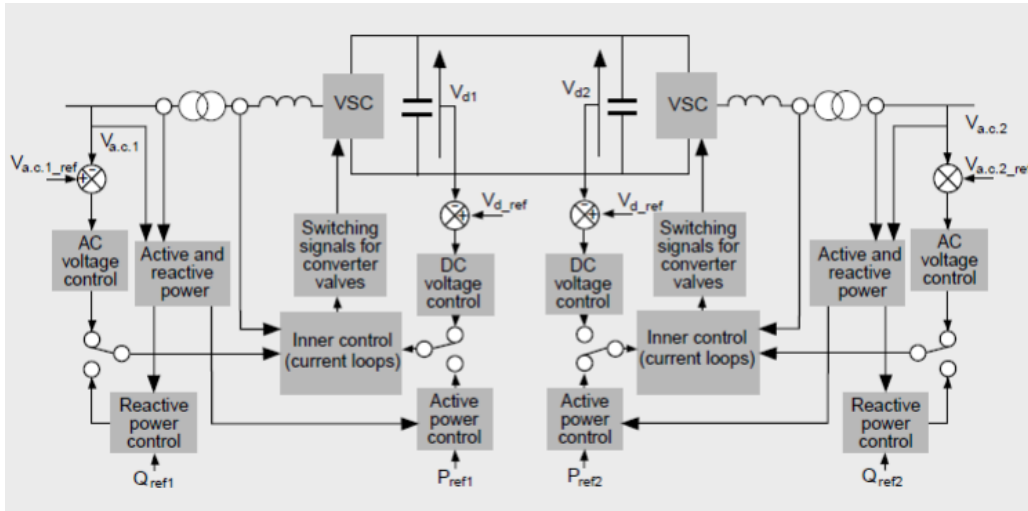


Figure 2.8 HVDC control principle. Taken from [22]

Vector control is done in two steps, a fast inner loop and a slower outer loop. The outer loop sets the current references in the dq reference frame. The current references can be set via active power control, reactive power control, DC voltage control, AC voltage control or frequency control. These different possibilities are shown in Fig. 2.8. The inner loop, given the current references computed by the outer loop, sets the voltage reference which is then applied to the VSCs by a PWM. A top-level controller provides the reference power, voltage and frequency to the outer controller.

Active and reactive power can be controlled independently by working in the synchronously rotating dq reference frame ($v_q = 0$ in Eq. 2.31 and 2.32). The instantaneous phase angle of the voltage used in the Clarke-Park transform is determined by a phase-locked loop (PLL).

The notations used in the following developments are referenced in Fig. 2.9.

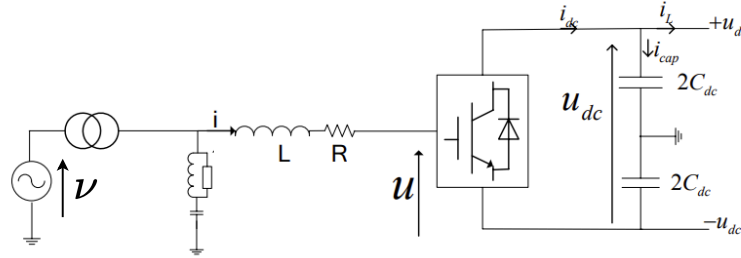


Figure 2.9 Single line diagram of a VSC. Taken from [21].

Inner Controller

The inner loop controls the AC currents. It is implemented using the system's dynamic model equations (Eq. 2.29 and 2.30). Fig. 2.10 shows the general block diagram of the inner controller.

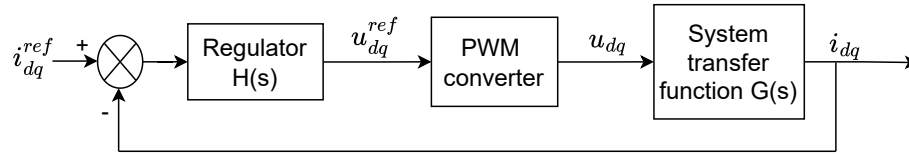


Figure 2.10 General block diagram of inner loop

According to [21], $u_{dq} = u_{dq}^{ref}$ because the PWM can be regarded as fast and accurate, it only adds switching harmonics which are filtered out. The system equations are rewritten as

$$\begin{aligned} v_d - u_d &= L_v \frac{d}{dt} i_d - \omega L_v i_q + R_v i_d \\ v_q - u_q &= L_v \frac{d}{dt} i_q + \omega L_v i_d + R_v i_q \end{aligned} \quad (2.33)$$

It can be seen in Eq. 2.33 that d and q axis are coupled through $\omega L_v i_q$ and $\omega L_v i_d$ terms. Decoupling will be done with compensation terms. After applying the Laplace transform to Eq. 2.33, Fig. 2.10 leads to :

$$u_{dq}^{ref}(s) = (i_{dq}^{ref}(s) - i_{dq}(s))H(s) \quad (2.34)$$

Adding the compensation terms, the equations become

$$\begin{aligned} u_d^{ref}(s) &= (i_d^{ref}(s) - i_d(s))H(s) + \omega L_v i_q(s) + v_d(s) \\ u_q^{ref}(s) &= (i_q^{ref}(s) - i_q(s))H(s) - \omega L_v i_d(s) + v_q(s) \end{aligned} \quad (2.35)$$

Due to the compensation terms, the system's transfer function seen by the regulator is simply that of an R-L circuit

$$G(s) = \frac{1}{R_v} \frac{1}{1 + \tau s} \quad (2.36)$$

with $\tau = \frac{L_v}{R_v}$. The regulator is a simple Proportional-Integral (PI) controller with transfer function

$$H(s) = K_p + \frac{K_i}{s} \quad (2.37)$$

with K_p the proportional gain and K_i the integral gain. The detailed control diagram is shown in Fig. 2.11.

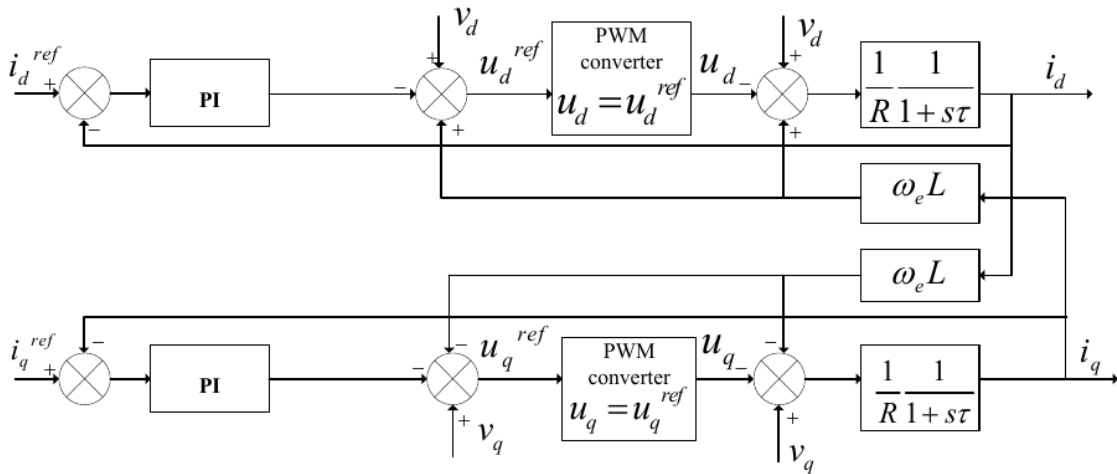


Figure 2.11 Detailed block diagram of inner loop. Taken from [21]

Outer Controller: DC voltage

As stated earlier, the outer controller includes the DC voltage control, the AC voltage control, active and reactive power control and frequency control. The following sections provide descriptions of these different controllers.

In order to ensure stable operation, the outer loop must be much slower than the inner loop. Thus, for the outer controller, the AC currents may be assumed to be equal to their references [23] (seen from the outer loop, the response of the inner loop is instantaneous).

A DC voltage controller is needed to maintain the active power exchange between con-

verters [21]. By working in the synchronously rotating reference frame, d and q axes can be controlled independently. Since $v_q = 0$, the active and reactive power equations (2.31,2.32) become

$$\begin{aligned} P &= v_d i_d^{ref} \\ Q &= -v_d i_q^{ref} \end{aligned} \quad (2.38)$$

The DC power is expressed as

$$P_{DC} = u_{DC} i_{DC}. \quad (2.39)$$

The power balance of the VSC terminal gives [19]

$$\begin{aligned} P_{ac} + P_{dc} + P_{cap} &= 0 \\ v_d i_d^{ref} + u_{dc} i_{dc} + u_{dc} i_{cap} &= 0 \end{aligned} \quad (2.40)$$

The current in the capacitor i_{cap} is expressed as

$$i_{cap} = C \frac{du_{dc}}{dt} \quad (2.41)$$

Combining Eq. 2.40 and 2.41 leads to

$$\frac{du_{dc}}{dt} = -\frac{v_d}{Cu_{dc}} i_d - i_{dc} \quad (2.42)$$

This shows that the DC voltage can be controlled by the direct current i_d . Fig. 2.12 shows the block diagram of the controller.

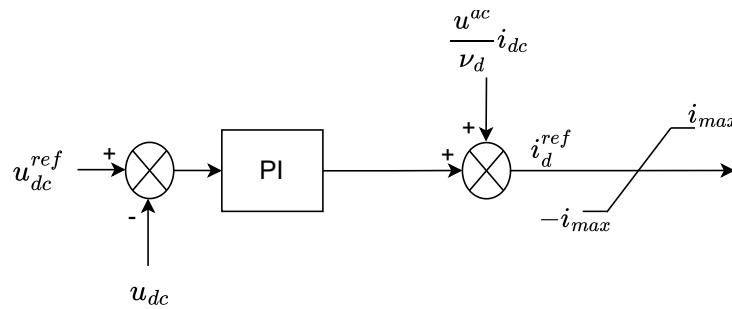


Figure 2.12 Detailed block diagram of the DC voltage controller

Outer Controller: Active and Reactive Power

Eq. 2.38 shows that the current reference can be obtained as :

$$\begin{aligned} i_d^{ref} &= \frac{P^{ref}}{v_d} \\ i_q^{ref} &= -\frac{Q^{ref}}{v_d} \end{aligned} \quad (2.43)$$

For more accurate control, a feedback loop is added using PI controllers [24]. The controllers are shown in Fig. 2.13 and 2.14.

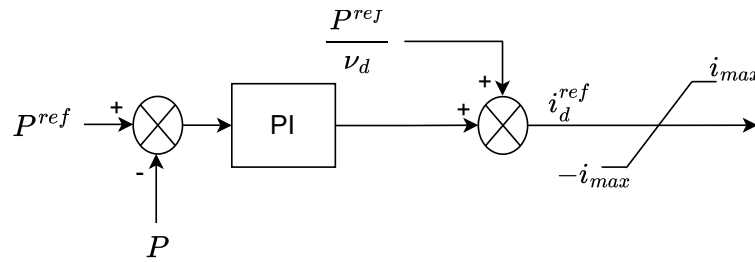


Figure 2.13 Active power controller block diagram

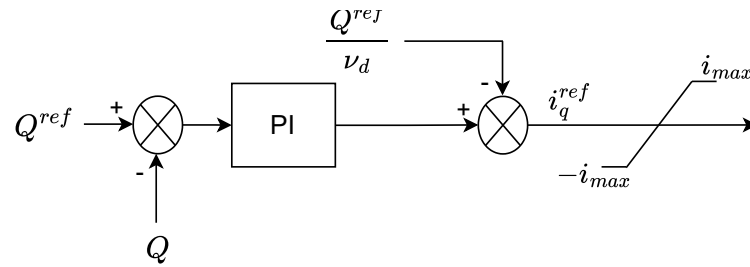


Figure 2.14 Reactive power controller block diagram

Outer Controller: AC Voltage

The voltage drop over the phase reactor $R_v + j\omega L_v$ can be approximated as [23]

$$\Delta v = v - u \approx \frac{R_v P + \omega L_v Q}{v} \quad (2.44)$$

Since $\omega L_v \gg R_v$, the voltage drop depends only on the reactive power Q . This means that the AC voltage can be controlled by the reactive component of the AC current flowing through the phase reactor. The controller is shown in Fig. 2.15.

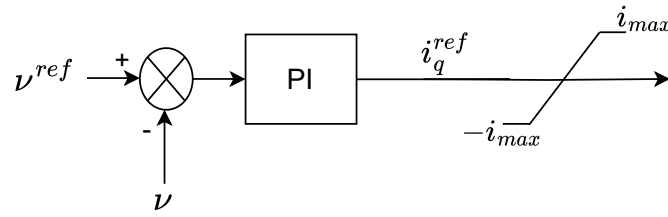


Figure 2.15 AC voltage controller block diagram

Limiting Strategies

Unlike synchronous generators, VSCs lack overload capability and thus cannot handle over-currents [21]. Over-currents occurring due to disturbances might thus damage the converter valves. Therefore, the VSC-HVDC must always operate within its rated limits.

The AC current magnitude $\sqrt{(i_d^{ref})^2 + (i_q^{ref})^2}$ is compared to the maximum current I_{max} . If the current exceeds this limit, both i_d^{ref} and i_q^{ref} must be limited to $i_{d,lim}$ and $i_{q,lim}$ respectively. There are three common strategies.

The first one is to prioritize the active component. This can be used when the converter is connected to a strong grid and the goal is to maximize active power transfer. The second is to prioritize the reactive component. This method is suitable when connected to weaker grids or when supplying sensitive loads, as it enables higher reactive power transfer to support AC voltage.

A third approach can be to apply the same limit to both active and reactive components.

These strategies are shown in Fig. 2.16.

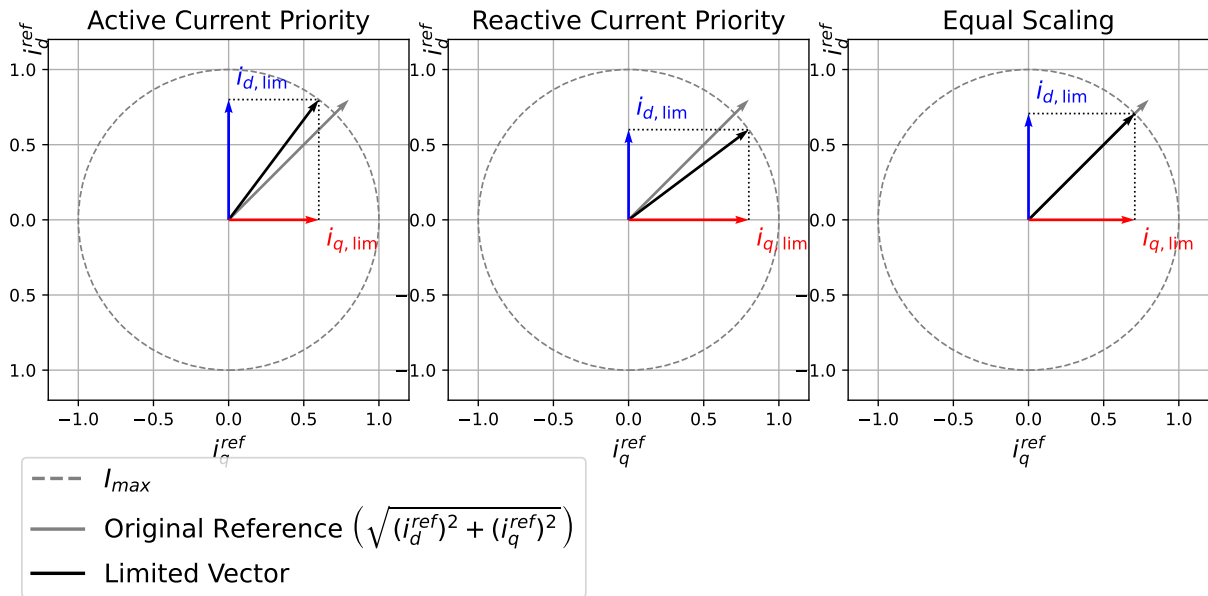


Figure 2.16 Current limiting strategies.

Controller Integral Windup

As mentioned in Sec. 2.5.6, controller outputs need to be limited due to the physical limitations of the converters. During this saturation, the integral term of the PI controller continues to accumulate error (integral windup) which can lead to overshooting in the controlled variable [21]. Integral windup can be prevented by either limiting the integral term to an appropriate value or temporarily disabling it during saturation.

2.6 Wind Turbine Technologies

Wind turbines are used to generate electrical power from wind. This operation is divided into two processes. The conversion of the kinetic energy of the wind into mechanical energy and then the conversion of the mechanical energy into electrical energy through a generator [25].

2.6.1 Types of Wind Turbines

Wind turbines can be classified by their mechanical control and further divided by their speed control. The two types of mechanical power control are stall control and pitch control.

Stall regulation is a cost effective and robust way of preventing damage in case of high

wind speeds. It is done by shaping the airfoils such that they produce less aerodynamic lift at high wind speeds thus stalling them and reducing the mechanical torque. Pitch control uses actuators in the hub to rotate the blades around their longitudinal axis to maximize energy capture or decrease it to protect the turbine.

Beyond mechanical regulation, wind turbines are further divided into 4 types: fixed speed, limited variable speed, variable speed with either partial or full power electronic conversion.

Type 1: Fixed-Speed Wind Turbines These wind turbines are implemented with squirrel-cage induction generators and are directly connected to the step-up transformer. Fig. 2.17 shows a type 1 generator.

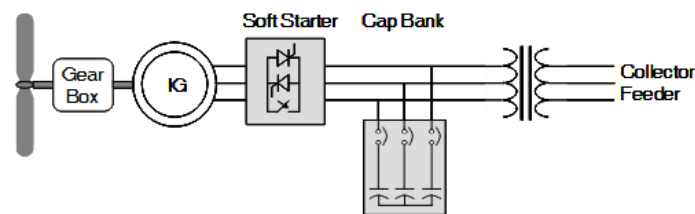


Figure 2.17 Typical configuration of a Type 1 wind turbine generator. Taken from [25]

These turbines typically operate at close to rated speed with some variability due to the slip of the induction generator. Therefore, wind speed fluctuations will result in power variations and thus affect the quality of the grid. Another drawback is that they consume reactive power for their excitation field and consume large currents at start-up. Mitigation techniques include a soft starter and capacitor banks.

Type 2: Variable-Speed Wind Turbines As shown in Fig. 2.18, type 2 wind turbines are similar to type 1. The only difference lies in the rotor circuit where variable resistors have been mounted. These resistors provide dynamic control of rotor currents which allows to keep near-constant output power during fluctuating wind conditions. By increasing the rotor resistance, the torque-speed characteristic of the generator is effectively modified. This allows rotor speed variations of 10% around synchronous speed.

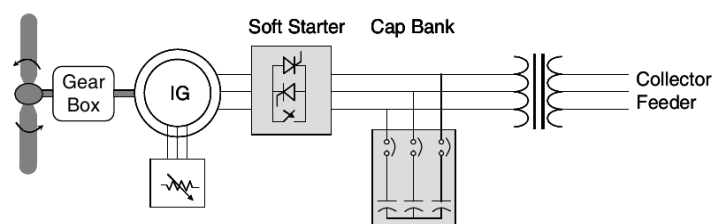


Figure 2.18 Typical Configuration of a Type 2 wind turbine generator. Taken from [25]

Type 3: Variable-Speed Wind Turbines with Doubly-Fed Induction Generator DFIG wind turbines are an evolution of type 2 turbines. Instead of being controlled by variable resistors, the rotor is energized by variable-frequency AC supplied through a rotor-side converter. This converter is connected back-to-back with a grid side converter which exchanges power with the grid. This system enables good control of the rotor current, allowing independent real and reactive power control. As power flows not only through the converters but also straight from the stator of the machine, the converters are only rated to 30% of the generator rating. Therefore, the power electronics losses are lower than in systems where the converters have to handle the entire power. The four-quadrant nature of the converters allows the DFIG to operate efficiently over a wide range of speeds (up to $\pm 50\%$ above synchronous speed) [26].

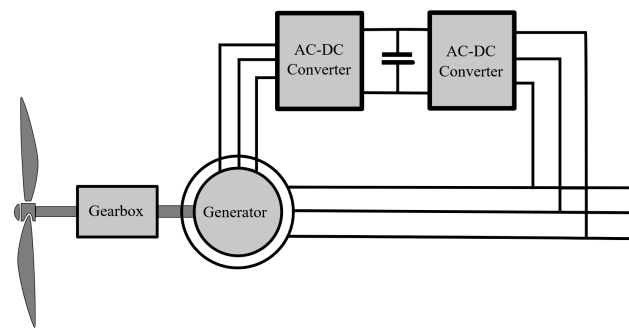


Figure 2.19 Typical Configuration of a Type 3 wind turbine generator. Taken from [27]

Type 4: Variable Speed Wind Turbines with Full Scale Back-to-back Converter Type 4 wind turbines are fully decoupled from grid thanks to a full-scale back-to-back converter. This allows the turbine to rotate at its optimal aerodynamic speed generating an electrical frequency well below that of the grid which is then converted to grid frequency by the back-to-back converters. In this way, the gearbox could even be removed altogether, simplifying the design. The converters being able to control active and reactive power independently, different type of generators can be used such as permanent magnet synchronous generators or squirrel cage induction generators. The downside of these wind turbines is that the power electronics have to handle the entire generated power [25].

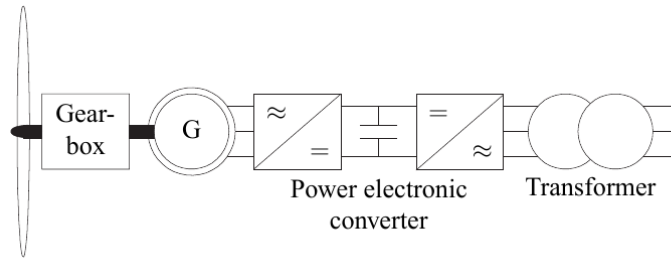


Figure 2.20 Typical Configuration of a Type 4 wind turbine generator. Taken from [26]

2.6.2 Mechanical Aspect

For wind turbine generators, the source of energy is the power of the wind, which can be written as :

$$P_{wind} = \frac{1}{2} \rho \pi R^2 v_w^3 \quad (2.45)$$

where ρ is the air density, $A = \pi R^2$ is the area swept by the blades, R is the blade radius and v_w is the axial wind speed [28]. The first step in the production of electricity is to convert the power of the wind into mechanical power that rotates the shaft. This is achieved by the blades of the turbine. However, only a part of the power of the wind can be converted into mechanical power :

$$P_m = T_m \omega_m = \frac{1}{2} C_p(\lambda, \beta) \cdot \rho \pi R^2 v_w^3 \quad (2.46)$$

The fraction of mechanical power produced P_m over the power of the wind P_{wind} is defined by the performance coefficient C_p . A maximum obtainable value for C_p is given by the Betz limit, which is around 0.6. The performance coefficient depends mainly on the tip-speed ratio λ and the pitch angle β . The tip-speed ratio (TSR) is a dimensionless value equal to the ratio of the tangential speed at the tip of the blades over the axial speed of the wind (Eq. 2.47). The pitch angle is the angle of the blades along their longitudinal axis.

$$\lambda = \frac{\Omega_m \cdot R}{v_{wind}} \quad (2.47)$$

The relation $C_p(\lambda, \beta)$ is obtained empirically. However, some common analytical expressions exist such as Eq. 2.48, where only the coefficient values are adjusted to match machine-specific performance [29], [30].

$$C_p(\lambda, \beta) = k_1 \left(\frac{k_2}{\lambda_i} - k_3 \beta - k_4 \beta^{k_5} - k_6 \right) e^{k_7 / \lambda_i} \quad \text{with} \quad \frac{1}{\lambda_i} = \frac{1}{\lambda + k_8 \beta} - \frac{k_9}{\beta^3 + 1} \quad (2.48)$$

An expression for the torque exerted on the rotor shaft is now desired. It should be kept in mind that, for a given power P_m , the corresponding torque is determined by

the rotational speed considered.

$$P_m = T_M \Omega_m = T_m \omega_m = \frac{T_m}{p} \omega_{em} \quad (2.49)$$

The notations used are Ω_m the rotation speed of the blades, ω_m the rotation speed of the rotor shaft and ω_{em} the electromechanical rotation speed. Ω_m and ω_m are linked by the gearbox ratio N and ω_m and ω_{em} are linked by the number of poles of the machine. A typical value for the different speeds is shown in Tab. 2.1.

$$\omega_{em} = p\omega_m = pN\Omega_m \quad \Rightarrow \quad T_M = NT_m \quad (2.50)$$

Ω_m [rad/s]	ω_m [rad/s]	ω_{em} [rad/s]
1.57	157.08	314.16

Table 2.1 Rotation speeds at synchronism for $p = 2$ and gearbox ratio $N = 100$

From the previous equations it is possible to obtain an expression for T_m :

$$T_m = \frac{1}{2} C_p \cdot \rho \pi R^2 v_w^3 / \omega_m \quad (2.51)$$

2.6.3 Maximum Power Point Tracking (MPPT)

For variable speed wind power generation systems, it is necessary to use Maximum Power Point Tracking (MPPT). The power is maximized by maximizing the performance coefficient C_p . $C_{p,max}$ is reached for a specific tip-speed ratio λ_{opt} which corresponds, for a given wind speed, to an optimum rotational speed $\Omega_{m,opt}$. The purpose of MPPT is thus to control Ω_m (or equivalently λ) in order to maximize the power produced. There is no unique way to obtain the MPP, and many MPPT techniques have been developed. The majority of MPPT can be divided in four categories : tip speed ratio (TSR) algorithm, hill climbing search (HCS)/perturb and observe (P&O) algorithm, optimal torque (OT)/power signal feedback (PSF) algorithm and hybrid and intelligent (H&I) algorithm [31].

TSR Control Method compares the actual λ to λ_{opt} and adjusts the rotational speed accordingly. It is an easy and common control technique. However, it requires measuring the wind speed in order to compute λ .

Perturb and Observe (P&O) Method consists in repeatedly perturbing/modifying the rotational speed and observing if it improves the amount of power produced. This method has a very low dependence on the model, but causes fluctuations of power

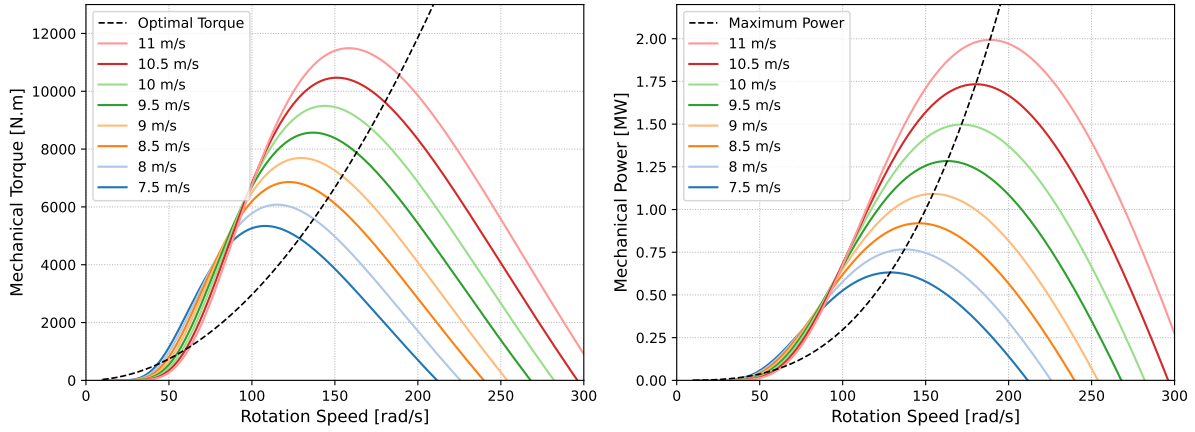


Figure 2.21 Mechanical torque (left) and Mechanical power (right) for different wind speeds

even when the wind speed is constant. The main difficulty lies in the choice of step size and searching direction.

Optimal Torque (OT) Control Method uses the aerodynamic equations developed earlier i.e. the relationship between rotational speed and torque. The wind turbine must run at λ_{opt} (or equivalently Ω_{opt}) to have $C_{p,max}$ and to produce maximum power.

$$\Omega_{opt} = \lambda_{opt} \cdot v_w / R \quad (2.52)$$

The corresponding torque is, starting from Eq. 2.51 :

$$T_{m,opt} = \frac{1}{2} \rho \pi R^2 \left(\frac{\Omega_{m,opt} R}{\lambda_{opt}} \right)^3 C_{p,max} / \omega_{m,opt} = \frac{1}{2} \rho \pi \frac{R^5}{\lambda_{opt}^3} C_{p,max} \Omega_{m,opt}^2 / N \quad (2.53)$$

Finally the OT method consists in :

$$T_{m,opt} = K_{opt} \cdot \Omega_m^2 / N \quad (2.54)$$

$$\text{with} \quad K_{opt} = \frac{1}{2} \rho \pi \frac{R^5}{\lambda_{opt}^3} C_{p,max} \quad (2.55)$$

The behaviour of the rotation speed ω_m of the shaft is described by Eq. 2.56.

$$J \frac{\partial \omega_m}{\partial t} = T_m(\omega_m) - T_r \quad (2.56)$$

J is the shaft inertia, T_m is the mechanical torque produced by the wind on the shaft and T_r is the electromechanical resistive torque absorbed by the alternator and converted in electrical power. By imposing $T_r = T_{m,opt}$, the rotation speed will naturally tend to $\omega_{m,opt}$. $T_m(\omega_m)$ expressed by Eq. 2.51 is plotted for different wind speeds on Fig. 2.21

as well the optimal torque (Eq. 2.53). Notice that $T_{m,opt}$ is not the maximum torque, since it maximizes $P_m = T_m \omega_m$. The optimal torque is located on the right flank, where $T_m(\omega_m)$ decreases with the rotation speed. This assures that $\omega_{m,opt}$ is a stable equilibrium and when imposing $T_r = T_{m,opt}$ the wind turbine will naturally tend towards $\omega_{m,opt}$. Intuitively, if the shaft turns too fast, the wind produces less mechanical torque $T_m(\omega_m)$ on the shaft slowing it down towards $\omega_{m,opt}$. If the shaft turns too slow, it will accelerate.

The OT method is simple but requires precise knowledge on the wind turbine performance ($C_{p,max}$, λ_{opt}). The quantities that need to be measured are the machine's rotating speed and electromechanical torque. The method has a slow response since it computes the torque using the rotating speed which varies slowly due to the shaft's inertia.

Hybrid and Intelligent (H&I) Algorithms are methods that combine the previously presented methods and/or use more advanced methods.

2.6.4 Typical Power Curve

A typical power curve of a pitch-regulated wind turbine is shown on Fig. 2.22. For insufficient wind speed ($v_{wind} < v_{cut\ in}$), the wind turbine is held still using brakes and no power is produced. In Region 2, MPPT algorithm is used to produce maximum power. The slope in this region is cubic, as explained by Eq. 2.46. The rotor speed increases with the wind speed. In Region 3, the rated power is reached. Pitch control is used to decrease the aerodynamic performance of the blades, which keeps the power output constant at the rated power. When wind speed becomes too high (Region 4), the wind turbine is held still in order to prevent damage.

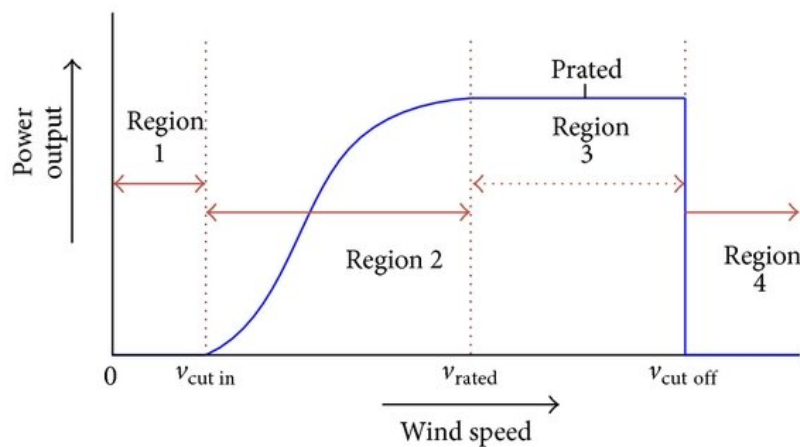


Figure 2.22 Typical power curve of a pitch regulated wind turbine. Taken from [32]

2.7 DFIG Wind Turbines

The wind turbines in the developed *MATLAB Simulink* model are Doubly-Fed Induction Generators (DFIG). The 3.5 GW Princess Elisabeth wind farm is only at a preliminary project stage, so the final technological choice for wind turbines is not yet known. From other projects, it is clear that nowadays DFIG and Permanent Magnet Synchronous Machine (PMSM) are the two main types of installed wind turbines. For simplicity, all wind turbines in the model are DFIG. So to understand the model, it is necessary to master the basics of DFIG technology.

2.7.1 Power Flow and Modes of Operation

A Doubly-Fed Induction Machine is an induction machine that is fed with currents both at the stator and rotor. The stator is directly connected to the grid while the rotor is connected through back-to-back converters to the grid. Therefore, the frequency of the rotor currents is independent of the grid frequency. We define ω_s as the frequency of the stator currents. The stator being directly connected to the grid, ω_s is generally equal to $2\pi \cdot 50 \text{ Hz}$ (for a Belgian grid). The frequency of the rotor currents is defined as ω_r and the rotor electrical speed $\omega_{em} = p \cdot \omega_m$ where p is the number of poles of the machine and ω_m is the mechanical speed of the shaft. Eq. 2.57 gives an important link between the frequencies in the machine [9].

$$\omega_s = \omega_r + \omega_{em} \quad (2.57)$$

The slip, s , is defined as:

$$s = \frac{\omega_s - \omega_{em}}{\omega_s} = \frac{\omega_r}{\omega_s} \quad (2.58)$$

Depending on the shaft speed, which is proportional to the wind speed through the MPPT algorithm, 3 modes of operation can be defined.

$\omega_m < \omega_s/p$	$\omega_r > 0$	$s > 0$	Subsynchronous operation
$\omega_m > \omega_s/p$	$\omega_r < 0$	$s < 0$	Hypersynchronous operation
$\omega_m = \omega_s/p$	$\omega_r = 0$	$s = 0$	Synchronous operation

Table 2.2 Modes of operation

The power is transferred through both the stator connection and the rotor connection. When losses (electromechanical and conversion) are neglected, the following simple equations can be written :

$$P_m = P_s + P_r \quad P_m = (1 - s)P_s \quad P_r = -sP_s \quad (2.59)$$

In subsynchronous operation (for low wind speeds), the rotor absorbs power ($P_r <$

0), while in hypersynchronous operation the rotor generates power ($P_r > 0$). The stator however always generates power. The power in function of wind speed are represented on Fig. 2.24.

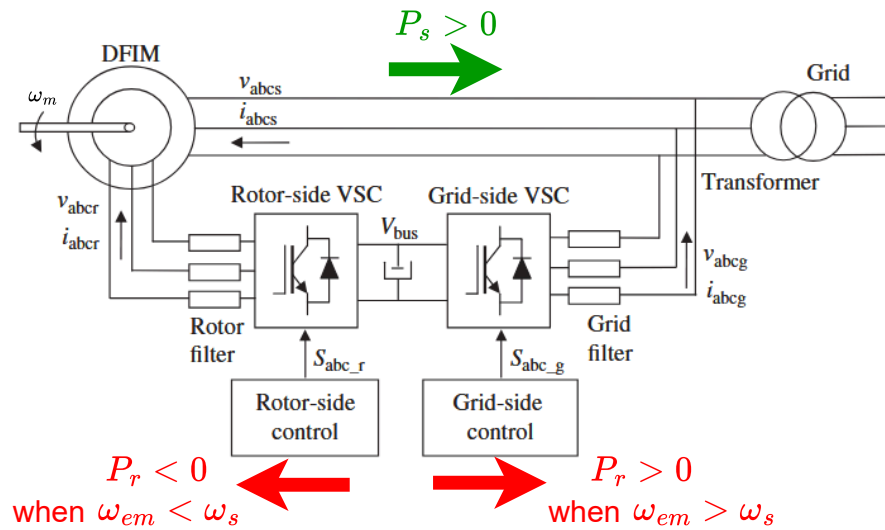


Figure 2.23 DFIG Power Flow. Adapted from [9]

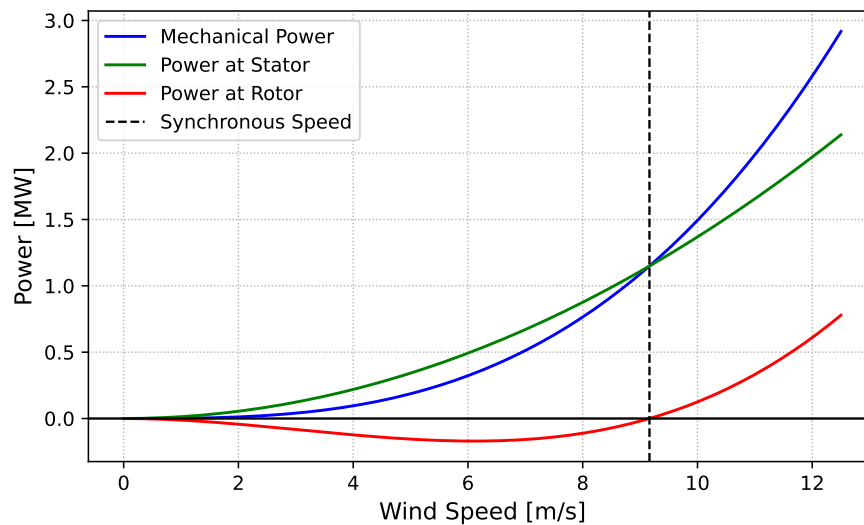


Figure 2.24 Steady-state power in function of wind speed

2.7.2 Electrical Equations

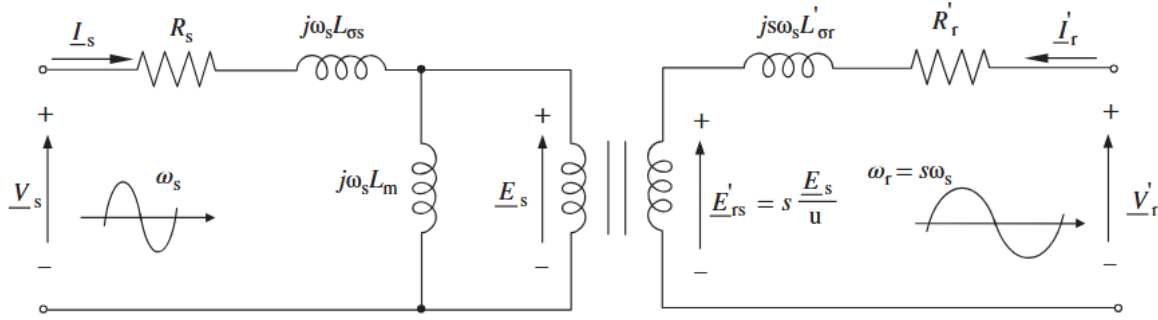


Figure 2.25 Equivalent one-phase electric circuit of a DFIG. Taken from [9].

The equivalent one-phase diagram of a DFIG is shown on Fig. 2.25. It contains the stator and rotor resistances R_s and R'_r , the stator and rotor leakage inductances $L_{\sigma s}$ and $L_{\sigma r}$, the mutual inductance L_m . Stator and rotor windings have a different number of turns per phase, expressed by the turns ratio $u = N_s / N_r$. The induced emf at the stator and rotor E_s and E'_{rs} are linked by following expression [9]:

$$E'_{rs} = s \frac{E_s}{u} \quad (2.60)$$

To facilitate the analysis, rotor quantities are reduced to the stator (turns ratio u) as well as brought to the same frequency (slip s). This gives the equivalent circuit shown on Fig. 2.26. Finally the electrical equations of the equivalent circuit can be obtained :

$$V_s = R_s I_s + j\omega_s L_{\sigma s} I_s + j\omega_s L_m (I_s + I_r) \quad (2.61)$$

$$\frac{V_r}{s} = \frac{R_r}{s} I_r + j\omega_s L_{\sigma r} I_r + j\omega_s L_m (I_s + I_r) \quad (2.62)$$

$$\Psi_s = L_m (I_s + I_r) + L_{\sigma s} I_s = L_s I_s + L_m I_r \quad (2.63)$$

$$\Psi_r = L_m (I_s + I_r) + L_{\sigma r} I_r = L_m I_s + L_r I_r \quad (2.64)$$

with the stator and rotor fluxes Ψ_s and Ψ_r , the stator inductance $L_s = L_m + L_{\sigma s}$, the rotor inductance $L_r = L_m + L_{\sigma r}$. From these equations, $\sigma = 1 - L_m^2 / (L_s L_r)$ can be defined.

Torque can be expressed by electrical parameters as follows :

$$T_{em} = 3p \frac{L_m}{L_s} \mathcal{I} \{ \vec{\Psi}_s \cdot \vec{I}_r \} \quad (2.65)$$

dq-Frame Equations A common choice of rotating reference frame is to align the d-axis with the stator magnetic flux. Since the stator is directly connected to the grid, the frequency of the stator flux is $\omega_s = 2\pi f$. Because the stator windings are stationary in

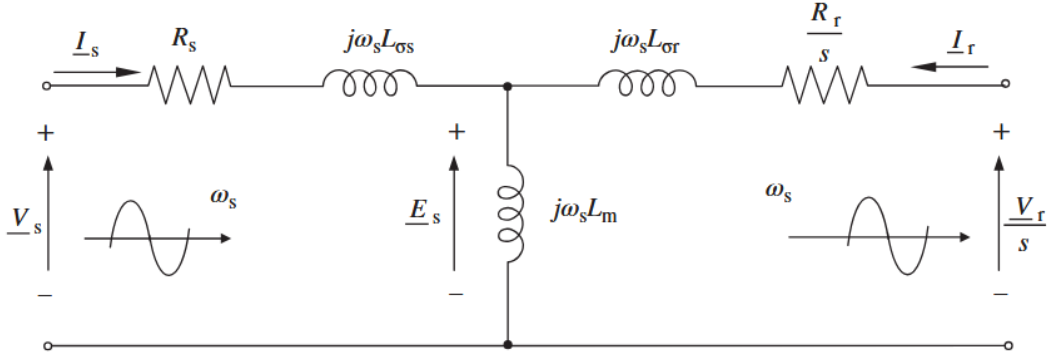


Figure 2.26 Equivalent one-phase electric circuit of a DFIG referred to the stator. Taken from [9].

space, the stator equations must be transformed by a frequency ω_s . The rotor windings are physically turning at ω_m . In order to represent them in a reference frame at $\omega_s = \omega_m + \omega_r$, the rotor equations must be transformed by frequency ω_r . The dq-equations for voltages and fluxes are then given by :

$$v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s \psi_{qs} \quad (2.66)$$

$$v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s \psi_{ds} \quad (2.67)$$

$$v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r \psi_{qr} \quad (2.68)$$

$$v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_r \psi_{dr} \quad (2.69)$$

$$(2.70)$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \quad (2.71)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (2.72)$$

$$\psi_{dr} = L_m i_{ds} + L_r i_{dr} \quad (2.73)$$

$$\psi_{qr} = L_m i_{qs} + L_r i_{qr} \quad (2.74)$$

Torque When applying the Clarke transformation (no p.u.) (Eq. 2.9), the expression for torque becomes :

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s} \mathcal{I} \{ \vec{\psi}_s \cdot \vec{i}_r \} \quad (2.75)$$

2.7.3 Control of DFIG

As shown on Fig. 2.23, both grid-side (connected to the grid) and rotor-side (connected to the rotor) AC/DC converters must be controlled. Each side is responsible for regulating different electrical quantities: the grid-side controls the DC bus voltage and the

reactive power, while the rotor-side controls the rotational speed of the machine and the reactive power control.

Both controllers are divided into two loops: an inner loop controlling the AC currents and an outer loop responsible for higher-level control objectives (e.g., voltage or speed). In order to ensure stable operation, the outer loop must operate significantly slower than the inner loop. As a result, for the outer controller, the AC currents may be assumed to be equal to their reference values—that is, the inner loop is considered to respond instantaneously.

The rotor-side control explained here is the one detailed in Chapter 10 of the reference book *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications* [9]. The grid-side control comes from Chapter 2 of the book *Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation* [33].

Rotor-Side Control

The control is done in the synchronously rotating dq reference frame where the d-axis is aligned with the stator flux ψ_s , and using the Clarke transformation (not in per-unit).

$$\psi_{ds} = |\vec{\psi}_s| \quad \psi_{qs} = 0 \quad (2.76)$$

Inner Loop Accordingly, the rotor-side voltage equations are expressed as Eq. 2.77 and 2.78 when rewritten to only depend on the rotor current and stator flux.

$$v_{dr} = R_r i_{dr} + \sigma L_r \frac{d}{dt} i_{dr} - \omega_r \sigma L_r i_{qr} + \frac{L_m}{L_s} \frac{d}{dt} |\vec{\psi}_s| \quad (2.77)$$

$$v_{qr} = R_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr} + \omega_r \sigma L_r i_{dr} + \omega_r \frac{L_m}{L_s} |\vec{\psi}_s| \quad (2.78)$$

From Eq. 2.77 and 2.78 it can be seen that it is possible to control the direct and quadrature components separately. There are however coupling terms ($-\omega_r \sigma L_r i_{qr}$ and $+\omega_r \sigma L_r i_{dr}$), which should be cancelled in control scheme. The constant terms ($\frac{L_m}{L_s} \frac{d}{dt} |\vec{\psi}_s|$ and $\omega_r \frac{L_m}{L_s} |\vec{\psi}_s|$) can be compensated in order to improve the control. This however requires to compute a value for ω_r and the stator flux. The rotor currents speed is given by

$$\omega_r = \omega_s - p\omega_m \quad \omega_s = 2\pi f. \quad (2.79)$$

The stator flux is approximated as in Eq. 2.80. This also shows that $|\vec{\psi}_s|$ is constant. Therefore, the term $\frac{L_m}{L_s} \frac{d}{dt} |\vec{\psi}_s|$ is zero and does not need to be compensated.

$$|\vec{\psi}_s| = \sqrt{\frac{2}{3}} \frac{V_s}{\omega_s} \quad (2.80)$$

For the reference frame transformation, the angle θ_r must be computed. First, the angle θ_s is computed. This is done by computing the stator voltage phase angle using a PLL

and subtracting 90° to it. The reason behind it is shown graphically on Fig. 2.27. When the voltage drop across the stator resistance is neglected, the stator voltage can be approximated as $\vec{v}_s \approx j\omega_s \vec{\psi}_s$. The stator flux angle θ_s is 90° behind the stator voltage space vector angle.

Fig. 2.27 shows graphically the current controller explained above.

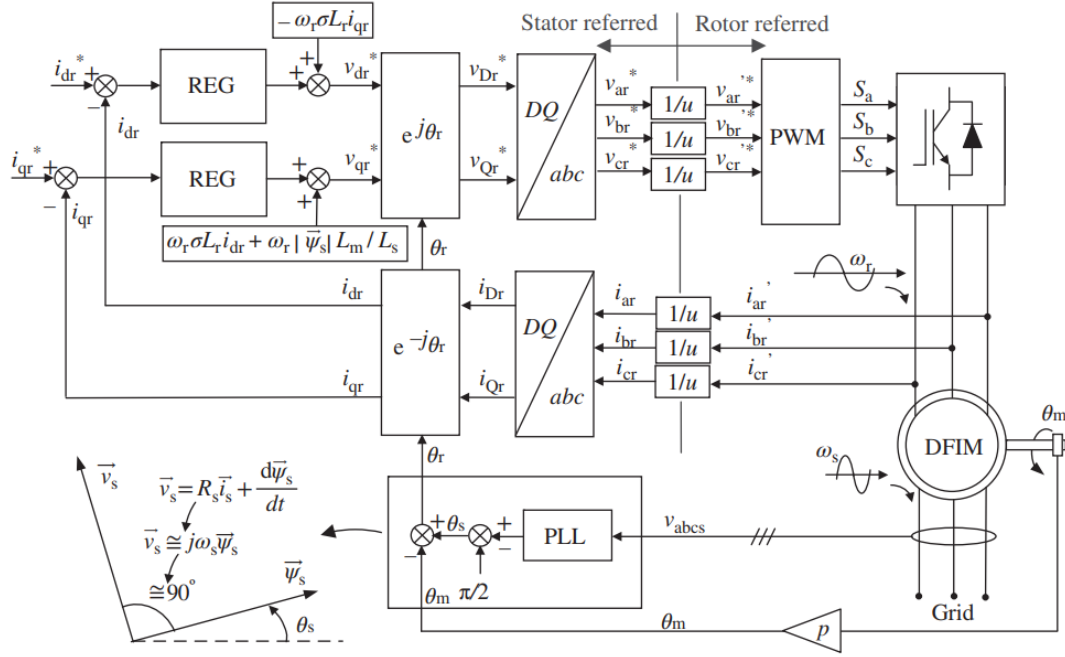


Figure 2.27 Rotor-side current control. Taken from [9]

Outer Loop The outer loop of the rotor-side controller is responsible for regulating the machine's rotational speed and the stator reactive power. By operating in the dq reference frame, these two control objectives are decoupled. Eq. 2.81 shows that the electromagnetic torque can be controlled through the q-axis rotor current:

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s} (\psi_{qs} i_{dr} - \psi_{ds} i_{qr}) \xrightarrow{\psi_{qs}=0} T_{em} = \underbrace{-\frac{3}{2} p \frac{L_m}{L_s} |\vec{\psi}_s|}_{=k_T} i_{qr} \quad (2.81)$$

Since torque directly influences the rotational speed, i_{qr} allows for speed regulation. Similarly, Eq. 2.82 shows that i_{dr} controls the stator reactive power Q_s :

$$Q_s = \frac{3}{2} (v_{qs} i_{ds} - v_{ds} i_{qs}) \Rightarrow Q_s = -\frac{3}{2} \omega_s \frac{L_m}{L_s} |\vec{\psi}_s| \left(i_{dr} - \frac{|\vec{\psi}_s|}{L_m} \right) \Rightarrow Q_s = k_Q \left(i_{dr} - \frac{|\vec{\psi}_s|}{L_m} \right) \quad (2.82)$$

Thus, by adjusting i_{dr} , the reactive power can be regulated independently of the speed control loop.

Fig. 2.28 illustrates the rotor-side outer control loop.

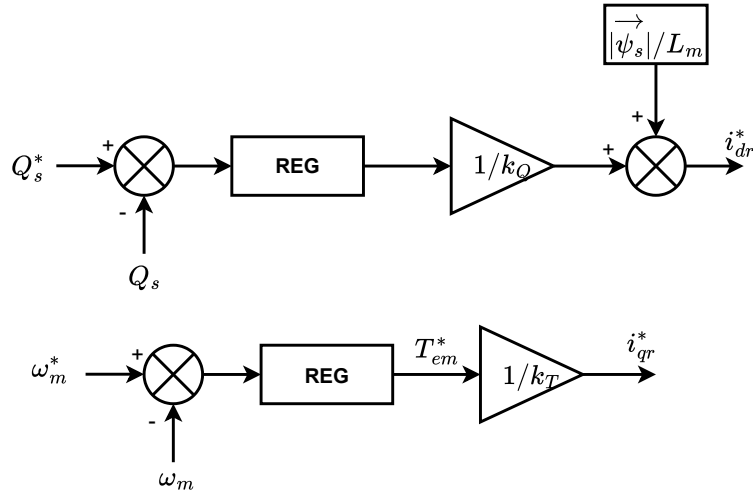


Figure 2.28 Outer control loop

Grid-Side Control

The objective of the grid-side converter is to regulate the DC bus voltage to ensure proper power flow through the back-to-back converters, while also controlling the reactive power exchanged with the grid. A simplified representation of the grid-side system is shown in Fig. 2.29.

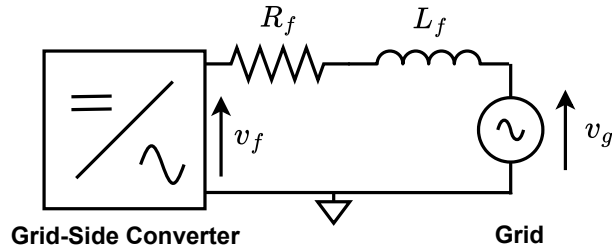


Figure 2.29 Single line diagram of grid-side system

The control is performed in the synchronously rotating dq reference frame where the d-axis is aligned with the grid voltage space vector $\vec{v}_g$.

Inner Loop The system equations in the chosen reference frame are :

$$v_{df} = R_f i_{dg} + L_f \frac{di_{dg}}{dt} + v_{dg} - \omega_s L_f i_{qg} \quad (2.83)$$

$$v_{qf} = R_f i_{qg} + L_f \frac{di_{qg}}{dt} + \omega_s L_f i_{dg} \quad (2.84)$$

where ω_s is the angular speed of the grid voltage. Eq. 2.83 and 2.84 are used to design the inner current control as shown in Fig. 2.30. Where the compensation terms are

$$e_{df} = -\omega_s L_f i_{qg} \quad e_{qf} = \omega_s L_f i_{dg} \quad (2.85)$$

Outer Loop The active and reactive power equations are written as:

$$P_g = \frac{3}{2} v_{dg} i_{dg} \quad (2.86)$$

$$Q_g = -\frac{3}{2} v_{dg} i_{qg} \quad (2.87)$$

indicating that the active power is controlled via i_{dg} , while the reactive power is regulated through i_{qg} , thanks to the dq-frame alignment. The controller is shown in Fig. 2.30, where

$$K_{P_g} = \frac{1}{\frac{3}{2} v_{dg}} \quad K_{Q_g} = \frac{1}{-\frac{3}{2} v_{dg}} \quad (2.88)$$

Ultimately, the control of active power is used to regulate the DC bus voltage. As previously discussed, the DC bus voltage must be kept constant to ensure proper active power transfer between the rotor-side and grid-side converters. The DC link is primarily composed of a capacitor, which stores energy and absorbs power fluctuations. A deviation in DC voltage indicates a mismatch between input and output power, which is corrected via active power control to restore balance.

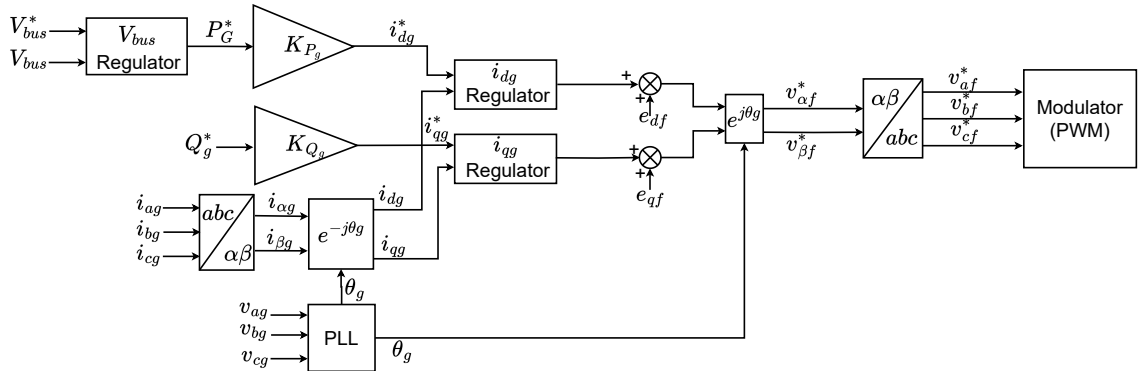


Figure 2.30 Grid side controller

2.8 Aggregated Wind Park Model

In this section, different methods for modelling wind parks are explored [34]–[36].

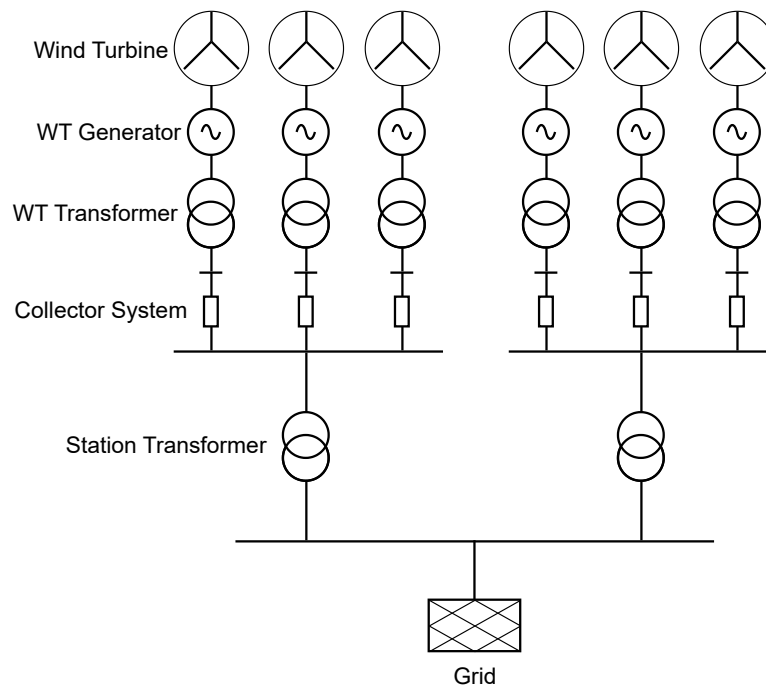


Figure 2.31 Wind park example

Fig.2.31 illustrates an example of a wind park.

2.8.1 Detailed Model

In a detailed model, all the wind turbines and their electrical networks (transformers, cables) are modeled individually. This is suitable when studying a small number of wind turbines. However, with large wind parks (as is the case of the Princess Elisabeth project) this method proves to be computationally heavy. Thus requiring an aggregated model.

2.8.2 Aggregated Models

The idea is to represent the wind park with a smaller number of wind turbines to reduce the complexity of the model and the computation time. However, the model must maintain the response of the entire wind park at the point of common coupling. The operating point of a wind turbine depends on the wind speed. Depending on the wind conditions throughout the wind park, there are different types of aggregated models.

Full Aggregated Model (FAM)

This method aggregates all wind turbines of the park into a single equivalent turbine and generator, assuming identical wind speed for the entire park.

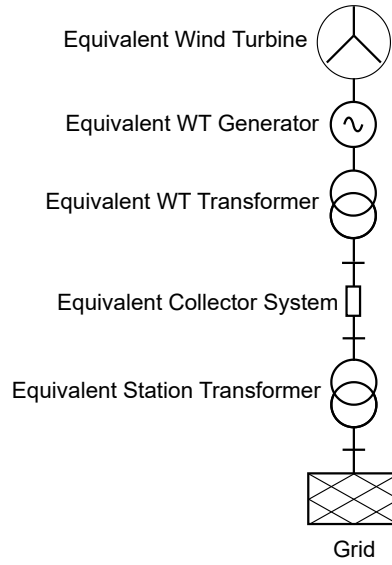


Figure 2.32 FAM representation of Fig. 2.31

While it simplifies greatly the model, its accuracy is limited as turbines in bigger wind parks don't often all receive the same wind speed. The equivalent wind turbine's parameters can be computed as follows.

The equivalent generator ratings are given by

$$S_{eq} = \sum_{i=1}^n S_i \quad P_{eq} = \sum_{i=1}^n P_i, \quad (2.89)$$

where S_i and P_i are the apparent power and the active power of the individual generators respectively and n is the number of generators in the park. The parameters of the generator are given by

$$\begin{aligned} x_{n,eq} &= \frac{x_n}{n} & x_{s,eq} &= \frac{x_s}{n} & x_{r,eq} &= \frac{x_r}{n} \\ r_{s,eq} &= \frac{r_s}{n} & r_{r,eq} &= \frac{r_r}{n} & H_{eq} &= \frac{\sum_{i=1}^n S_i H_i}{\sum_{i=1}^n S_i} & D_{eq} &= \frac{\sum_{i=1}^n S_i D_i}{\sum_{i=1}^n S_i} \end{aligned} \quad (2.90)$$

where x_n is the excitation reactance of the generator, x_r and x_s are respectively the rotor and stator reactances, r_r and r_s the rotor and stator resistances, H is the inertia time constant and D the damping coefficient.

The apparent power and impedance of the equivalent wind turbine transformer is modeled by

$$S_{WT,eq} = \sum_{i=1}^n S_i \quad Z_{eq} = \frac{Z_{WT}}{n} \quad (2.91)$$

In the case of Fig. 2.31, the collector systems are in parallel and are identical, the equiv-

alent collector system is thus modeled by

$$Z_{CT,eq} = \frac{Z_{CT}}{n} \quad (2.92)$$

where Z_{CT} and n are respectively the impedance of the collector system of one wind turbine and the number of wind turbines.

The equivalent station transformer is modeled by

$$Z_{ST,eq} = \frac{Z_{ST}}{n_{ST}} \quad (2.93)$$

where Z_{ST} is the impedance of a station transformer and n_{ST} is the number of station transformers.

Semi Aggregated Model (SAM)

This method is used when we want to take into account the different incoming wind speeds in the park. The generators will be aggregated into a single equivalent generation unit while the turbines will all be represented individually.

Multi Machine Model (MMM)

A way to deal with different wind speed distribution throughout the wind park is to aggregate together all wind turbines facing the same wind speed. Thus representing the wind park by multiple equivalent wind turbines. This method can also take into account the different types of wind turbine generators in the park.

3

Dynamic Model of Separate Components

This chapter explains how each component has been implemented in the *MATLAB Simulink* model. Simulations are conducted to validate the HVDC and the DFIG model.

3.1 Cable Modelling

Two main models exist for modelling a line: the distributed parameters line and the PI section line.

The distributed parameters line model (or transmission line model) is based on the travelling wave theory. The resistance, inductance and capacitance (per-unit length) are uniformly distributed along the entire length of the line, which corresponds to the physical reality. The line is characterized by the surge impedance $Z_c = \sqrt{l/c}$ and the wave propagation speed $v = 1/\sqrt{lc}$. Compared to the PI section model, the distributed parameter model is more complex but is also more accurate in specific cases. It is useful when the wavelength becomes comparable to the length of the line. This can happen for long lines or when high frequencies are considered [37], [38].

The PI section line is a lumped-element model. The resistance, inductance and capacitance are grouped into finite electrical components joined by perfectly conducting wires, as shown in Fig. 3.1. The model is slightly less accurate, but the solving is much easier.

3 | Dynamic Model of Separate Components

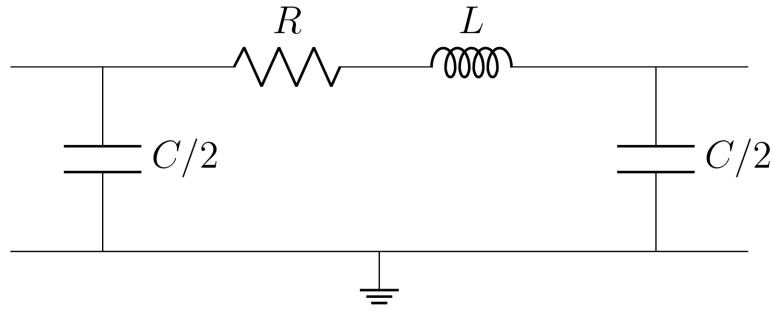


Figure 3.1 PI section model. Taken from [5]

Let's consider the case of the Princess Elisabeth Project. The propagation speed is $v = 1/\sqrt{lc} = 174078 \text{ km/s}$. According to [39], an approximation of the maximum frequency range represented by the PI section model is given by $f = v/8L$. For the length $L = 45 \text{ km}$, we obtain $f = 484 \text{ Hz}$. The purpose of the developed model is to analyse slow phenomenons in the range from 0 Hz to 100 Hz . Using a distributed line parameter model is therefore not mandatory. Therefore, PI section models are used in the *MATLAB Simulink* model.

3.1.1 DC Export Cable

Parameter	Unit	525 kV (export cable)
Rated Power	[MW]	1000
Maximum current	[A]	1905
Resistance r	[Ω/km]	0.0072
Inductance l	[mH/km]	0.15
Capacitance c	[$\mu\text{F}/\text{km}$]	0.22
Cable cross-section	[mm ²]	2500

Table 3.1 DC cable parameters for positive and negative polarity

An important component of the HVDC link is the DC export cable itself. In the case of the Princess Elisabeth project, the working voltage is 525 kV and the cable is 45 km long. The parameters used in the model come directly from cable manufacturers [5], [40]. They are shown in Table 3.1.

3.1.2 AC Inner and Export Cables

The studied system contains two sets of undersea AC cables. 66 kV inner cables are used for connecting the wind turbines to the energy island. The 45 km connection between the island and the continent is done by 220 kV export cables. The AC cables

are represented using PI section models. The values used are taken from datasheets from cable manufacturers [5], [41], [42].

Parameter	Unit	66kV (inner cable)	220kV (export cable)
Rated Power	[MW]	70	350
Maximum current per phase	[A]	615	920
Resistance	[Ω/km]	0.034	0.048
Inductance	[mH/km]	0.34	0.37
Capacitance	[μF/km]	0.29	0.18
Cable cross-section	[mm ²]	500	1000

Table 3.2 66kV and 220kV cable parameters

In practice, electrical outputs of the wind turbines are grouped together at 66kV in packs of around 70 MW. A single 70 MW cable connects the subset of wind turbines to the energy island. The distance between the wind farm and the energy island varies but is approximated to be 10 km.

The implemented wind farm consists of wind turbines which have a rated power of 2 MW. They are aggregated in equivalent wind turbines models of rated power $n_{wt,agg} \times 2$ MW. The 66kV cables of 70 MW rated power are therefore also aggregated in equivalent cables for the connection of each aggregated wind farm. The impedances from Tab. 3.2 are thus modified as follows :

$$\begin{cases} Z_{eq,cable} = \frac{Z}{n_{cable}} \\ C_{eq,cable} = C \cdot n_{cable} \end{cases} \quad \text{with} \quad n_{cable} = \frac{2 \text{ [MW]} \cdot n_{wt,agg}}{70 \text{ [MW]}} \quad (3.1)$$

3.1.3 Shunt Reactors

Cables have a higher dielectric permittivity and a smaller distance between the conducting part (core) and the ground (sheath of the cable), compared to overhead lines. Due to the important capacitive effect in the cables, a non-negligible amount of reactive power is generated. To compensate the reactive power from the cables, shunt reactors are used at both ends of the cables. The shunt reactors have already been designed in [5]. Here are the main results.

Consider a PI section model with conventions shown on Fig. 3.2. Let $Z \angle \theta = R + j\omega L$ and $Z_C \angle -90^\circ = \frac{-j}{\omega C/2}$. The active and reactive power at both generator and load end can then be written as in Eq. 3.2 and 3.3.

$$\begin{cases} P_G = \frac{V_G^2}{Z} \cos(\theta) - \frac{V_G V_L}{Z} \cos(\theta + \delta), \\ Q_G = \frac{V_G^2}{Z} \sin(\theta) - \frac{V_G V_L}{Z} \sin(\theta + \delta) - \frac{V_G^2 \omega C}{2} \end{cases} \quad (3.2)$$

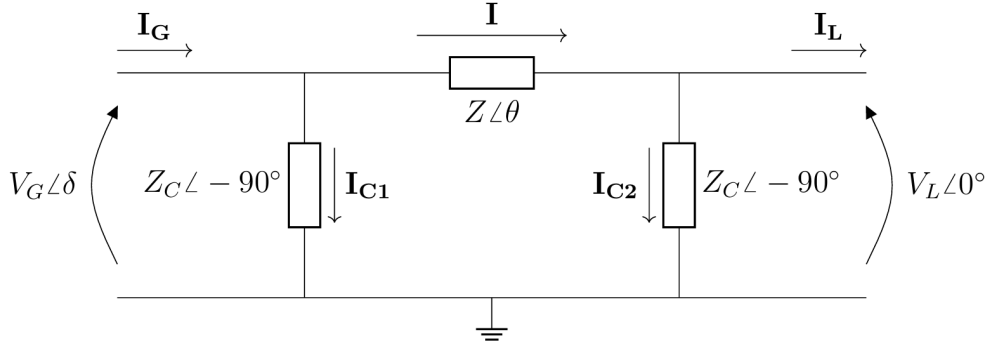


Figure 3.2 PI section with notation convention. Taken from [5]

$$\begin{cases} P_L = \frac{V_G V_L}{Z} \cos(\theta - \delta) - \frac{V_L^2}{Z} \cos(\theta), \\ Q_L = \frac{V_G V_L}{Z} \sin(\theta - \delta) - \frac{V_L^2}{Z} \sin(\theta) + \frac{V_L^2 \omega C}{2} \end{cases} \quad (3.3)$$

Shunt reactors are placed to cancel the reactive power. On the PI section model, they can be represented as in parallel to the lumped capacitance $C/2$. The shunt reactor consists of an inductance L_{sh} on each phase. The reactive power compensated by the shunt reactor is expressed in Eq. 3.4, with V the line-to-line voltage at the shunt location.

$$Q_{comp} = 3 \left(\frac{V}{\sqrt{3}} \right)^2 \frac{1}{\omega L_{sh}} = \frac{V^2}{100\pi L_{sh}} \quad (3.4)$$

For 3x350 MW AC export cables at rated power with parameters from Tab. 3.2, the reactive power to be compensated at each side has been measured in [5] and is equal to $Q_{comp} \approx 175$ MVar.

3.2 HVDC Connection Model

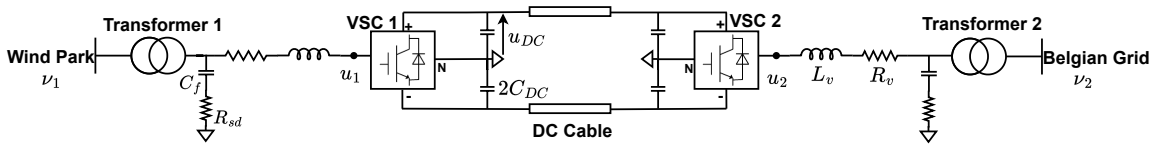


Figure 3.3 HVDC link model.

This section details the *MATLAB Simulink* model of the HVDC link. The single line diagram of the HVDC link is shown in Fig. 3.3. The model's parameters are listed in Tab. 3.3, while the DC cable parameters were already listed in Tab. 3.1 (Sec. 3.1.1). The AC filter parameters are computed in Sec. 3.2.3 and the DC capacitor value is computed in

Sec. 3.2.2.

The *MATLAB Simulink* implementation of the HVDC link is inspired by the *VSC-Based HVDC Transmission System* model available on *Mathworks* [43]. Screenshots of the model are provided at the end of this document.

Parameter	Value
Rated power	2 GW
Rated frequency	50 Hz
DC line length	45 km
Wind park voltage	220 kV
Belgian grid voltage	380 kV
Transformer 1 rated voltages	220 / 525 kV
Transformer 2 rated voltages	525 / 380 kV
Switching frequency	1350 Hz
u_{DC}	525 kV
C_{DC}	25.2 μ F
Transformer 1 and 2 resistance	0.005 p.u.
Transformer 1 and 2 inductance	0.194 p.u.
R_v	0.0015 p.u.
L_v	0.178 p.u.
DC cable resistance	5.224×10^{-5} p.u./km
DC cable inductance	3.419×10^{-4} p.u./km
DC cable shunt capacitance	0.0095 p.u./km
C_f	0.05 p.u.
R_{sd}	2.62×10^{-4} p.u.

Table 3.3 Parameters of the HVDC test setup

3.2.1 HVDC Control

The implemented controller is based on the one presented in Sec. 2.5.6. In the case of the Princess Elisabeth project, it is reported in [5] that the grid side converter will control reactive power and DC voltage while the one on the wind farm's side controls active power and reactive power. The only modification made to the controller described in Sec. 2.5.6 is in the DC voltage control loop: the term $\frac{u_{dc}}{v_d} i_{dc}$ is omitted, and the output of the PI controller is used directly as the reference current.

3.2.2 DC Capacitor and Smoothing Reactor

The DC capacitors connected at the VSC terminals are chosen to have a charging time constant $\tau = 7$ ms [43].

$$C_{dc} = \frac{\tau}{Z_B} = 25.4 \mu F \quad \text{with} \quad Z_B = \frac{V_{DC}^2}{S_{nom}} = \frac{(525 \text{ kV})^2}{1 \text{ GW}} \quad (3.5)$$

On the DC side, smoothing reactors are used to filter the DC voltage. It consists in placing in series an inductance and resistance $L = 0.022 \text{ H}$ and $R = 0.07 \Omega$. These values are the ones used in [43] and converted to keep the same per-unit value. The theory behind this smoothing reactor is not considered.

3.2.3 AC Filter

Applying the method detailed in Sec. 2.5.4 and using the base parameters detailed in Tab. 3.3, the following filter parameters are found :

$$L_1 = 0.178 \text{ p.u.} \quad C_f = 0.05 \text{ p.u.} \quad L_2 = 0.1947 \text{ p.u.} \quad R_{sd} = 2.62 \times 10^{-4} \text{ p.u.}$$

L_1 corresponds to the phase reactor and L_2 the transformer's series inductance.

3.2.4 Synchronization Technique

Synchronization with the grid is required for the computation of the dq-components used in the space vector control. Simulations showed that the use of a regular PLL from *MATLAB Simulink* did not allow proper control of the HVDC. The presence of the VSCs lead to harmonics injected in the grid, even though an AC filter is used. The grid voltage not being totally balanced and containing harmonics, the PLL is unable to properly compute the phase angle.

Instead, a simple open-loop phase detection using the atan2 function is implemented (Eq. 2.19). The computed angle and frequency show big oscillations. However, the atan2 function assures, by its nature, that the q-component of the voltage is always equal to zero. Since the controller technique is based on the assumption that $u_q = 0$, the use of atan2 shows some benefit, as could also be observed during simulations. Consequently, atan2 phase detection is used, which enables a proper control of the HVDC link as will be shown in Sec. 3.3.

3.3 HVDC Connection Model Validation

In this section, different scenarios are simulated in the *MATLAB Simulink* software to validate the HVDC link model. In these simulations, the Belgian grid and the wind farm are replaced by ideal sources. The wind park is called *AC Grid 1* and the Belgian grid is called *AC Grid 2*. As mentioned previously, the converter at the wind farm controls active and reactive power while the converter at the Belgian grid manages the DC voltage and reactive power. For this reason only the following control configuration is tested: Converter at *AC Grid 1* regulates P and Q while converter at *AC Grid 2* regulates u_{DC} and Q .

3.3.1 Start-up Procedure

The start-up procedure is important to ensure safe and stable operation. This subsection details how to start an HVDC link connecting two infinite grids [17], [43]. The active power and DC voltage are shown in Fig. 3.4.

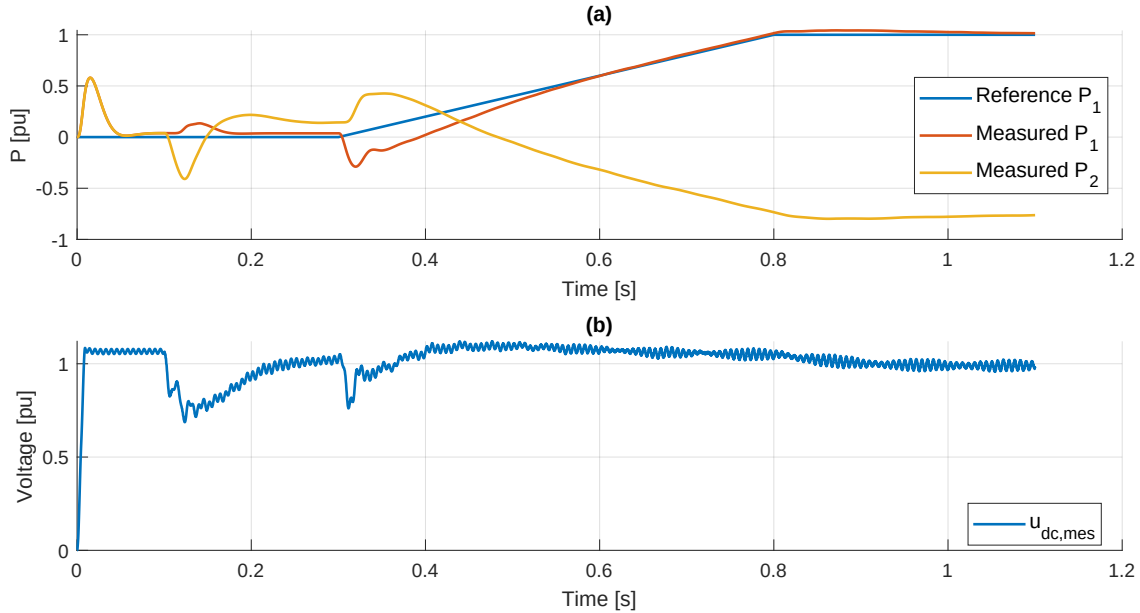


Figure 3.4 Active power and DC voltage during start-up

- (i) Initial state ($t < 0$ s): the HVDC link is not connected to the grids, the DC capacitors are not charged.
- (ii) Connection to the grids ($t = 0$ s): the HVDC link is connected to the grids at the PCCs but the controllers are disabled. Without controllers, the IGBT valves are turned off and current flows through the diodes (see Fig. 2.4), charging the DC capacitors. Indeed, Fig. 3.4(a) shows active power going into the link from both VSCs. This causes the DC voltage to exceed $1 p.u.$, it needs to be controlled.
- (iii) Enabling VSC2's controller ($t = 0.1$ s): this controller is responsible for the control of the DC voltage. It can be observed that the DC voltage is brought down to its reference value of $1 p.u.$ by evacuating the excess active power through VSC2.
- (iv) Enabling VSC1's controller ($t = 0.3$ s): once the DC voltage is stabilized, active power can be transferred through the link.

3.3.2 Active Power

The first test consists of a ramp in active power at grid 1. During this test, the reference DC voltage was set to $1 p.u.$ and the reactive power reference was set to 0 on both sides. Fig. 3.5(a) shows that when grid 1 sends $1 p.u.$ of active power, only $0.75 p.u.$ reach grid 2. This is due to various sources of losses in the HVDC link (such as mainly AC/DC conversion losses and Joule losses). The amount of losses is surprisingly high.

3 | Dynamic Model of Separate Components

For example, in the model from [43] the losses are only of 0.1 p.u.. Reasons for higher losses in our model could not be found.

After applying a steady ramp on the active power reference at VSC1 to reverse the power flow, it can be seen that the active power at grid 2 reaches above 1 p.u.. That is to counter the losses in the HVDC link so that 1 p.u. reaches grid 1 which is now the receiving end of the link. The active power difference between Grid 1 and Grid 2 remains non-zero even when $P_{1,ref} = 0$, this suggests that there are static losses in the link independent of the power sent from the Grid 1.

It can be seen in Fig. 3.5(b) and 3.5(c) that during variations of active power, only the d-axis component of the current is affected. As explained previously, this decoupling between axes is due to working in the synchronously rotating reference frame where u_q equals 0.

However, VSC1 is drawing more active power than VSC2 can deliver which causes the DC voltage to drop. Which in turn results in small variation of the voltage at the point of common coupling with grid 2. Grid 2 then delivers reactive power to compensate for the voltage drop as illustrated in Fig.3.5(d).

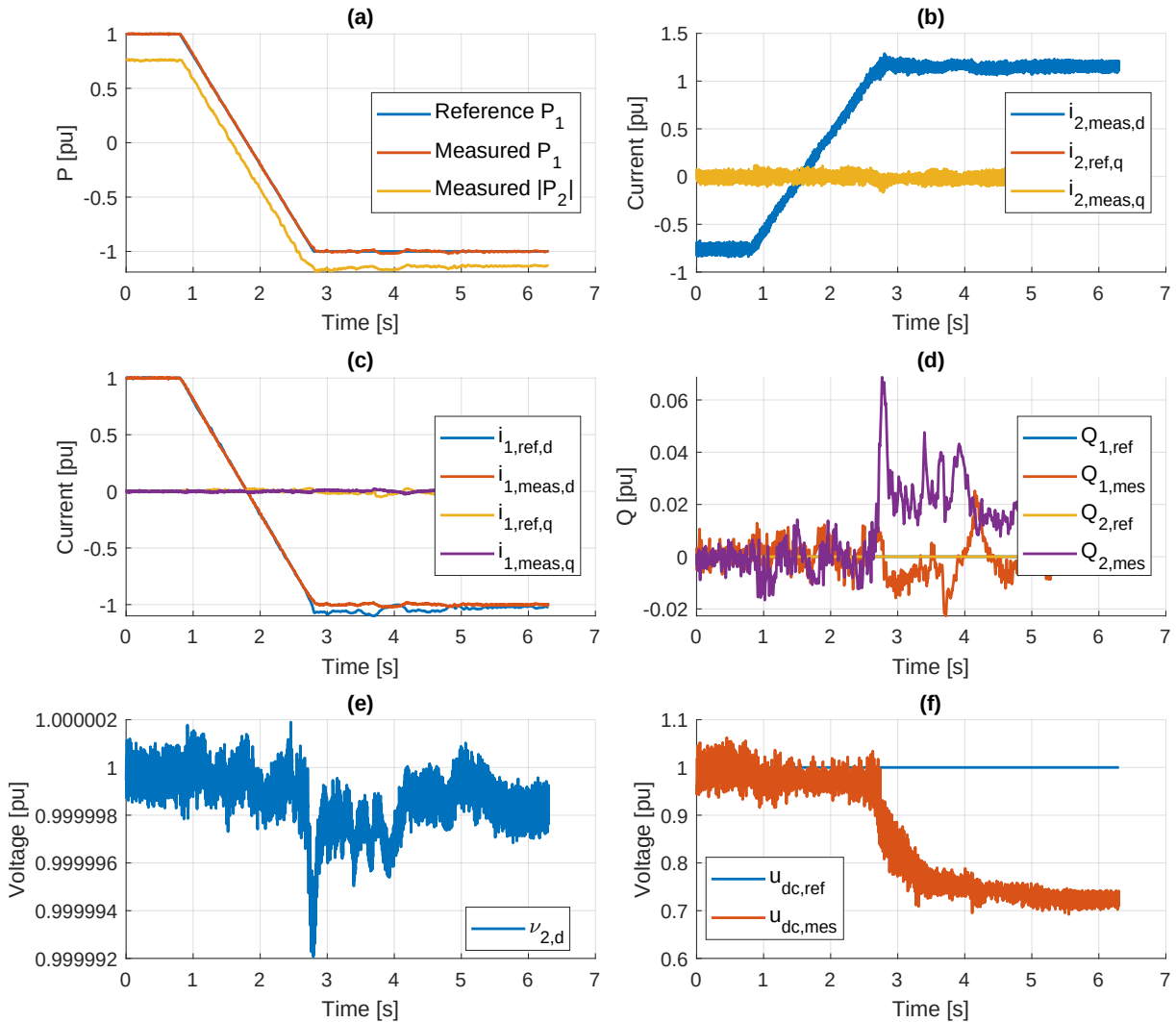


Figure 3.5 Transient response to active power variations

If, however, a ramp is applied from 0.4 to -0.4 p.u. instead of 1 p.u., Fig.3.6(b) shows that the DC voltage drops only very slightly during the ramp and stabilizes back to 1 p.u. after the ramp. This shows that the power flow can be reversed but only for smaller than nominal power values.

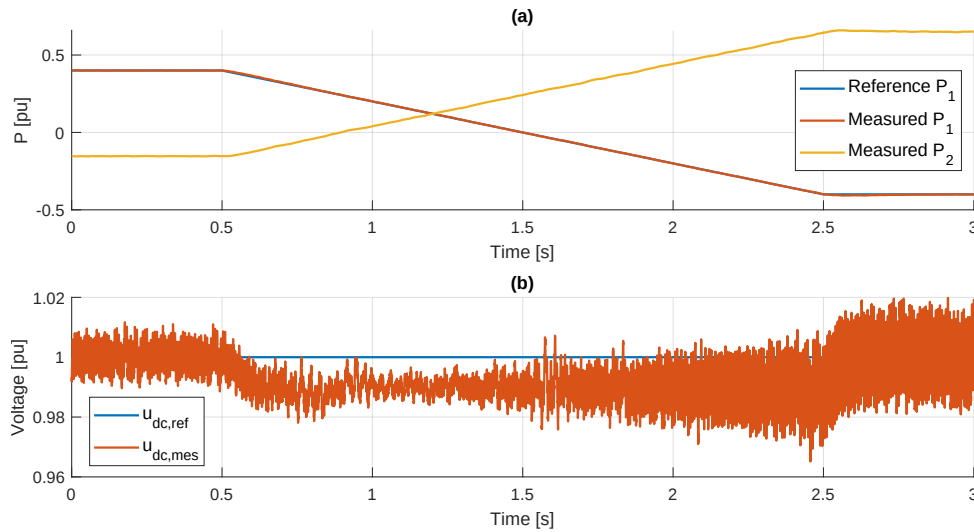


Figure 3.6 Transient response to active power variations

3.3.3 Reactive Power Variations

The link's response to reactive power set point variation is now tested. A ramp is applied to the reactive power set point of VSC1. Reactive power is controlled independently at each converter (since it does not flow through the DC link [17]). This is illustrated in Fig. 3.7(d), the variation of reactive power at VSC1 does not affect reactive power at VSC2. The figure also shows that the measured reactive power doesn't follow the reference very closely during the transient, this might be due to the PI controller's tuning.

3 | Dynamic Model of Separate Components

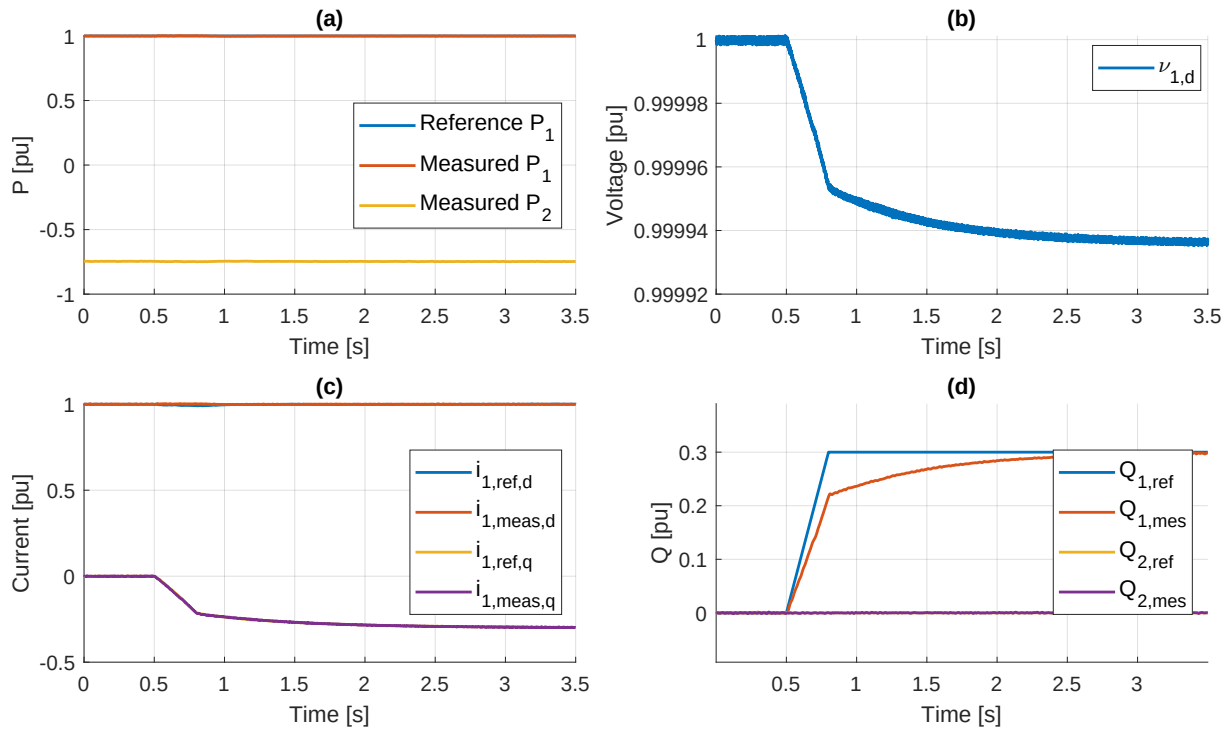


Figure 3.7 Transient response to reactive power variations

Fig. 3.7(c) shows that only the q axis component of VSC1's current varies with the reactive power showing the decoupling of d and q axes in the control. Moreover, Fig. 3.7(a) shows that the active power is not affected by the reactive power variations. Moreover, the step in reactive power causes a very slight drop in voltage at the point of common coupling.

3.3.4 AC Balanced Voltage Dip

A 20% balanced voltage dip is applied to AC grid 1 at time 0.5 s of duration 20 ms. The system's response is illustrated in Fig. 3.8. As shown in Fig. 3.8(a), the voltage dip causes a drop in the active power delivered by VSC1 to the DC link. To compensate for this, the d-axis component of the reference current of VSC1 increases. However, due to current saturation, the converter cannot deliver the full required current, which prevents the active power from reaching its reference value.

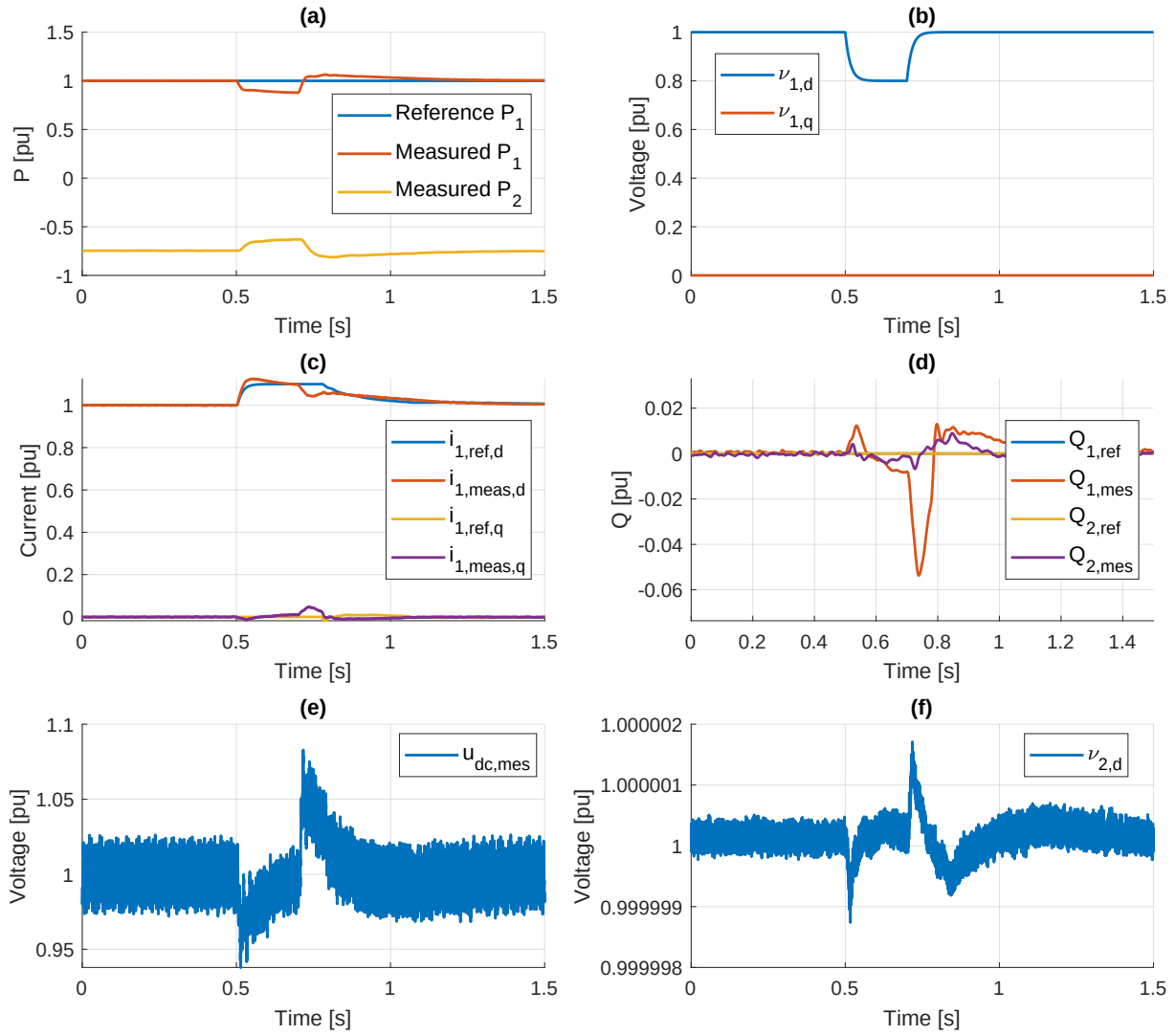


Figure 3.8 Transient response to a 20% voltage dip at AC Grid 1

Small perturbations can also be observed on the AC Grid 2 voltage, the DC link voltage and the reactive powers, however, they stabilize quickly and return close to their reference values. The voltage dip has minimal impact on them.

3.3.5 AC Fault

A three-phase balanced short circuit with fault resistance of 0.001Ω is applied at the point of common coupling with AC Grid 2 at 0.3 s and is cleared at 0.4 s. The initial state of the HVDC link is: $P_{1,ref} = 1 \text{ p.u.}$, $Q_{1,ref} = 0 = Q_{2,ref}$ and $u_{dc,ref} = 1 \text{ p.u.}$

3 | Dynamic Model of Separate Components

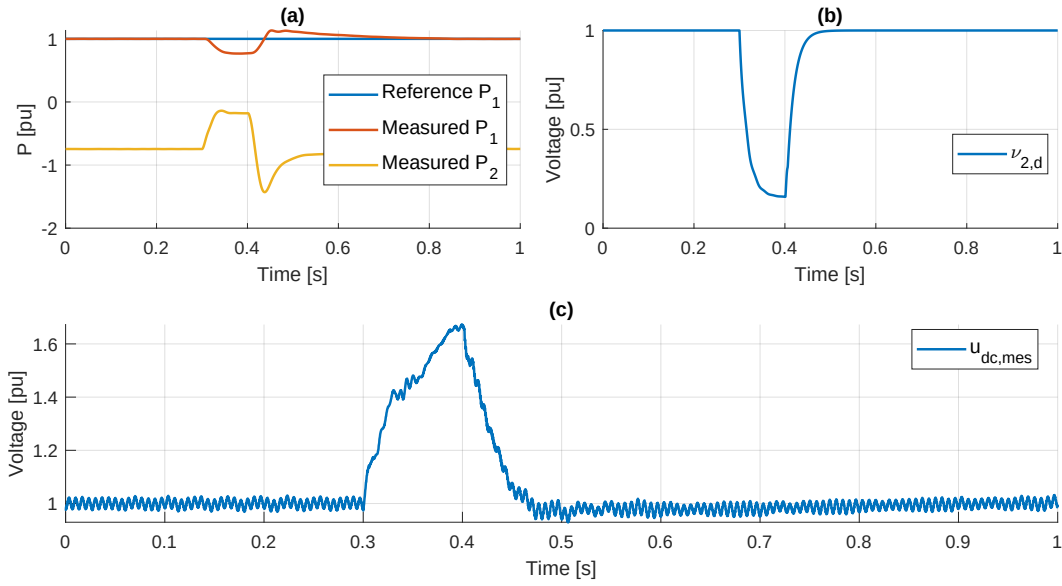


Figure 3.9 Transient response to a three-phase short circuit at the PCC with AC Grid 2

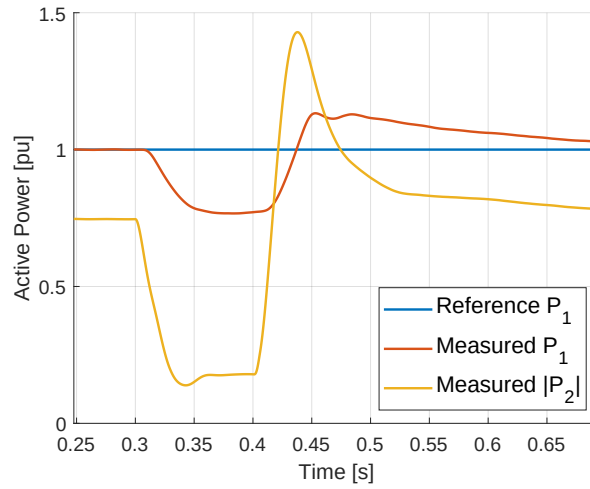


Figure 3.10 Zoom on Fig. 3.9(a)

Fig. 3.9 illustrates the system's transient response. The voltage dip causes the converter's AC side voltage $u_{2,ref}$ to drop because it is controlled in part by v_2 . This leads to a decrease of active power P_2 drawn from the DC link by VSC2 (Fig.3.10). Because VSC1 is pushing more power than what VSC2 can absorb, the DC voltage rises. Indeed, looking at the DC capacitor energy balance

$$\frac{d}{dt} \left(\frac{1}{2} C u_{dc}^2 \right) = P_{in} - P_{out}$$

with $P_{in} = P_1$, $P_{out} = P_2 + P_{losses}$, if $P_{in} > P_{out}$

$$\frac{du_{dc}}{dt} > 0.$$

The rise of u_{dc} leads to a reduction of active power sent by VSC1 into the DC link. DC overvoltage can damage the cable's insulation and the converters, which is why during such faults the HVDC link should be disconnected.

3.4 Wind Farm Model

3.4.1 DFIG Wind Turbine Model

A DFIG wind turbine has been modelled in *MATLAB Simulink*. The model is greatly inspired by the reference book *Power Electronics for Renewable Energy Systems, Transportation and Industrial Applications* [9], as well as the corresponding video tutorial by Prof. Gonzalo Abad from Mondragon University [44].

The implemented wind turbine has a nominal power of 2 MW as it uses the same parameters as in [44]. The wind turbines to be built in the Princess Elisabeth Zone are most probably state-of-the-art offshore wind turbines, typically reaching 15 MW rated power. However, no detailed data could be found concerning the mechanical and electrical parameters of such wind turbines. The use of 2 MW wind turbines in the developed model is not problematic as the wind turbines will be aggregated into bigger ones.

The pitch control is not implemented, neither are the cut-in and cut-out for too low and too high wind-speeds. The model must therefore only be used for wind speeds where MPPT is used (Region 2 in Fig. 2.22). For the chosen parameters this means that the maximum wind speed input is 11 m/s.

Screenshots of the model are provided at the end of this document.

Mechanical Aspect Since pitch is not implemented, C_p only depends on λ . $C_p(\lambda)$ is shown on Fig. 3.11. This relation is obtained by using the expression from Eq. 2.48 with $\beta = 0$ and the coefficients shown in Tab. 3.4.

β	k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	k_9
0	0.73	151	0.58	0.002	2.14	13.2	-18.4	-0.02	-0.003

Table 3.4 Coefficient values for $C_p(\lambda, \beta)$ (Eq. 2.48)

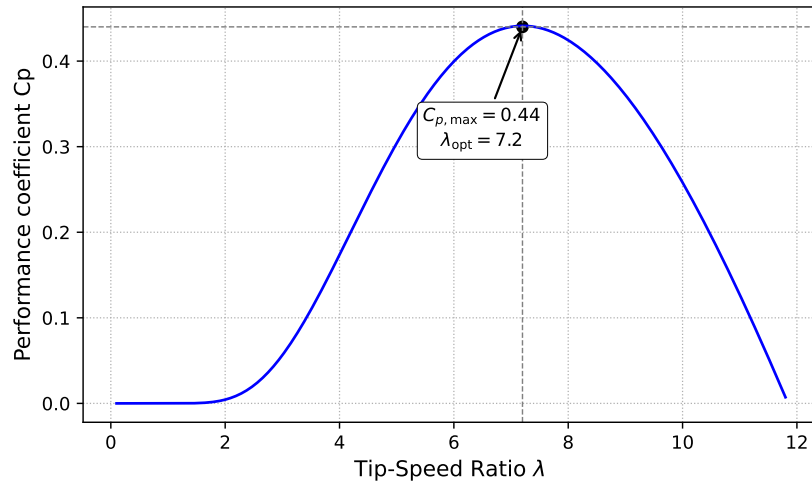


Figure 3.11 $C_p(\lambda)$

The aerodynamic model implemented in *MATLAB Simulink* is shown on Fig. 3.12. It takes as input the wind speed and determines the torque exerted on the shaft, effectively representing the behaviour of the blades. The theory behind it is explained in Sec. 2.6.2. First, the λ is computed in order to obtain the value of C_p . Then P_m and T_m can be computed using Eq. 2.46. Since the induction machine model is in motor convention, mechanical torque that produces power, as in a wind turbine generator, is therefore negative. You can also notice the factor $n_{wt,agg}$ which is required to model a wind farm. This is further explained in Sec. 3.4.3. The values used are shown in Tab. 3.5.

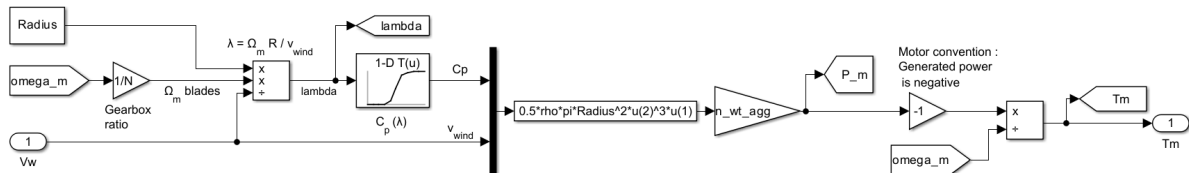


Figure 3.12 Aerodynamic model in *MATLAB Simulink*

Radius [m]	Air Density ρ_{air} [kg/m ³]	Gearbox Ratio N
42	1.225	100

Table 3.5 Values for aerodynamical model

Maximum Power Point Tracking The MPPT algorithm implemented in the Simulink model is the Optimal Torque Control Method, in its simplest form, as explained in Sec. 2.6.3. It is shown on Fig. 3.13. Once again a negative sign is used to work in motor convention and the factor $n_{wt,agg}$ is used for the aggregated wind farm model.

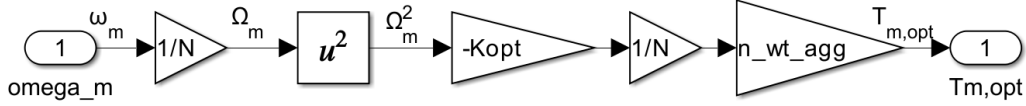


Figure 3.13 MPPT algorithm in *MATLAB Simulink*

3.4.2 Control of DFIG

The control technique implemented in the *MATLAB Simulink* model is the one explained in Sec. 2.7.3. With the presence of the HVAC link, the AC grid of the energy island is connected to the European grid. The wind turbine has thus access to a grid and the control technique is grid following. This is in opposition to a grid-forming control.

At the rotor-side converter, reactive power control has not been implemented, and the reference current i_{dr}^{ref} is set to zero. On the other hand, the grid-side controller is implemented exactly as explained in Sec. 2.7.3.

V_{bus} is set at 3450 kV, which corresponds to a modulation index $m = 0.98$ (Eq. 2.23).

Similarly to the control of the HVDC link, the atan2 function is used for the synchronization in the DFIG controllers, as explained in Sec. 3.2.4.

3.4.3 Wind Farm Aggregated Model

For simplicity, a full aggregated model (Sec. 2.8.2) was initially chosen to model the wind park in the *MATLAB Simulink* model. The number of wind turbines in the aggregated model can be chosen by setting the parameter $n_{wt,agg}$. This parameter increases the values of power, torque and currents of the equivalent wind turbine. The values of speed (wind and rotation) and voltages are then unchanged. In consequence, the values of impedances are decreased by the factor $n_{wt,agg}$. The values of the control constants are also adapted to stay coherent.

When running simulations, it showed that the model implemented in *MATLAB Simulink* performed poorly for a high number of wind turbines ($n_{wt,agg} > 200$), leading to the decision to model the wind park using multiple smaller, equivalent wind turbines. The aggregate wind park model is thus composed of 11 equivalent wind turbines each representing 150 2 MW turbines resulting in a total of 3.3 GW. In the Princess Elisabeth project, the wind park was originally planned to have a capacity of 3.5 GW. However, with ongoing changes to the project due to cost increases, it is uncertain what will actually be built, thus it is not essential that the modelled park matches the exact capacity.

3.5 Steady-State Analysis of the Wind Turbine Model

A steady-state analysis at different wind speeds has been conducted on the *MATLAB Simulink* 2MW wind turbine model. The power at different points of the wind turbine has been measured. Fig. 3.14 shows the results and compares them to the theoretical expected values.

The mechanical power is computed by the aerodynamic model while the stator and rotor powers are measured at the connection of the grid with respectively the stator and the grid-side converter. It can be seen that the measured values follow closely the theoretical values, which is a first step in the validation of the model. The power delivered to grid $P_{out} \approx P_s + P_r$ is not plotted. It follows the mechanical power $P_{out} = \eta P_m$ with an electromechanical efficiency $\eta \approx 97 - 98\%$. Note that the delivered power $P_{out} = \eta P_m$ does not follow a classical wind turbine power curve, but is purely cubic. This is because our model does not implement pitch control nor cut-in and cut-out.

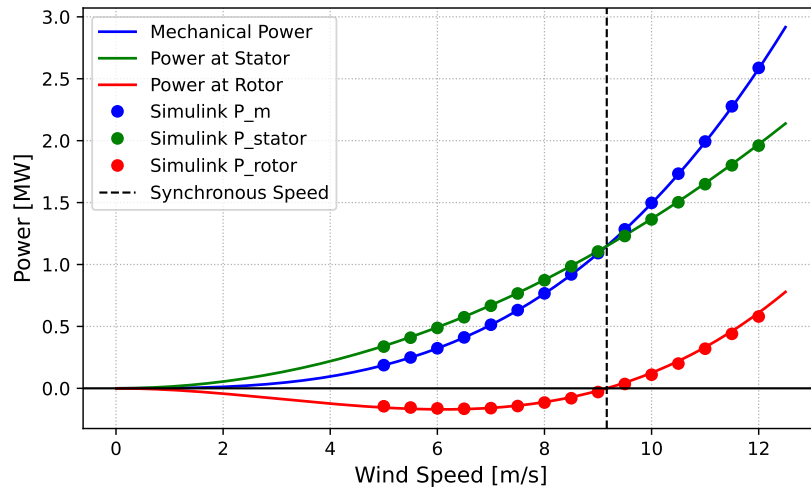


Figure 3.14 Steady-state power in function of wind speed (Theoretical + Simulink results)

Induction Machine The induction machine is implemented using a *MATLAB Simulink* model. The parameters of the induction machine are shown in Tab. 3.6.

Parameter	Symbol	Value
Rated power	P_{rated}	2 MW
Rated frequency	f	50 Hz
Rated stator voltage	V_s	690 V
Number of pair of poles	p	2
Stator/rotor turns ratio	u	1/3
Stator resistance	R_s	2.6 m Ω
Stator leakage inductance	$L_{\sigma s}$	0.087 mH
Rotor resistance (stator referred)	R_r	2.9 m Ω
Rotor leakage inductance (stator referred)	$L_{\sigma r}$	0.087 mH
Mutual inductance	L_m	2.5 mH
Inertia	J	127 kg.m ²

Table 3.6 Parameters of the Induction Machine - 2 MW Wind Turbine

3.6 Wind Farm Model Validation

The model has been implemented and tested in *MATLAB Simulink* software. First, a single 2MW wind turbine is connected to an ideal source. Then the same test is reproduced for the aggregated wind farm model and finally a 10 km undersea cable is added between the wind farm and the energy island (modeled as an ideal source). The wind turbine start-up is not modeled properly. Simulation results start from a steady-state.

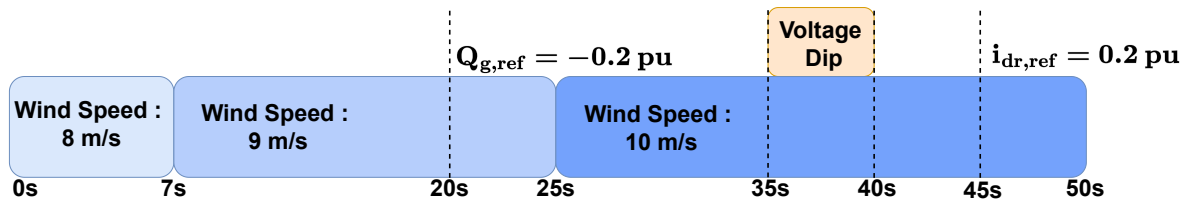


Figure 3.15 DFIG model test procedure

The test procedure is schematically represented on Fig. 3.15. The simulation starts at an initial steady-state for a wind speed of 8 m/s with the references for Q_g and i_{dr} at 0. At $t = 7$ s, wind speed increases to 9 m/s. At $t = 20$ s, the reference for reactive power is set to -0.2 pu. The wind turbine generator is asked to absorb reactive power in order to compensate the reactive power produced in the cable, the latter being mainly capacitive. At $t = 25$ s, wind speed increases to 10 m/s. At $t = 35$ s, the grid voltage drops to 0.8 pu for 0.3 s. Starting from $t = 35.3$ s the voltage dip is at 0.9 pu and is finally restored at $t = 40$ s. Finally, at $t = 45$ s, the reference value for i_{dr} is set at 0.2 pu.

3.6.1 2 MW Wind Turbine

The main electrical and mechanical quantities are plotted on Fig. 3.16.

Power and modes of operation

Fig. 3.16a shows the wind speed which was imposed for this simulation. When a change in wind speed happens, the active power reaches a new steady-state within a few seconds. The response speed is limited by the inertia of the wind turbine, as explained in Sec. 2.6.3. The rotor rotation speed (Fig. 3.16e) always tends towards the optimal rotation speed, which is computed by the MPPT algorithm within the rotor-side controller. The Tip-Speed Ratio (Fig. 3.16g) always tends towards its optimal value $\lambda_{opt} = 7.2$. The MPPT computes $T_{m,opt}$ and imposes $T_r = T_{m,opt}$. The reference on electromagnetic torque is expressed into a reference for the quadrature component of the rotor current (Eq. 2.51). i_{qr} is directly proportional to the torque and is shown on Fig. 3.16f. Notice how $i_{qr,ref}$ does not instantaneously reach the new steady-state value. Instead it follows a first-order response, which is due to the chosen MPPT algorithm i.e. Optimal Torque Control.

Due to the increasing wind speed, the induction machine, which is initially in subsynchronous operation, switches into hypersynchronous operation. Fig. 3.17 zooms on this instant. According to the relation $\omega_r = \omega_s - p\omega_m$ (Eq. 2.57), the rotor current has its frequency changing sign when passing synchronous speed. This can clearly be seen on Fig. 3.17b.

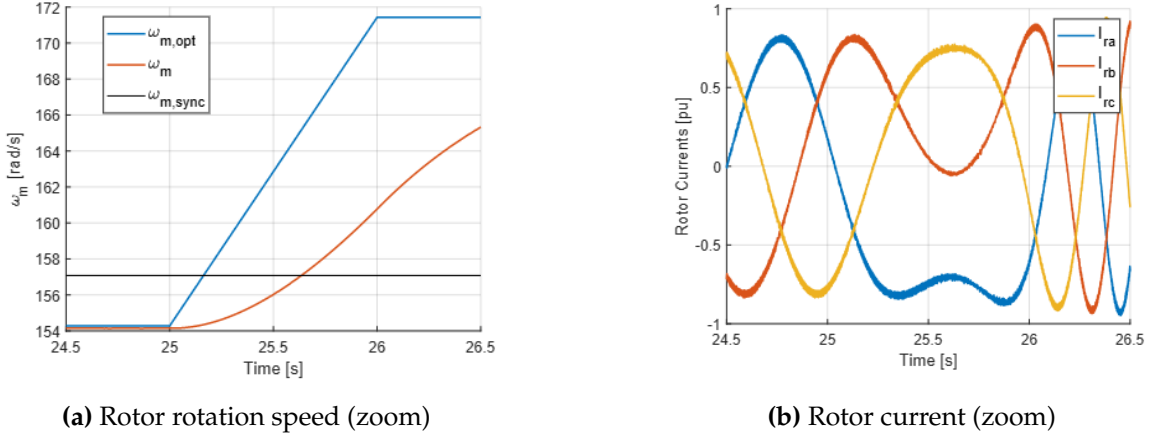
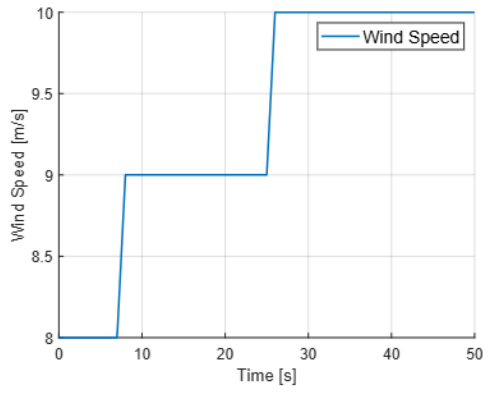


Figure 3.17 From subsynchronous to hypersynchronous

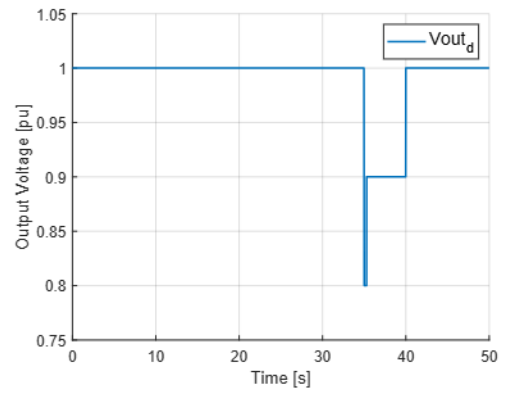
Reactive Power Control

The reference of reactive power is set to -0.2 p.u. at $t = 20$ s. From Fig. 3.16d it can be seen that the reactive power follows correctly the reference. The reactive power controller works as intended. A reference for reactive power is expressed into a reference for the quadrature component of the current at the grid-side converter. i_{qg} is shown on Fig. 3.18.

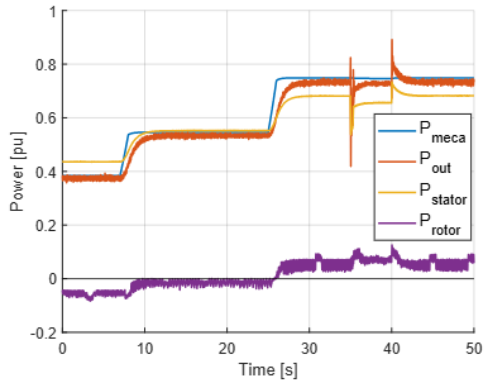
The change in reactive power does not affect the other quantities, clearly showing that the direct and quadrature component of the currents can be controlled independently.



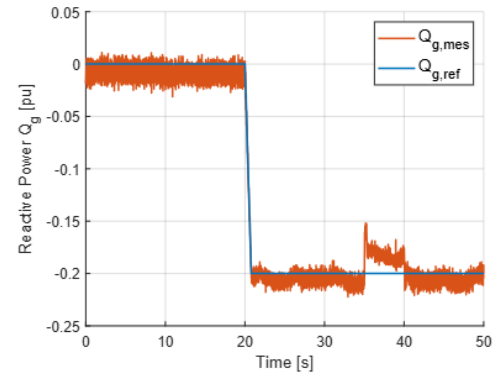
(a) Wind Speed



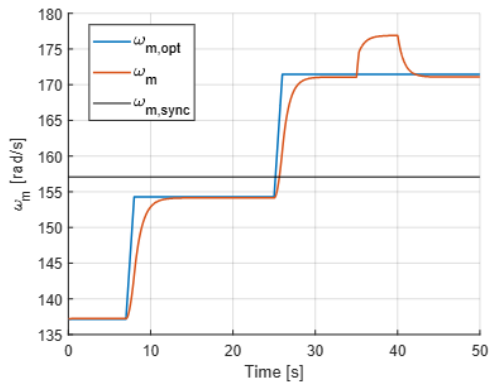
(b) Stator Voltage (d-axis)



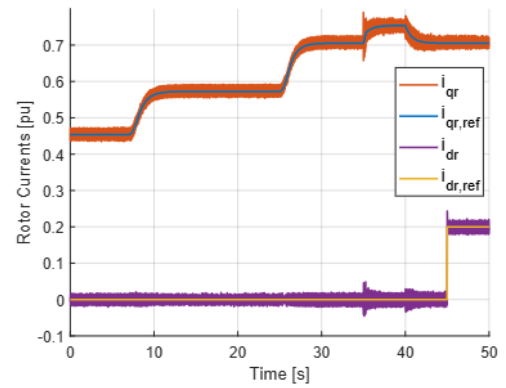
(c) Active Power



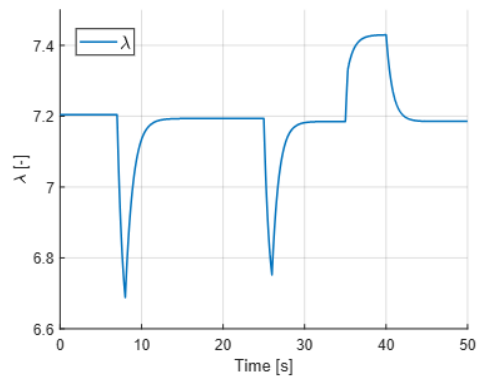
(d) Reactive Power



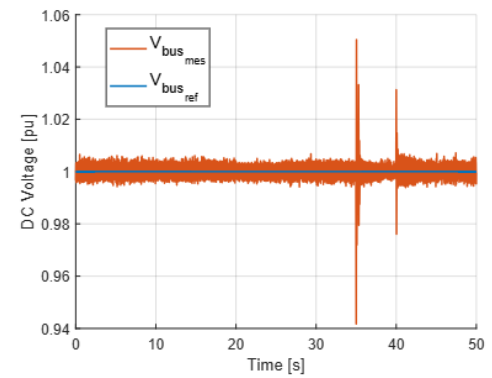
(e) Rotor Rotation Speed



(f) Rotor Currents



(g) Tip Speed Ratio



(h) DC Voltage

Figure 3.16 MATLAB Simulink 2MW wind turbine test simulation

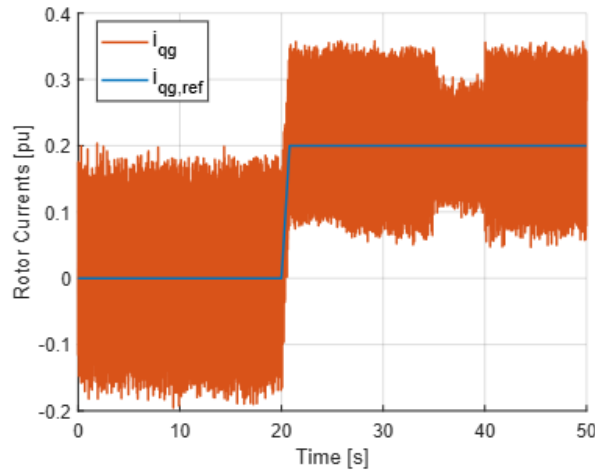


Figure 3.18 Quadrature component of the current at the grid-side converter

I_{dr} **Control**

The rotorside converter can control the direct current component of the rotor currents. This is shown on Fig. 3.16f. At time $t = 45$ s the reference for i_{dr} is changed to 0.2 pu. The actual value follows swiftly the reference, showing that the controller works as intended.

V_{dc} **Control**

The gridside converter controls the DC bus voltage. This is shown on Fig. 3.16h. The actual value stays close to the nominal value, showing that the controller works as intended.

Voltage dip

Fig. 3.16b shows the grid voltage that was imposed for this simulation. There is a voltage dip starting at $t = 35$ s. The voltage dip impacts many quantities. Due to a reduced voltage, the power delivered to the grid is reduced. As a consequence the wind turbine turns faster. The absolute amount of reactive power is also reduced.

3.6.2 300 MW Wind Farm

The same procedure is applied to the aggregated model of 150 2MW wind turbines. The results are very similar to the case of a single 2MW wind turbine, which validates the aggregation model. The results are not shown in this thesis.

3.6.3 300 MW Wind Farm with 10 km AC Cable

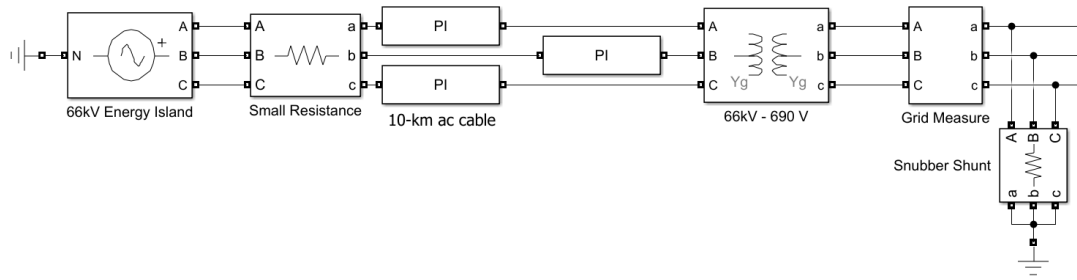


Figure 3.19 10 km AC connection

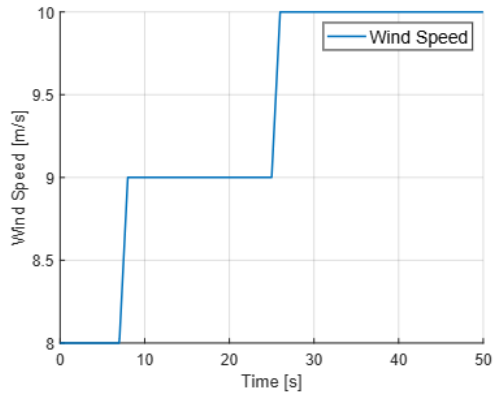
In a next step to modelling the global Princess Elisabeth Island system, a 10 km long cable is added to the output of the wind park. This models the connection of the wind turbines to the energy island, which is done in AC at 66 kV. Depending on the wind turbine, the real distance varies between 4 and 19 km [5]. For simplicity, the distance is taken equal to 10 km for all wind parks in the developed model. The cable is modelled using a pi-section, as explained in Sec. 3.1, with the parameters from Tab. 3.2 in Sec. 3.1.2, which are modified to correspond to an equivalent 300 MW wind turbine using Eq. 3.1.

Adding a cable in *MATLAB Simulink* is not so straightforward. Firstly, the addition of the 66kV/690V transformer causes trouble. The DFIG model is not connected to an ideal voltage source but to a transformer, which is modelled as an inductance by *MATLAB Simulink*. The outputs of the DFIG are the stator windings of the induction machine, modelled as an inductance in the *MATLAB Simulink* block, and the grid filter transformer which is once again equivalent to an inductance. A node where all connectors are inductances creates unsolvability for *MATLAB Simulink*. To solve this issue, a snubber shunt, consisting of a high value resistance, is added to the node.

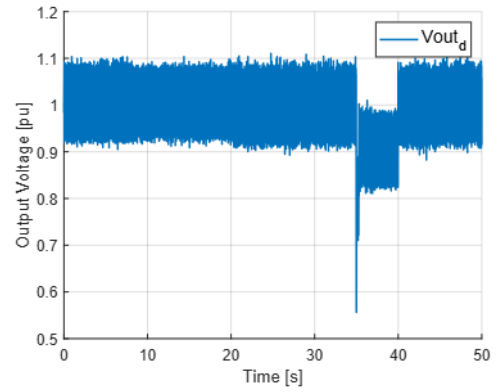
In a similar way, the ideal voltage source cannot be connected directly on the capacitance present in the PI section model. To solve this issue, a small resistance is added between the source and the cable.

Once again, the same test procedure as described in Sec. 3.6 is applied on this model. The results are shown on Fig. 3.20. The main difference lies in the voltage at the machine output, which shows important oscillations (3.20b). The AC voltage generated by the grid-side converter is not perfectly sinusoidal, but contains lot of harmonics. Since the DFIG is not connected to an ideal voltage source anymore due to the addition of the cable, impurities of the grid-side converter affect the DFIG output voltage. This negatively impacts the overall operation of the DFIG. All electrical quantities show bigger oscillations compared to Sec. 3.6.1, but more importantly, the active power output is reduced. The electromechanical efficiency is reduced to approximately 93%, while the previous measures with ideal source showed an efficiency of $\eta \approx 97 - 98\%$ (Sec. 3.5). This demonstrates the importance of using filters for the AC/DC converters. Such filters are however not implemented in our model.

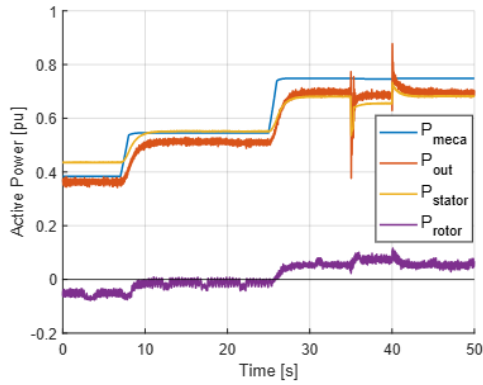
3 | Dynamic Model of Separate Components



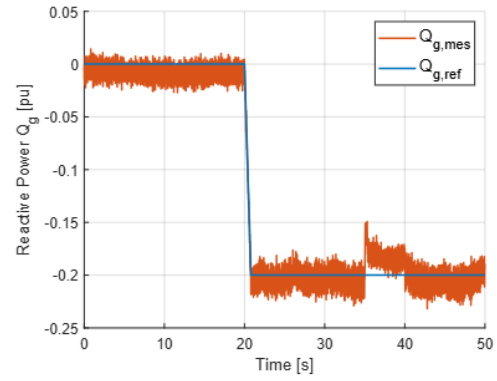
(a) Wind Speed



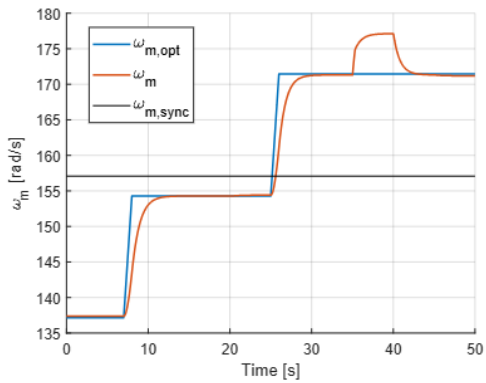
(b) Stator Voltage (d-axis)



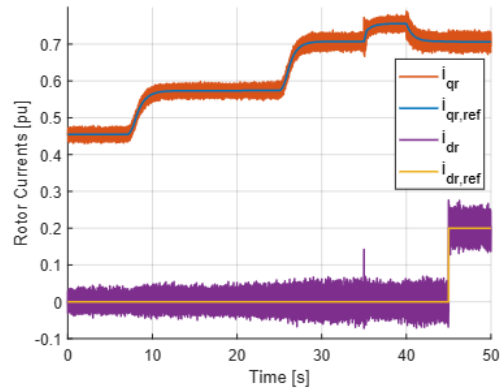
(c) Active Power



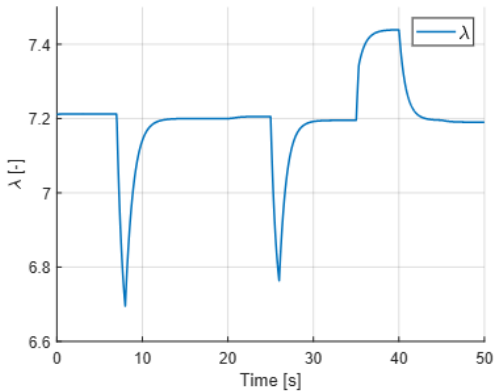
(d) Reactive Power



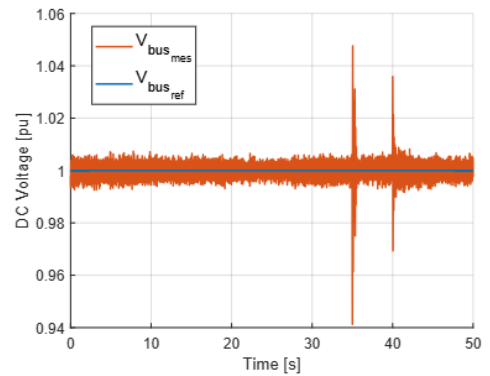
(e) Rotor Rotation Speed



(f) Rotor Currents



(g) Tip Speed Ratio



(h) DC Voltage

Figure 3.20 MATLAB Simulink 300MW wind turbine + 10km AC connection test simulation

3.7 Power Dispatch

Since active and reactive power can be controlled at the DC link, it is necessary to implement a power dispatch controller. Its role is to set the references for the DC link converters in order to efficiently dispatch the power either through the DC link or the AC link. The active power dispatch controller implemented in this model is the one designed in [5]. However, no reactive power dispatch controller has yet been implemented.

The goal of the controller is to minimize active power losses during transmission. Using the loss models of both AC and DC paths, it has been found that the best strategy is to prioritize the HVDC link up to its rated power. Once the DC capacity is fully utilized, any additional active power is dispatched through the AC link.

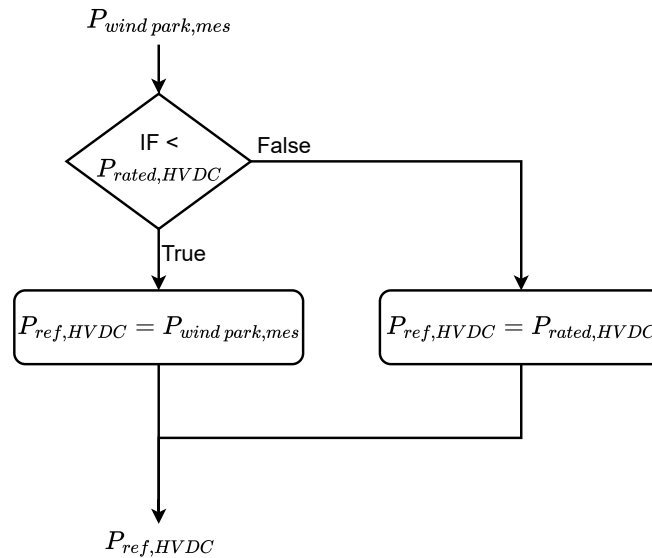


Figure 3.21 Active power dispatch controller.

Complete Model : Simulations and Results

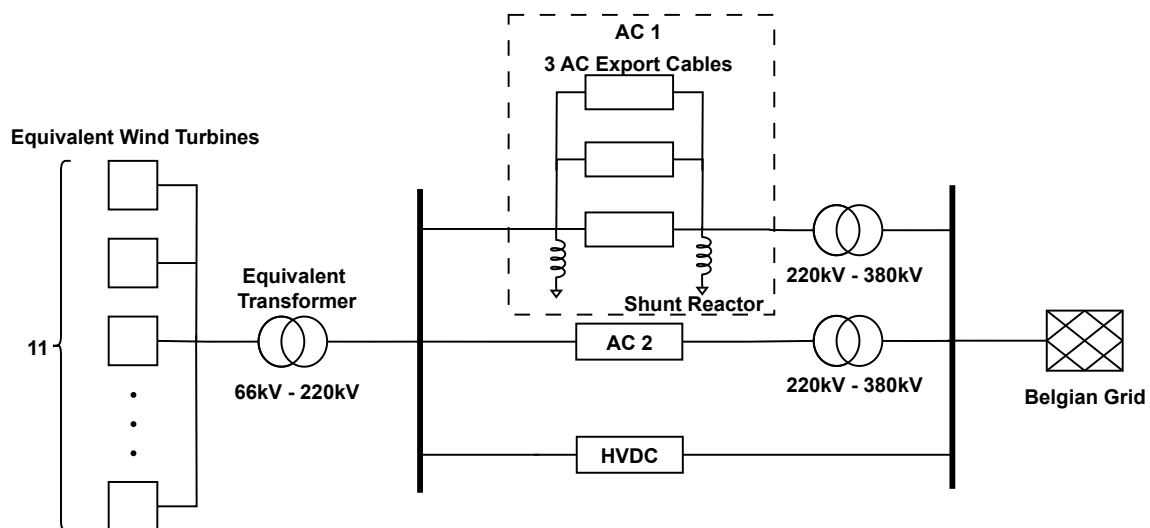


Figure 4.1 Single line diagram of the complete model

This chapter presents the complete model implemented in *MATLAB Simulink* along with its simulation results. Figure 4.1 shows the single-line diagram of the overall system. The HVDC link is represented here as a single block, while its detailed model was already presented in Figure 3.3. The wind farm is modelled by 11 equivalent wind turbines, each with a rated power of 300 MW. The total rated power of the wind farm is therefore 3.3 GW.

The presence of 11 DFIG models is not ideal as it adds a lot of complexity to the solving of the complete model in *MATLAB Simulink*. This heavy computation would often lead to *MATLAB* crashing. In consequence, only short simulations were carried out.

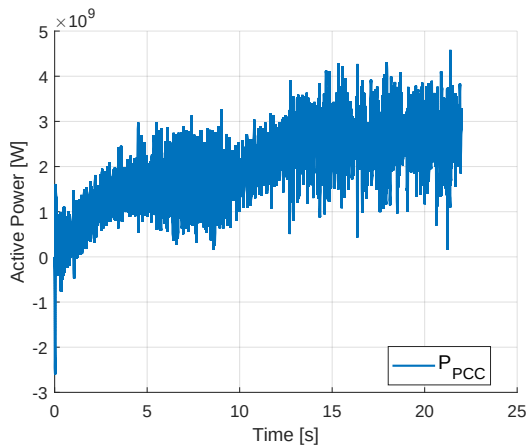
The simulation performed on the complete model consists solely of an increase of the wind speed, shown on Fig. 4.3d. Initially the wind speed is set to 9 m/s. At $t = 8$ s

the wind speed increases to 11 m/s, which corresponds to the value at which the wind turbines produce (in theory) their rated power. Note that each equivalent wind turbine could receive a different input wind speed, however for simplicity the wind speed input is the same for the 11 of them.

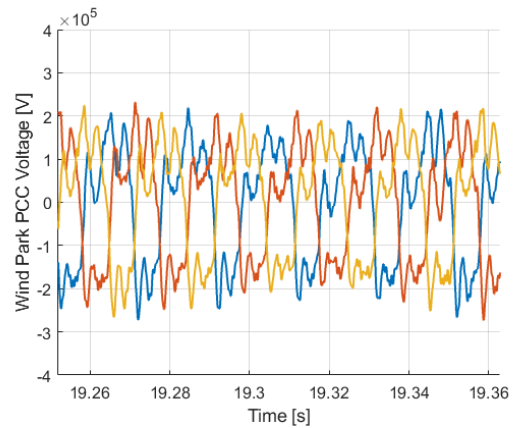
The wind turbines' output active power is maximized by the MPPT algorithm. The references for reactive power Q_g at the grid-side converter and i_{dr} at the rotor-side converter are both set to zero.

On the HVDC link, the power reference is set by the active power dispatch controller described in Sec. 3.7. The reactive power reference of the HVDC link at the windfarm side is set to 0.2 p.u. = 0.4 GW throughout the whole simulation, in order to test the proper functioning of the implemented controller. This is the only reactive power reference set to a non-zero value.

The 6 AC export cables are regrouped in two sets of 3 cables each. Each set also contains the shunt reactors described in Sec. 3.1.3. The Belgian grid is simply modelled as a 380 kV voltage source with a short-circuit power in the tens of GVA. Faults or voltage dips were not tested out due to the long duration and complexity of the simulations.



(a) Active power produced by the wind park at the PCC with the hybrid link



(b) Zoom of the voltage at the PCC of the wind park with the hybrid link

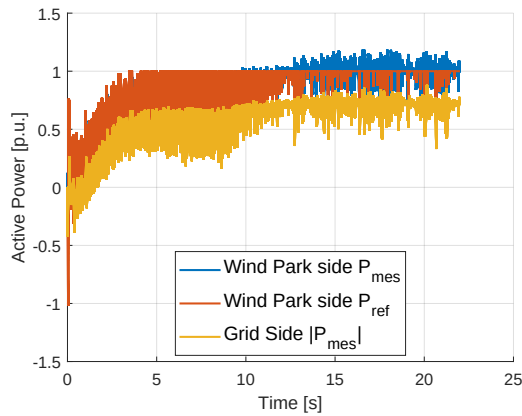
Figure 4.2 Simulation of the complete model : Wind park active power and voltage

The total active power produced by the wind park, measured at the point of common coupling with the hybrid link, is shown in Fig. 4.2a. For a wind speed of 11 m/s, the amount of power produced by the wind park oscillates considerably, with an average at 2.8 GW. This means that from the 3.3 GW mechanical power, only $\eta \approx 85\%$ is converted into electricity. The big amount of losses can be explained by the voltage quality at the PCC on the wind park. Fig. 4.2b shows that it is clearly not smooth and contains a lot of harmonics, which are caused by the AC/DC converters of the DFIGs and the HVDC link. Their impact is very noticeable due to the wind park not being connected to an 'ideal' source and the absence of filtering systems as explained in Sec. 3.6.3. The connection to the 'strong' Belgian grid is done through 45 km of AC cables at 220 kV, 10

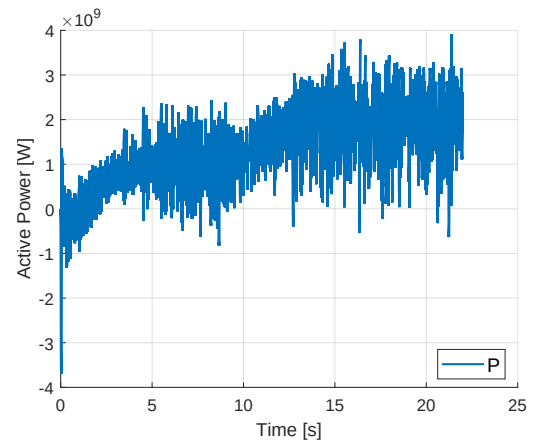
km of 66 kV AC cables as well as multiple transformers. The series impedance of these elements decreases the strength of the grid perceived at the wind turbines' output, as explained in Sec. 2.4.

Fig. 4.3 shows the active power flowing through the HVDC link and through one set of 3 AC cables. Due to the symmetry, the power in the second set of AC cables is the same as in the first set and is therefore not represented here. Fig. 4.3a clearly illustrates how the active power dispatch works: when the wind park's generated power is smaller than the HVDC rated capacity (2 GW), all of the power is transmitted through the HVDC link. Around $t = 10$ s, the power generated by the park reaches 2 GW, at which point the dispatch controller limits the HVDC link's reference to 1 p.u. and the excess power then flows through the AC lines.

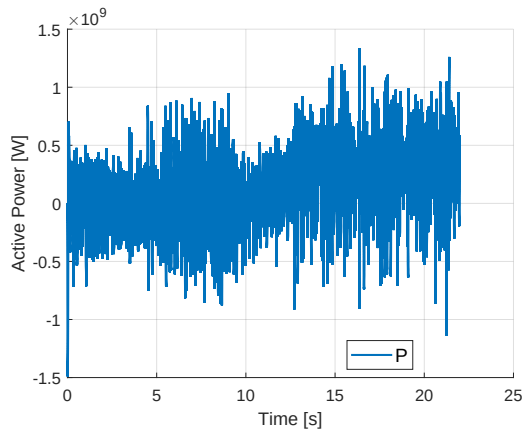
It can once again be observed that for 1 p.u. injected at the wind park side, only 0.7 p.u. is retrieved at the Belgian grid side of the HVDC link. When the wind park produces 2.8 GW (on average), the total active power transferred to the Belgian grid has an average of 2 GW. This shows a transfer efficiency of $\approx 70\%$. The losses in the AC export cables are therefore comparable to the losses in the HVDC link.



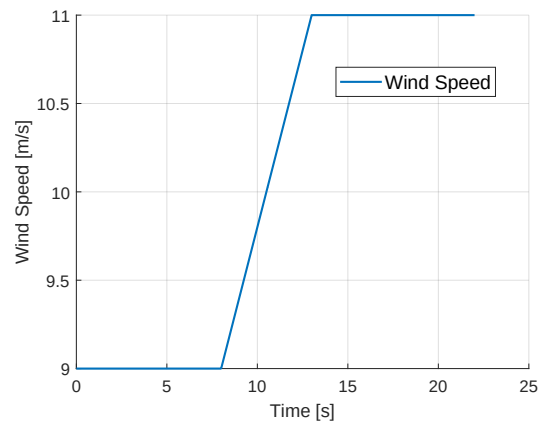
(a) Active power at both terminals of the HVDC link



(b) Active power at PCC with Belgian grid



(c) Active power in AC 1

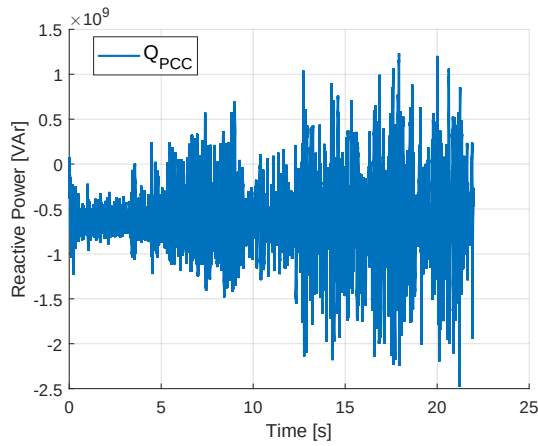


(d) Wind speed

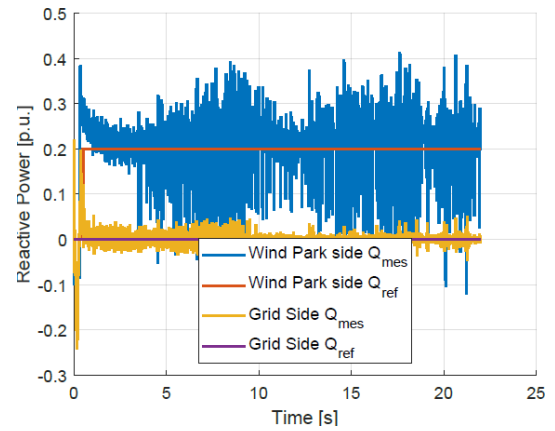
Figure 4.3 Simulation of the complete model : Active power in hybrid link

The convention used for all reactive (and active) power computations is such that current flowing from wind farm to the Belgian grid is positive. The reactive power measured at the wind farm is -0.5 GVar (Fig. 4.4a). The HVDC link also injects -0.2 p.u. = 0.4 GVar towards the energy island (Fig. 4.4b). The total reactive power in the AC cables is therefore -0.9 GVar, -0.45 GVar for each of the two sets (Fig. 4.4c). The HVDC link, by its nature, does not transport reactive power. The measured reactive power at the Belgian grid is -0.9 GVar (Fig. 4.4d), the same amount that is injected at the wind farm side. This means that the AC export cables do not generate reactive power and that the shunt reactors are well designed.

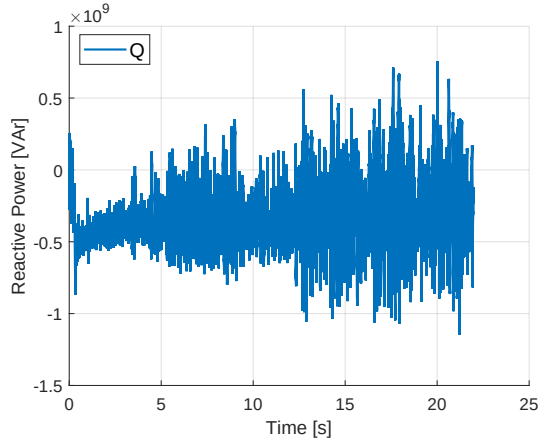
The great amount of reactive power showcases the need of developing a reactive power dispatch controller in order to reduce the reactive power in the system and to consequently reduce the power losses.



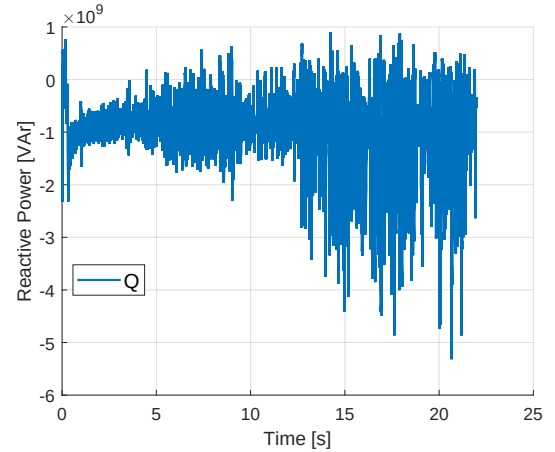
(a) Reactive power produced by the wind park at PCC with the hybrid link



(b) Reactive power at both terminals of the HVDC link



(c) Reactive power in AC 1



(d) Reactive power at PCC with Belgian grid

Figure 4.4 Simulation of the complete model : Reactive power

Conclusions and Outlooks

The main output of this thesis is the production of a model of the global electrical system of the Princess Elisabeth Island (initial) project. The system consists of a 3.5 GW wind power plant connected to the energy island. The connection to the mainland consists of a hybrid link i.e. HVDC (2 GW) and HVAC (2.1 GW). The model is capable of simulating the dynamic response of the system to different operating scenarios. It is however still a preliminary version and should be improved for more accurate results. The different components are detailed below, accompanied by some improvement proposals.

A functional 2MW DFIG wind turbine model has been developed. Simulations could attest that it functions correctly. However, in order to be able to simulate the response of the DFIG on a wider range of wind speeds, the pitch control as well as the cut-in and cut-out of the turbine should be implemented. The wind turbine parameters should also be changed to model state-of-the-art offshore wind turbines. The design of filters is also still required to make the model totally accurate.

A simple wind turbine aggregation method was chosen to represent a wind farm by an equivalent wind turbine. The proper implementation can however not be validated as it does not work for aggregating more than $n_{wt,agg} \approx 200$ wind turbines. The model should be checked to find the reasons behind this.

A functional HVDC bipolar VSC-based link has been developed. Simulation showed that it can effectively be controlled. However, the amount of conversion losses should be looked upon, as its value is surprisingly high. The filtering system should also be studied in greater detail.

The overall computation time can be reduced by for example using Average-Value Models to represent the VSCs. The enhancement of the wind turbine aggregation method and the modification of the wind turbine parameters to a higher power rated wind turbine will reduce the required amount of DFIG models to reach 3.5 GW. This

will also reduce the complexity of the solving.

A more in-depth analysis should be carried out on the reactive power flows in the system. An overall reactive power dispatch controller could be designed, as it could provide services to the grid by enhancing the voltage stability.

Additionally, the model could easily incorporate the planned HVDC connectors to the UK and Denmark, in order to analyse the power exchange between countries.

Finally, the developed model can be used to analyse the dynamic response of the system. Scenarios could consist of the disconnection of some wind turbines, a fault on one of the AC export cables or DC cable, a voltage dip at the Belgian grid, etc. The robustness of the grid could hereby be tested out.

Appendices

Simulink Screenshots

1.1 Wind Turbine

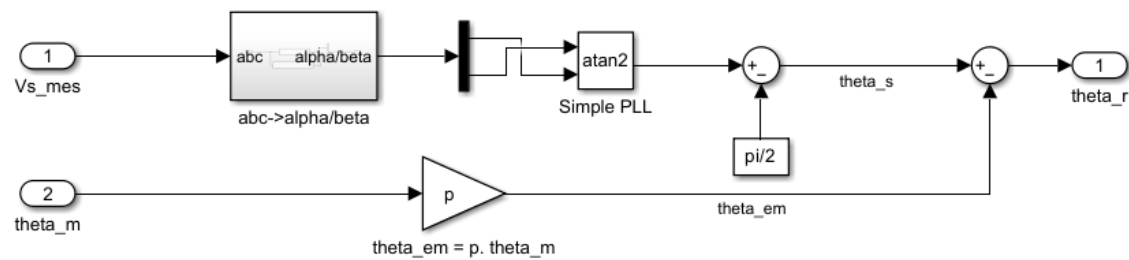


Figure A.3 Rotorside Control θ_r Computation

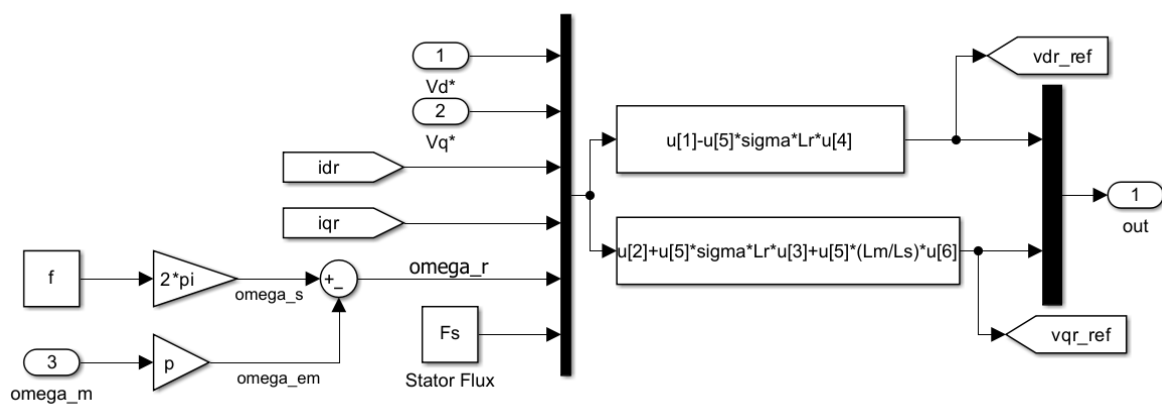


Figure A.4 Rotorside Current Control Back Compensation and Coupling Terms Cancellation

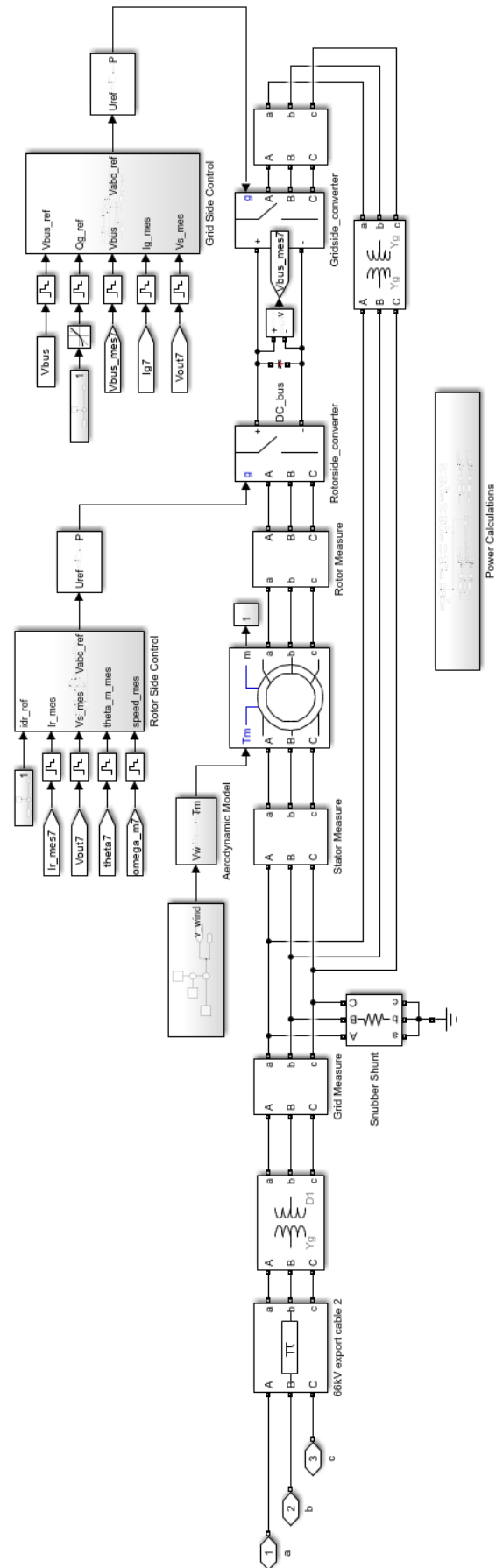


Figure A.1 Wind Turbine

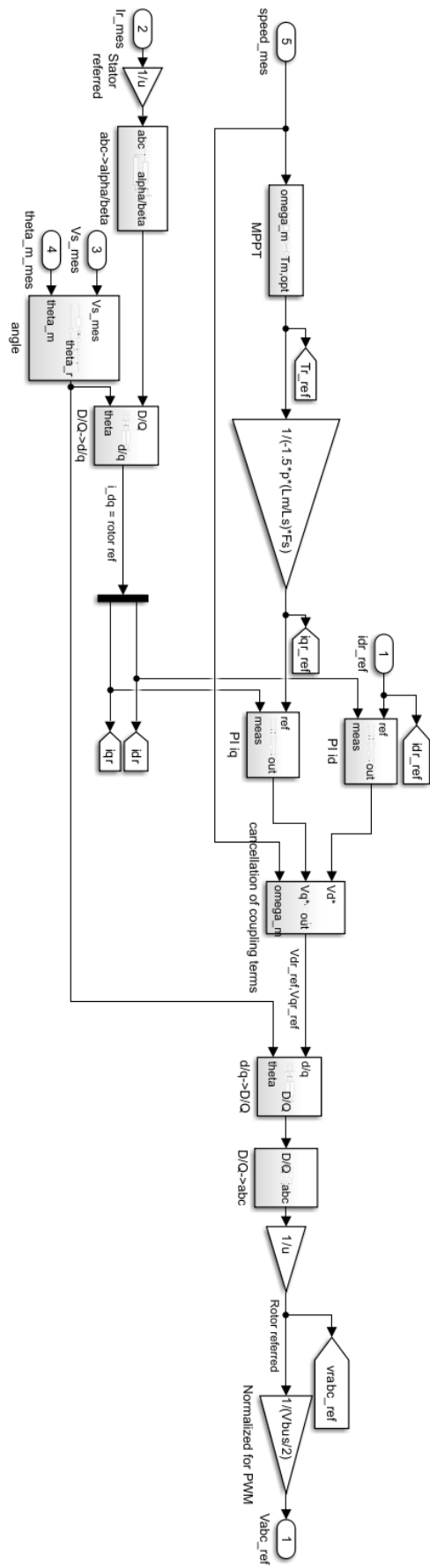


Figure A.2 Rotorside Control

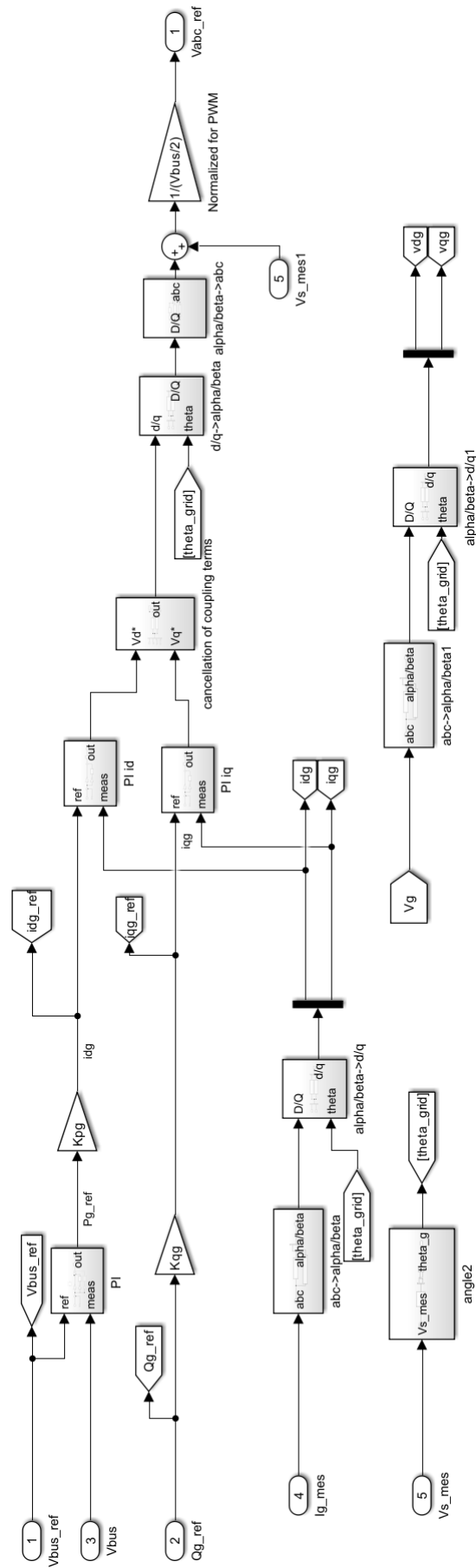


Figure A.5 Gridside Control

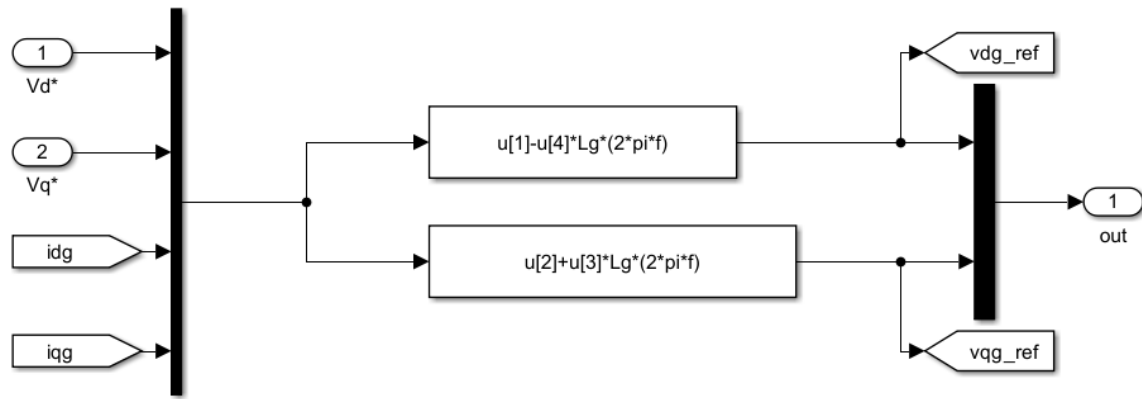


Figure A.6 Gridside Control : Cancellation of Coupling Terms

1.2 Complete Model

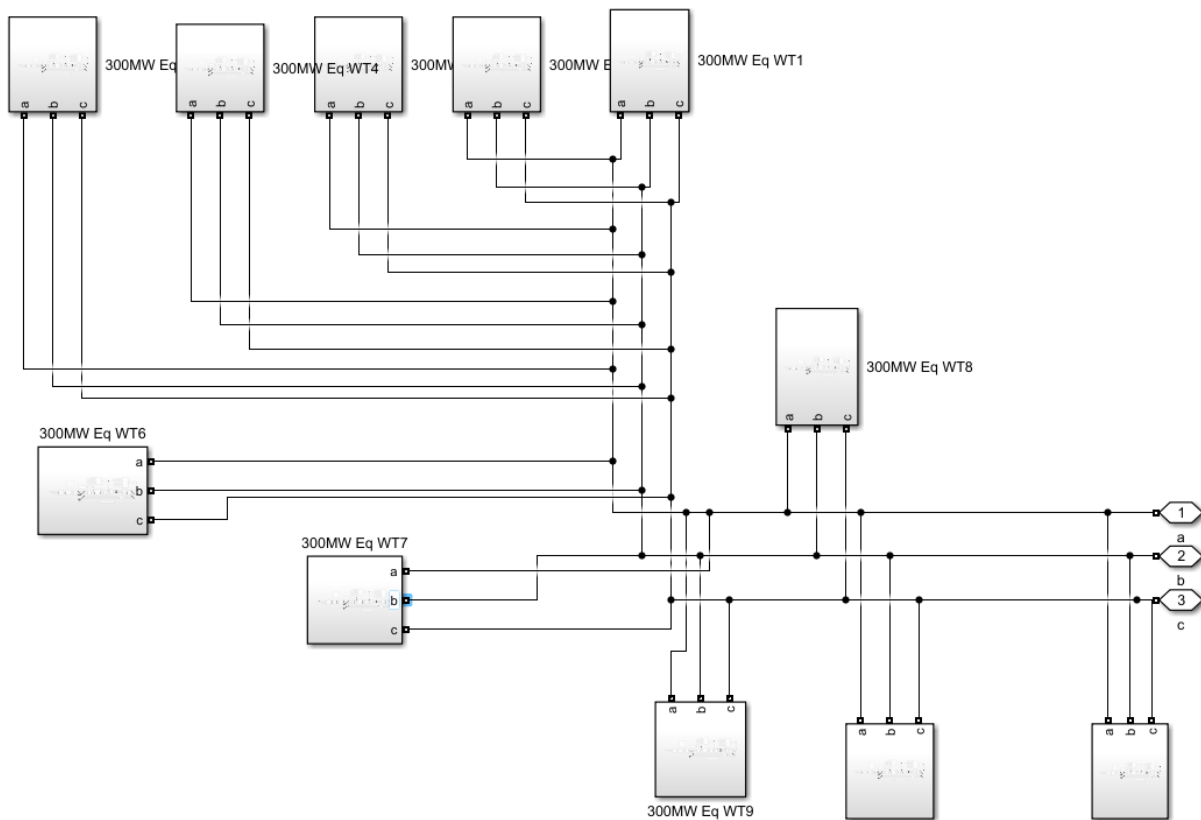


Figure A.8 Wind farm

1.3 HVDC Link

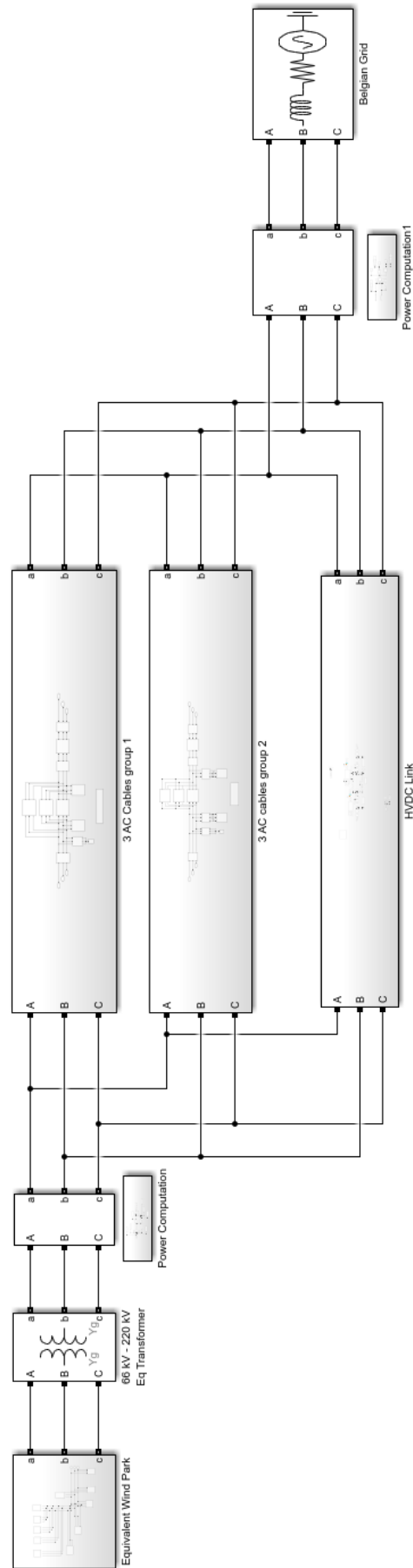


Figure A.7 Complete Model

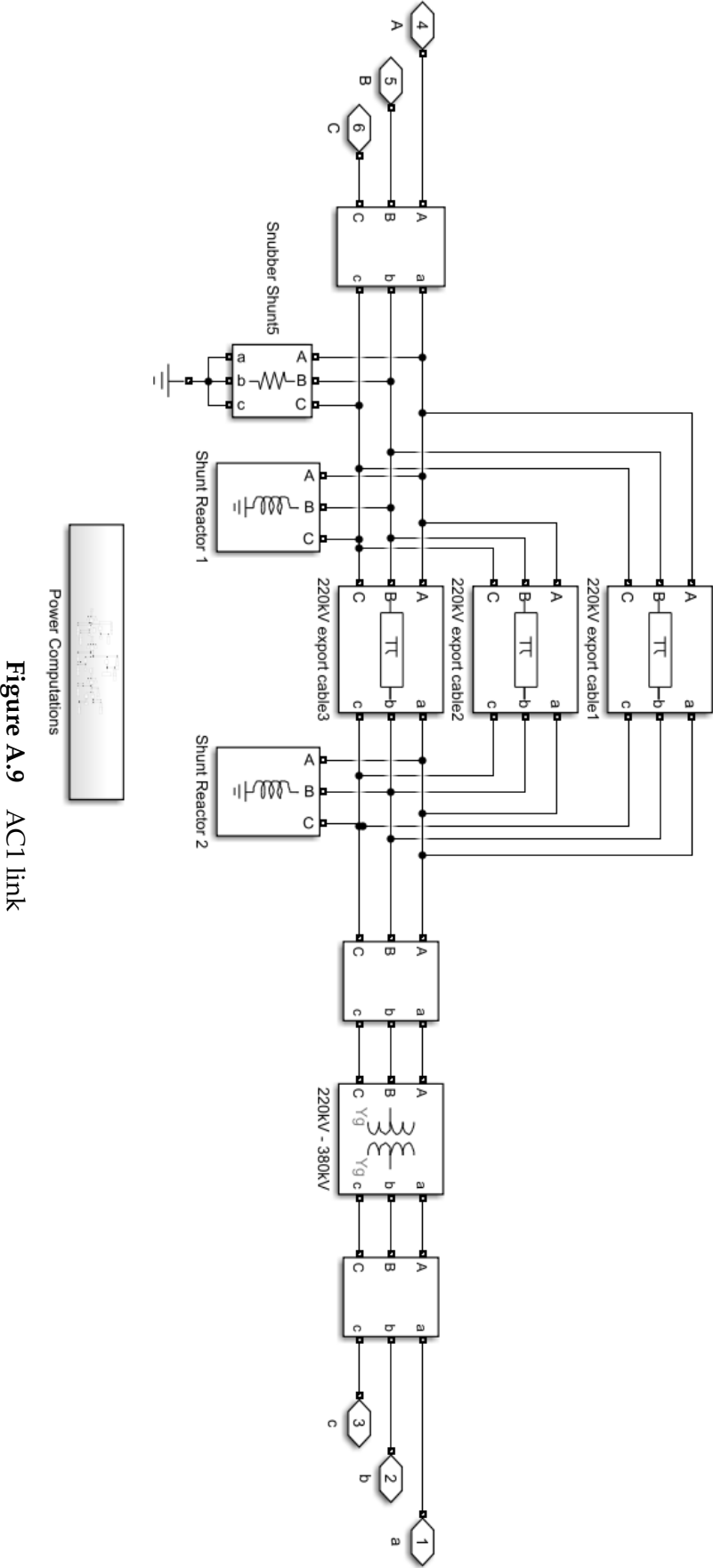


Figure A.9 AC1 link

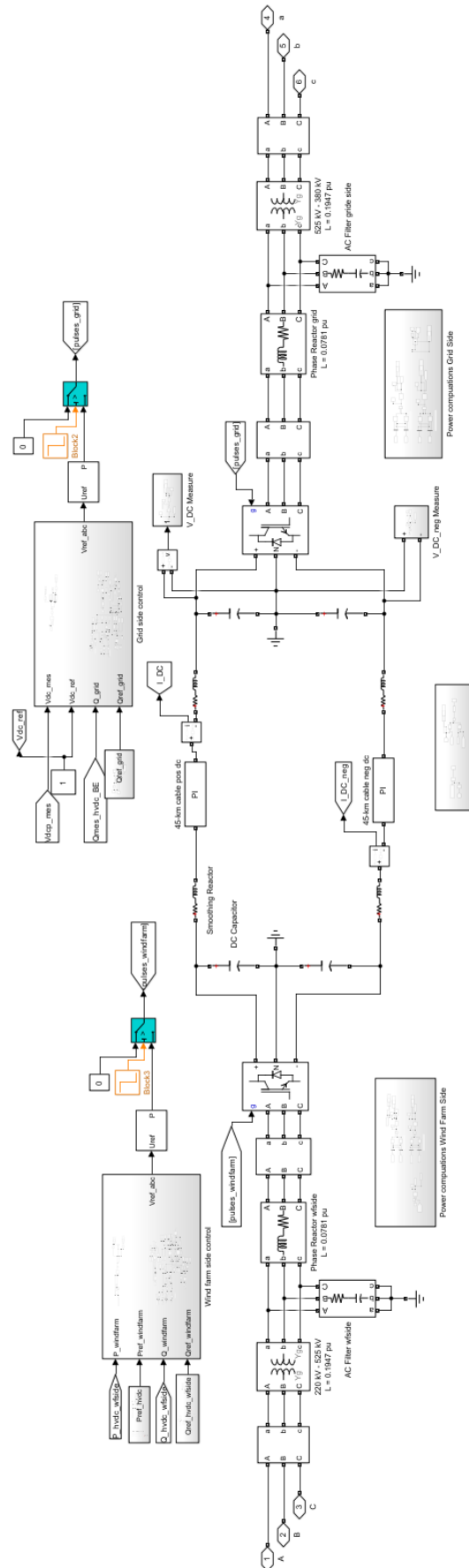


Figure A.10 HVDC link

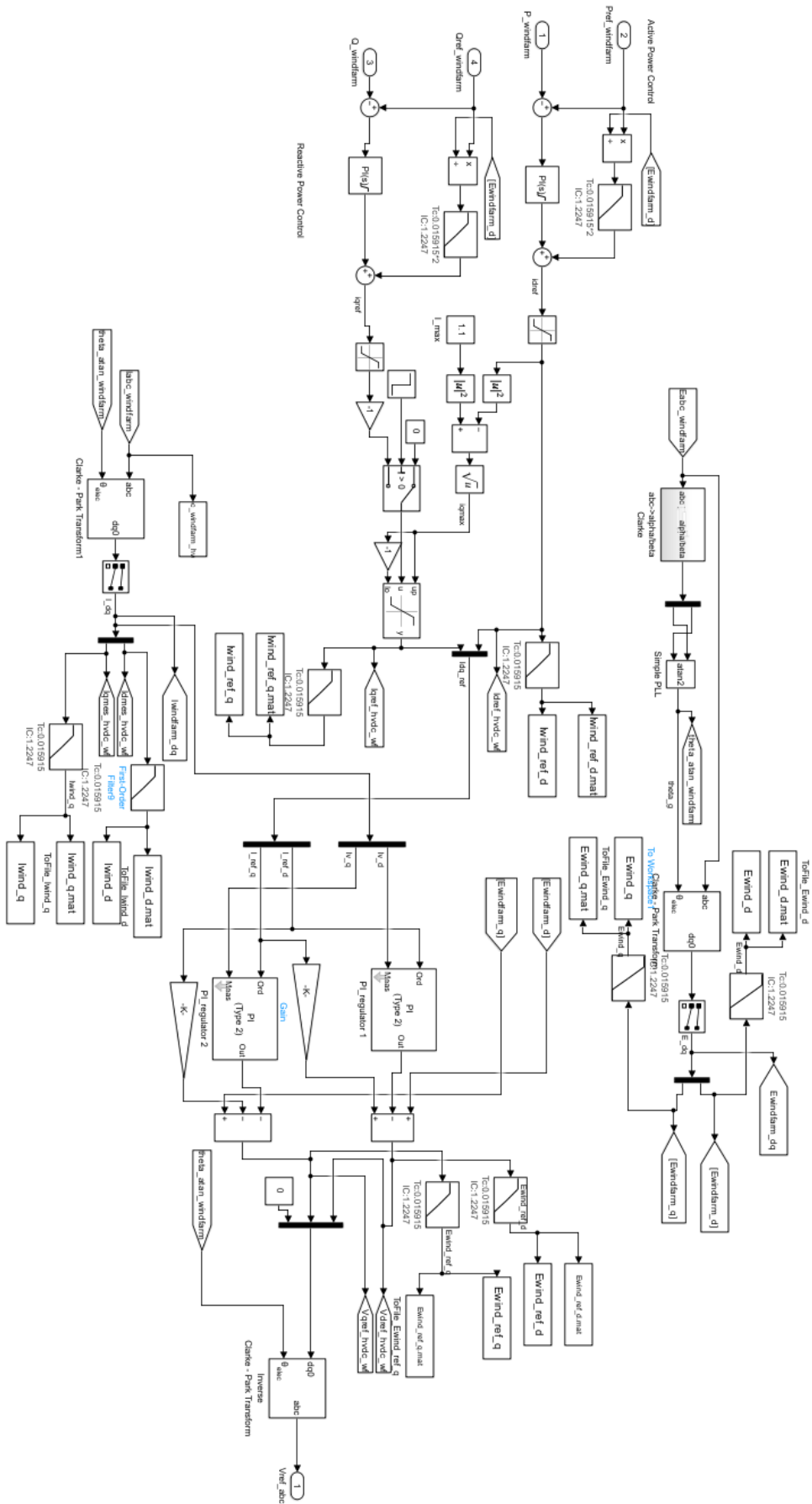


Figure A.11 HVDC link wind farm side control

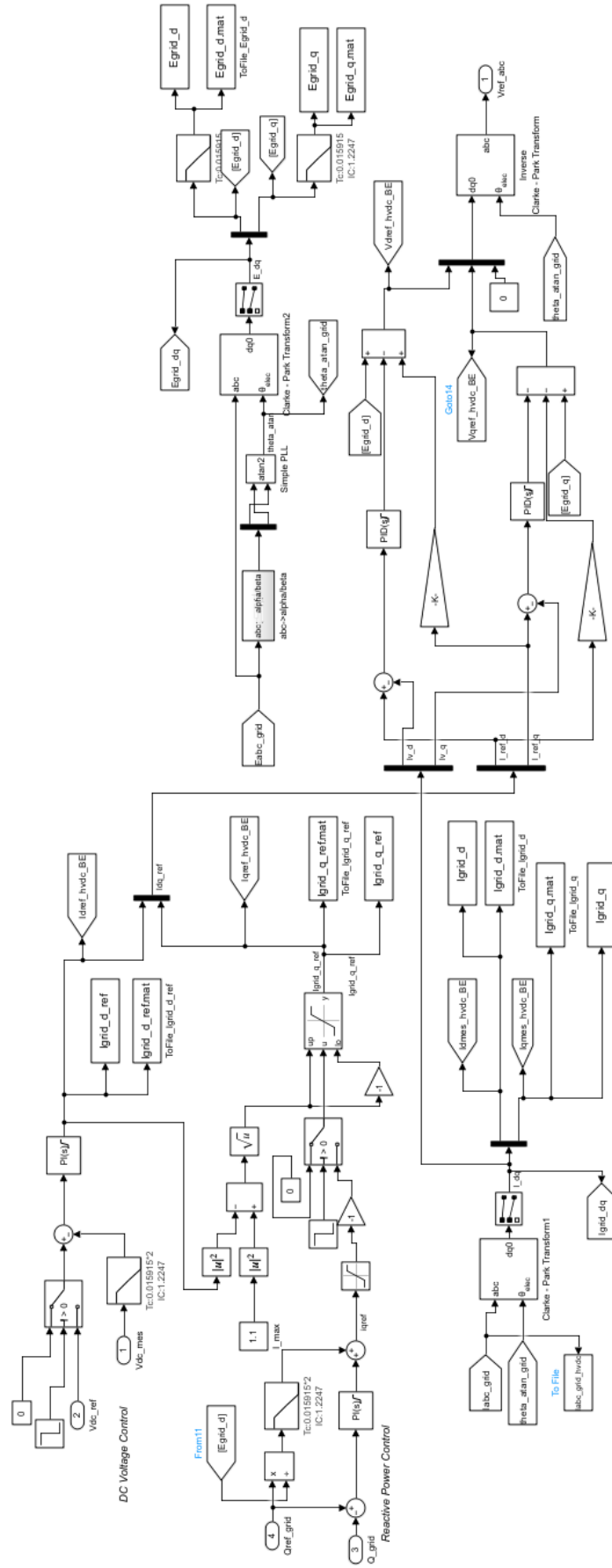


Figure A.12 HVDC link grid side control

PI Regulator Gains

2.1 DFIG Wind Turbine Controller

From [44], the rotor-side inner loop PI controller gains are expressed

$$k_{p,i_d} = 2\omega_{n,i}\sigma L_r - R_r = 0.5771 = k_{p,i_q}, \quad k_{i,i_d} = \omega_{n,i}^2 L_r \sigma = 491.59 = k_{i,i_q}, \quad (\text{B.1})$$

with k_{p,i_d} , k_{i,i_d} , k_{p,i_q} , k_{i,i_q} the proportional and integral gains of the d-axis and q-axis inner controller, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ and $\omega_{n,i} = \frac{100}{\tau_i}$ with $\tau_i = \sigma \frac{L_r}{R_r}$. The grid-side inner loop PI gains are

$$k_{p,i_d} = 2\omega_{n,i} L_g - R_g = 0.2513 = k_{p,i_q}, \quad k_{i,i_d} = \omega_{n,i}^2 L_g = 39.47 = k_{i,i_q}, \quad (\text{B.2})$$

with $\omega_{n,i} = 2\pi f$. The outer controller (DC voltage controller) PI gains are

$$k_{p,v} = -1000, \quad k_{i,v} = -300000. \quad (\text{B.3})$$

2.2 HVDC Link Controller

The proportional gain (K_p) and the integral gain (K_i) of the PI controllers were set based on [43]. First approximations of the gains were made by taking the same gains as in [43], they were then tuned by trial and error. This process lead to the following gains

- Active power controller: $K_p = 2$ p.u., $K_i = 10$ p.u.
- Reactive power controller: $K_p = 2$ p.u., $K_i = 4$ p.u.
- DC voltage controller: $K_p = 2$ p.u., $K_i = 40$ p.u.
- Inner Controller:

- d axis controller: $K_p = 0.6 \text{ p.u.}$, $K_i = 6 \text{ p.u.}$
- q axis controller: $K_p = 0.6 \text{ p.u.}$, $K_i = 6 \text{ p.u.}$

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