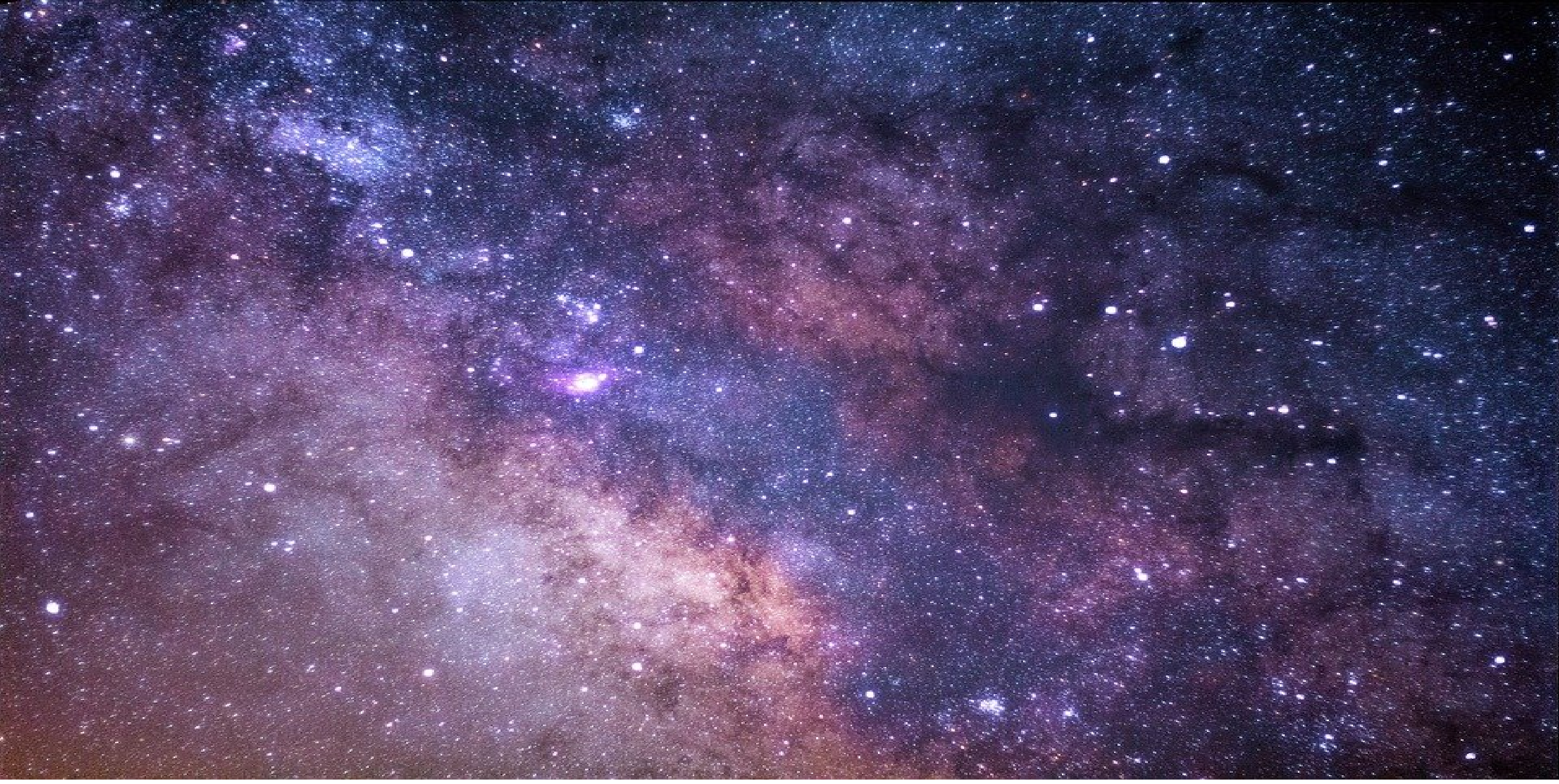

Modelling, Analysis and Control of High-Power Offshore Wind Power Converter

Yuxin Jiang

Power Electronics and Drives, PED4-1040, 2024-5 2025-5

Long Master Thesis

STUDENT REPORT

AALBORG UNIVERSITY

AALBORG UNIVERSITY
STUDENT REPORT

AAU Energy
Aalborg University
http://www.aau.dk

Title:
Modelling, Analysis and Control of High-Power Offshore Wind Power Converter

Project Period:
Autumn Semester 2023 to Spring Semester 2025

Project Group:
PED4-1040

Participant(s):
Yuxin Jiang

Supervisor(s):
Yanbo Wang

Page Numbers: 49

Date of Completion:
March 12, 2025

Abstract:

Three-level NPC converter is an important solution for converting wind energy of high power. Grid-connected control is essential to realize the control of Three-level NPC. This project aims to design and analyze a High-Power Offshore Wind Power Converter. Furthermore, grid-connected control strategy is used.

Contents

List of Acronyms

2L	Two-Level
3L	Three-Level
AC	Alternating Current
ANPC	Active Neutral Point Clamped
B2B	Back-to-Back
DC	Direct Current
DERs	Distributed Energy Resources
EJ	Exajoules
GW	Gigawatts
HVDC	High Voltage Direct Current
IEA	International Energy Agency
IES	Integrated Energy System
LVRT	Low Voltage Ride Through
MLCs	Multilevel Converters
MSC	Machine Side Converter
MPPT	Maximum Power Point Tracking
NPC	Neutral Point Clamped
P2P	Peer-to-Peer
PLL	Phase-Locked Loop
PMSG	Permanent Magnet Synchronous Generator

Pulse-Width Modulation PWM

PV Solar Photovoltaic

Space Vector PWM SVPWM

Sinusoidal PWM SPWM

THD Total Harmonic Distortion

VSC Voltage Source Converter

VSG Virtual Synchronous Generator

VPPs Virtual Power Plant

WTs Wind Turbines

Chapter 1

Introduction

In this chapter, an introduction to the project is given. The project background gives a motivation for relevance to the topic. The role of 3L-NPCs plays in an inverter system is described, while different types of 3L-NPCs are elaborated, and their performances are compared.

1.1 Project Background

Renewable energy refers to the energy sources derived from natural processes that could be continuously replenished. Nowadays renewable energy is increasing rapidly. Global installed renewable energy capacity will exceed 4,800 GW in 2023, meeting 38% of global electricity demand for the first time. The main types of today include wind power generation[1], PV power generation[2], green hydrogen energy [3] and biomass energy[4], as shown in Figure 1.1, which are to be introduced in the content below.

Figure 1.1: The Main Types of Renewable Energy-Based Power Generation. Upper Left: Wind Power Generation. Upper right: Solar PV power generation. Lower Left: Green hydrogen energy generation. Lower Right: Biomass Energy Generation.

Wind energy is a renewable energy source that converts atmospheric flow kinetic energy into electrical energy using WTs. It has some characteristics such as zero carbon emissions and wide resource distribution.
Actually, the development of WT's height and capacity over time reflects the continued advancement of technology and the growing demand for wind power energy[5]. The 1980s belong to the initial stage, WT capacity is usually 50-300 kW and the height of wheel hubs is usually 30-50 meters; the typical example is Danish V15 (55 kW). In the 1990s, the MW level breakthrough was achieved, the WT capacity was 0.5-1.5 MW, and the wheel hub height was 50-80 meters; the typical types include Vestas V44 (600 kW) and Enercon E-40 (500 kW). After the 21st century, large-scale and offshore wind power gradually started, the WT capacity can reach 2-5 MW and the wheel hub height is 80-120 meters; in addition, with the development of direct drive technology, the offshore wind power promoted the WT capacity; the typical representative of this stage is Siemens SWT-3.6-107 (3.6 MW). After 2010, wind power generation gradually developed to large-scale and intelligent, and there were 6-10 MW capacity and 100-150 meters of wheel hub height; at this stage, both carbon fiber blades and floating foundations appeared, the intelligent control optimized the efficiency, and offshore WT dominated the large-capacity market; the typical examples are Siemens Gamesa 8MWE-167 (8MW) and

MHI Vestas V164 (9.5 MW). After 2020, it belonged to an era of super-large units, and the WT had a capacity of 12-16 MW and a wheel hub height of 130-170 meters (the total height exceeded 250 meters); moreover, one single power generation can supply more than 10,000 households; the typical examples are GE Haliade-X (14 MW) and China Mingyang Smart MySE 16-260 (16 MW). Figure 1.2 shows the development of the total height and capacity of WT over time.

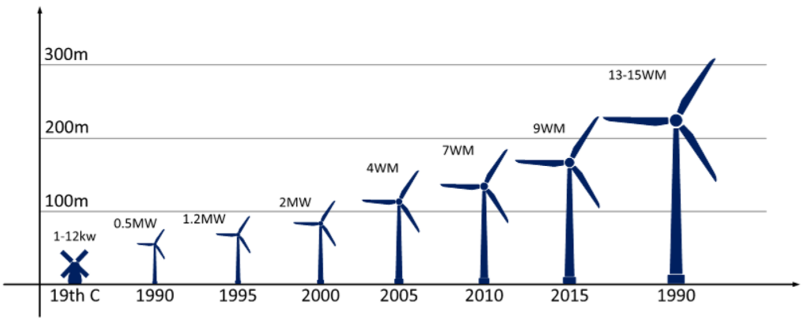

Figure 1.2: Development of the Total Height and Capacity of WT Over Time

Wind energy includes offshore and onshore wind energy. Offshore wind energy refers to a form of renewable energy that generates electricity from WTs in the marine environment[6]. Compared with onshore wind power, its wind speed is higher and more stable, and the average capacity factor can reach 50-65% (IRENA, 2024), but the construction cost and technical complexity are significantly increased.
As for the onshore wind power, its construction and operation costs are significantly lower, since there is no need for complex facilities such as submarine cables and offshore platforms. In addition, the onshore WTs are close to the load center, where the difficulty of grid connection is low and the installation cycle of a single WT is short, which is suitable for large-scale expansion. However, it has more geographical restrictions - its construction needs to avoid densely populated areas, ecological reserves, and areas with complex terrain.
To utilize wind power, a PMSG-based wind power system can be established, where an AC / DC-MSC is included, as shown in Figure 1.3, where pitch angle β of WT rotor is the only controllable variable to adjust the dynamical performance of WT.

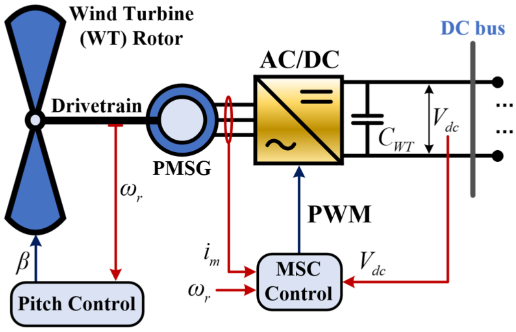

Figure 1.3: The PMSG-Based Wind Power System

1.1.1 Solar PV power generation

The PV power generation uses the PV effect of semiconductor materials (such as silicon) to directly convert solar radiation energy into electrical energy. When photons (light particles) hit the surface of a PV cell, the energy is absorbed by the semiconductor and excites electron-hole pairs, forming an electric potential difference, thereby generating direct current photovoltaic electricity. The solar energy has several advantages, including inexhaustible supply, wide distribution, zero carbon emissions, low operating costs, etc.
In order to utilize solar power energy, the PV arrays are really important, which are comprised of a huge number of PV cells, as shown in the left side of Figure 1.4, where V_{cell} is the output voltage of a PV cell. The solar PV control system is shown in the right side of Figure 1.4, where T and G are outside input ambient temperature and solar irradiance respectively which are the inputs of the module for the maximum output power.

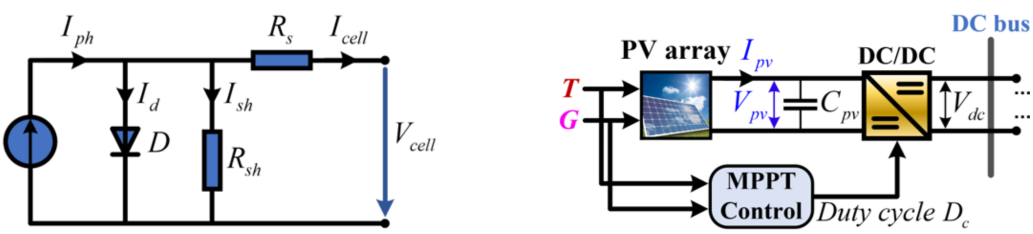

Figure 1.4: The Important Parts in Solar PV System. Left: Diagram of a Solar PV Cell. Right: Diagram of Solar PV Control System

1.1.2 Green Hydrogen Energy

Hydrogen energy has characteristics including high energy density, high calorific value, abundant reserves, wide sources, and high conversion efficiency. It is a clean secondary energy source that can be used as an efficient energy storage carrier. It can be an effective solution for large-scale cross-seasonal storage and transportation of renewable energy. Experts and scholars considered it to be one of the most promising energy sources[7]

Table 1.1: The 4 Types of Hydrogen Production Methods and their Characteristics

Types of hydrogen production	**Production process and characteristic**
Brown hydrogen	From gasification of lignite coal or biomass through industrial processes, with high CO_2 production.
Grey hydrogen	From steam methane reforming of natural gas by utilizing non-renewable energy sources, with high CO_2 production.
Blue hydrogen	From steam methane reforming of natural gas by utilizing non-renewable energy sources, with CO_2 captured and stored underground (significantly lower discharge into the atmosphere).
Green hydrogen	From electrolysis of water, with zero CO_2 production.

Table 1.1 concludes 4 types of hydrogen production methods[8]. It can be seen that green hydrogen can make the emission of CO_2 down to zero, which is good for a low-carbon environment. The process of green hydrogen production from renewable energy is shown in Figure 1.5. Using abundant renewable energy to produce hydrogen by electrolysis, while using storage and transportation technology, hydrogen can be transported to energy consumption centers for diversified use can effectively solve the problems of instability and long-distance transportation of renewable energy such as wind power, photovoltaics, and hydropower.

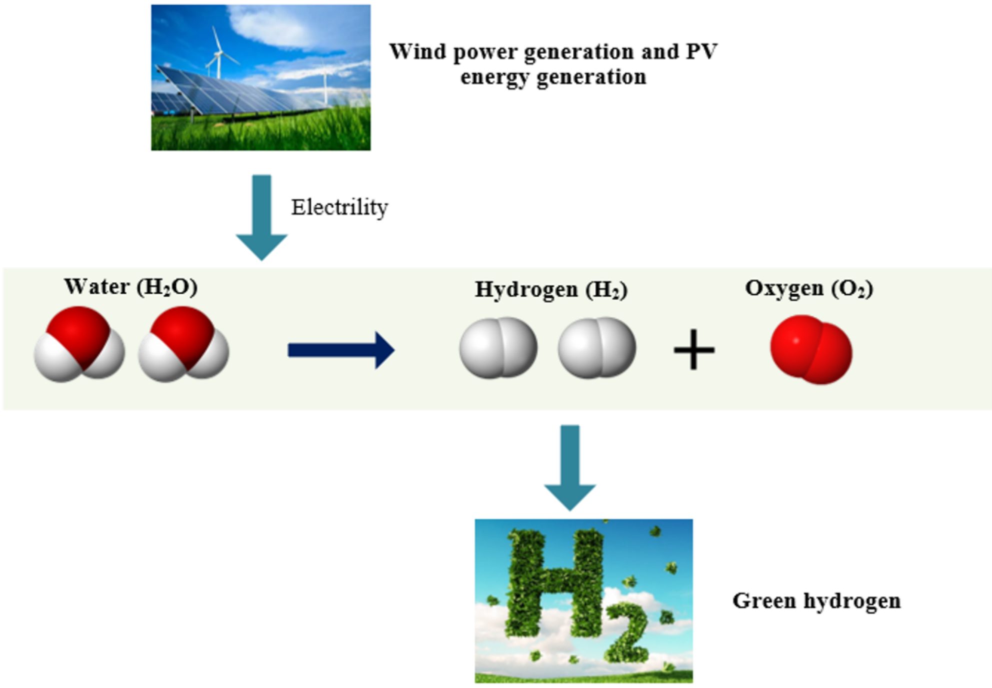

Figure 1.5: The Diagram of Hydrogen Production from Renewable Energy

At present, the world produces about 117 million tons of hydrogen each year, of which 48 million tons are by-product hydrogen and about 69 million tons are dedicated hydrogen production. Of the world's pure hydrogen, about 98% is gray hydrogen produced by carbon-intensive methods using natural gas or coal as raw materials, and the remaining 2% is green hydrogen produced by electrolysis.

1.1.3 Biomass energy

Biomass energy is solar energy fixed in organisms through photosynthesis and is a renewable energy source obtained through a physical, chemical, or biological transformation using agricultural and forestry waste (straw, wood chips), energy crops (Miscanthus, switchgrass), organic waste (kitchenware, livestock, and poultry manure), etc. Modern biomass energy technology is different from traditional firewood combustion, emphasizing efficient and clean utilization. The carbon cycle of this kind of energy is usually 1-10 years (fossil energy is in the billion-year range). It is listed as a key path to carbon neutrality by the IEA.
Biomass energy is carbon neutral. The carbon dioxide released by its combustion is approximately equal to the amount absorbed by plants during their growth stage,

and the carbon emission reduction benefiting over the entire life cycle reaches 78%-95% (IPCC, 2023). Because the world's resource reserves are abundant, the global annual development potential reaches 1500 EJ, which is equivalent to three times the current global energy consumption. In addition, biomass energy has the ability to produce multiple co-productions, while simultaneously producing electricity, heat, transportation fuels (such as bioethanol), and high-value-added materials (such as bioplastics). Moreover, biomass energy can be stored in solid form for a long time (energy density 15-18 GJ/ton), effectively solving the intermittent problem of renewable energy.

1.1.4 Integrated Energy System

Integrated Energy System (IES) is a modern energy framework that integrates multiple energy carriers, including electricity, heat, natural gas, and hydrogen, through advanced information technology and optimized management strategies. Unlike traditional energy systems that operate in isolation, IES enables coordinated planning, real-time optimization, and interactive response among heterogeneous subsystems, enhancing overall energy efficiency and system flexibility. By leveraging energy conversion and storage technologies, IES facilitates the efficient utilization of renewable energy sources, reduces carbon emissions, and improves energy security. The fundamental objective of IES is to achieve a seamless integration of different energy networks, creating a highly interconnected and resilient energy ecosystem. Figure 1.6 shows what an IES system consists of and how it works.

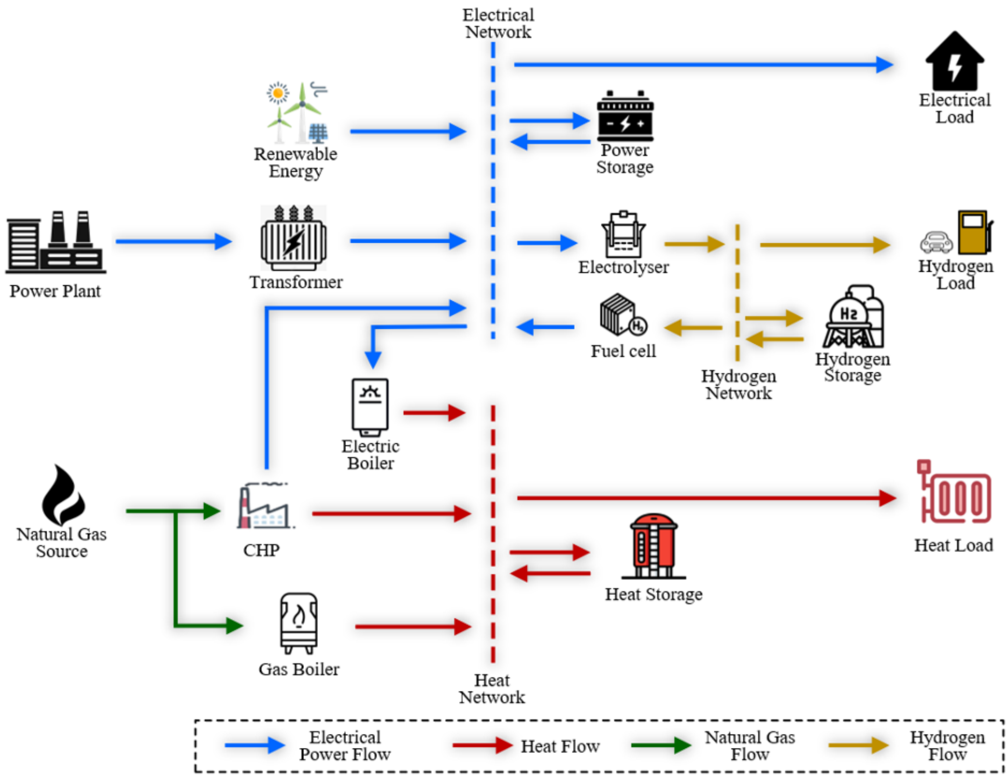

Figure 1.6: The Structure and Working Method of an IES

With the global push toward carbon neutrality, the development of IES is evolving in multiple directions. One major trend is the deep coupling of different energy sectors to maximize energy efficiency and minimize waste. This requires advancements in energy storage technologies to ensure the reliable and flexible operation of IES under variable renewable energy generation. Another key development is the adoption of artificial intelligence, digital twin simulations, and blockchain technology to optimize real-time energy dispatch, enhance system control, and facilitate transparent energy transactions. Additionally, IES is shifting toward more decentralized and market-oriented operations, where DERs and demand-side participation play a crucial role in local energy trading, VPPs, and P2P energy exchange, enabling a more flexible and consumer-driven energy landscape.

Despite these advancements, the widespread adoption of IES presents challenges such as system complexity, market integration, and interdisciplinary research requirements. Addressing these challenges necessitates the development of standardized evaluation frameworks, robust simulation tools, and market-driven mechanisms to enable seamless energy transitions. As global policies increasingly emphasize sustainability, IES will play a crucial role in achieving carbon neutrality by promoting energy innovation, fostering economic viability, and ensuring long-term energy security.

1.2 Wind power generation

As a branch of new energy generation, offshore WTs typically have larger capacities and longer blades than onshore ones and transmit power to the power grid via undersea cables. The advantages of offshore wind power are obvious. First of all, offshore wind is more stable and stronger, whereas power generation efficiency is higher. Besides, it can avoid occupying land resources and is more suitable for coastal areas with high demand. To transmit wind power to the power grid the control of a wind power-based converter is important, which is explained in this subsection.

1.2.1 Evolution of Wind Power Converters

Wind power converter is the core component of WT, which can convert the unstable wind energy captured by the WT into stable electric energy and transmit it to the power grid. Its technological evolution is closely related to the progress of power electronics, control theory, and material science. During the 1990s-2000s when AC frequency conversion technology rose, PMSG appeared, and gearbox was not needed anymore; moreover, full power converters enabled wide-range variable speed operation to improve reliability. Nowadays, wind power converters can support VSG technology to enhance grid stability. At the same time, digital control (such as predictive control model, and artificial intelligence algorithm) can optimize its dynamic response.

1.2.2 Two-Level Back-to-Back Converter

The 2L-B2B wind power converter consists of two VSCs connected by a DC bus, as shown in Figure 1.7.

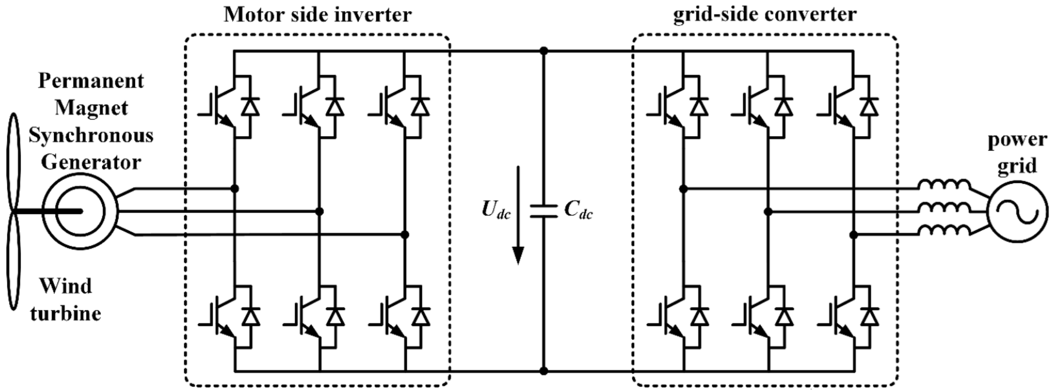

Figure 1.7: The Diagram of 2L-B2B WT-based Grid-connected Converter

The MSC connects to the PMSG-based wind power generation system and controls the generator speed to achieve maximum wind energy capture. The GSC is connected to the power grid, regulates the voltage of the DC bus, and outputs the electric energy that meets the requirements of the power grid. DC bus capacitor C_{dc}, as an intermediate energy storage link between MSC and GSC, balances power fluctuations on both sides.
Each phase bridge arm of each converter consists of only two switching devices and outputs two levels (positive and negative DC bus voltage). The structure of the 2L-B2B converter is simple.
However, the structure of this 2L-B2B converter also has certain limitations. In applications where both voltage and power are high, this two-level converter faces many challenges. For example, for offshore wind power generation systems, as the single capacity of WT increases, the voltage level and power capacity requirements of converters are also getting higher and higher. Due to the limited output levels of the two-level converter, when operating at high voltage and high power, the switching devices need to hold higher voltage stress, which not only increases the cost and difficulty for heat dissipation of the devices but also easily causes device damage and reduces the reliability of the system. In the meanwhile, the output voltage waveform by the two-level converter has a high harmonic content, which will pollute the power grid, affect the power quality, and increase both the difficulty and cost of filter design.

1.2.3 Three-Level Neutral Point Clamped Converter

With the rapid development of modern industry, the application of power electronics technology has become more and more common in various fields. Among many topologies of power electronic converters, the 3L-NPC converter has become the hotspot of research and applications, which effectively solves the problems in two-level converters. Figure 1.8 shows the diagram of 3L-NPC-based wind power conversion system[9].

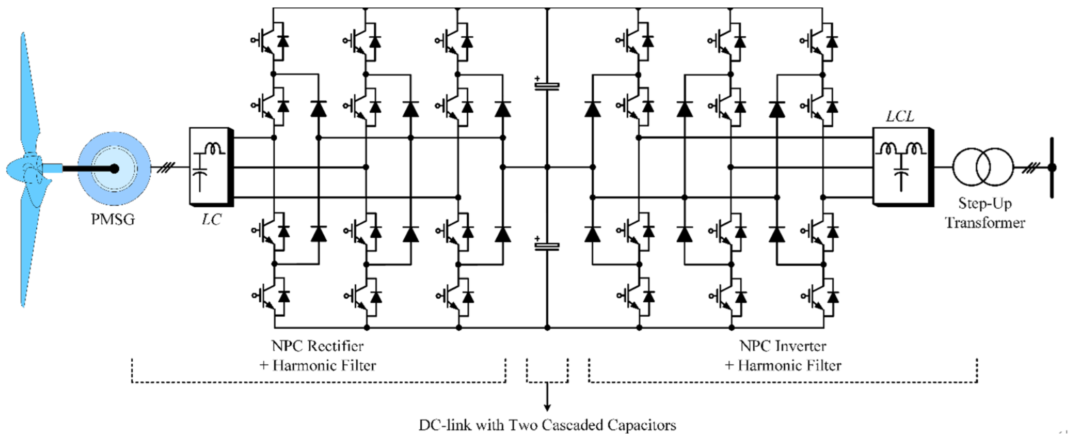

Figure 1.8: The Diagram of 3L-NPC Converter-Based Wind Power Conversion System

As seen in Figure 1.9, by introducing an NPC diode on the DC side, its topology structure divides the DC voltage into three levels, thereby increasing the number of output voltage levels. In a two-level topology, only one IGBT blocks the DC-link voltage. By introducing a three-level topology, one IGBT blocks half of the DC-link voltage, doubling the blocking capacity of the inverter. In this way, the rated power of the inverter system increases. The 3L-NPC converter introduces two extra switches and two clamping diodes per leg. The two diodes are connected between switch S1-S2 and the neutral point of the converter and between the potential S3-S4 and the neutral point. Two DC-link capacitances are used. They are located between the high potential point P, neutral point O, and the negative potential N.

Table 1.2: Switching sequence of a single-phase NPC converter

Voltage level	State	S1	S2	S3	S4
$V_{DC}/2$	P	1	1	0	0
0^*	O	0	1	1	0
$-V_{DC}/2$	N	0	0	1	1

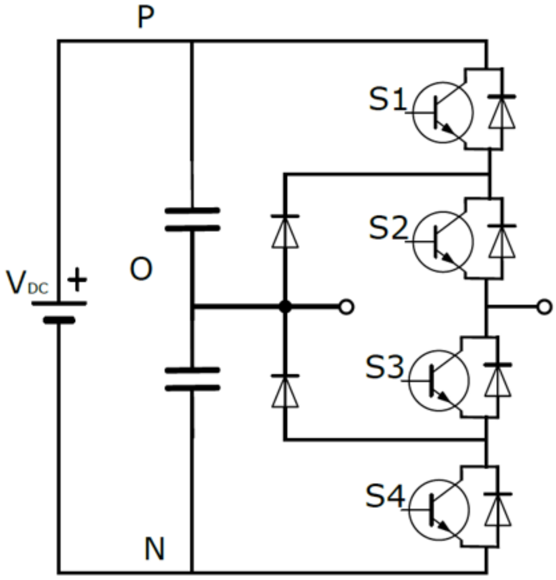

Figure 1.9: One Phase of an NPC Converter

The three-level converters can produce three different output states: positive state P with a voltage of $V_{DC}/2$, negative state N at -$V_{DC}/2$, and the neutral state O which corresponds to zero volt output. If the circuit of one phase of an NPC converter is analyzed, it is found that there are three possible switching states, which are referred to as P, O, and N. Table 1.2 shows the voltage level and switching states of different switches.

Compared with two-level converters, 3L-NPC converters have the following significant advantages:

- The three-level converter has 27 possible switching states, while the two-level topology only results in 8.
- The voltage stress of the switching device is reduced to half of the DC bus voltage, which allows the selection of switching devices with lower withstand voltage levels, reduces device costs and heat dissipation requirements and

improves system reliability.

- The output voltage waveform is closer to a sine wave, while the harmonic content is greatly reduced, which reduces harmonic pollution to the power grid and reduces the design requirements and costs of the filter.
- At the same switching frequency, the 3L-NPC converter can achieve higher power conversion efficiency and improve energy utilization.

Moreover, the application of 3L-NPC converters can improve the overall performance of the system in offshore wind power generation systems

- 3L-NPC converters can adapt to the harsh environmental conditions at sea and realize the conversion and transmission of high-power electric energy.
- Its output characteristics of low harmonics improve the quality of electric energy and meet the strict requirements of the power grid for clean energy access.

In addition, 3L-NPC converters have also shown broad prospects in their applications in other fields, such as electric vehicle fast charging, high-voltage direct current transmission, industrial motor drives, etc. Apparently, an in-depth study of 3L-NPC converter has important theoretical significance together with practical value for application. Through the study of its basic principles, modulation strategy, control strategy, and key technologies such as neutral point balance control, the performance of the converter can be further optimized, and its wide application in more fields can be promoted, providing technical support for the realization of efficient, reliable and clean energy conversion and utilization.
However, there are also negative aspects of this type of converter:

- When a dynamic load is connected, the neutral point must be controlled actively. The unbalanced loads may shift the neutral point combinations to a voltage level different from 0.
- The uneven loss distribution among the semiconductors is also a problem of 3L-NPC converter since some switches have higher losses than others, which limits the switching frequency and the maximum phase current of converter[10][11].

To solve the problem of uneven loss distribution in the NPC topology, active switches are introduced to replace the passive diodes in the branches of the neutral point. As shown in Figure 1.10, the different topologies of NPC converters are explained.

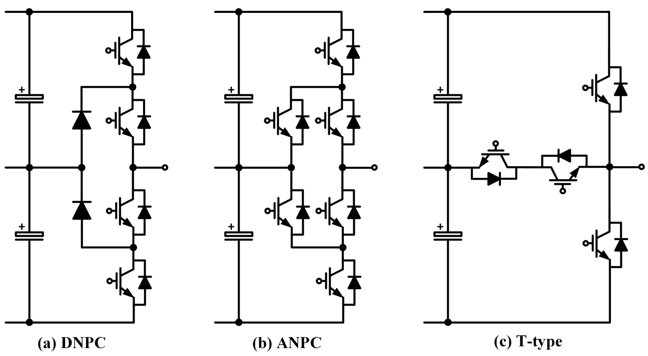

Figure 1.10: The Different Topologies of NPC Converters. (a) Diode-Based NPC Converter. (b) Active NPC Converter. (c) T-type Converter.

The topology in Figure 1.10 (b) is called active NPC converter and was first introduced in 2001, where the active switches make the output with more states that can fully utilize the neutral tap and the distribution of thermal stresses are significantly improved[12]. Therefore, the output capability of the NPC converter can be improved with the suitable strategies of thermal balancing.
Moreover, the T-type converter, shown in Figure 1.10(c), is mainly applied in the low switching frequency conditions, where both the upper switches and lower switches are paralleled with DC-link capacitors by the bi-directional switches to the midpoint[13]. Therefore, the active switches in Figure [**fig:nine**](c) can be with low voltage rating where the power losses can be highly reduced[13]. T-type converters can improve efficiency by reducing the number of power devices, thereby reducing hardware costs.

1.3 Problem Formulation

- How to design a back-to-back wind power converter?
- What grid code should be considered?
- What is the requirement of wind power converter for grid-friendly connection?

1.3.1 System design

- What is the control responsibility of wind power converter?
- What is the control objective of machine side converter?
- What is the control objective of grid-side converter?

1.3.2 Control System design

- What are the grid requirements for high-power wind turbines
- How to design a 3L-NPC wind power converter to achieve wind power conversion system?
- How to simulate dynamic performance of wind turbine in hardware-in-loop platform?

1.3.3 Research Questions

How to design a 3L-NPC wind power converter to achieve wind power conversion in high power?
This project aims to develop a high-power WT system based on a 3L-NPC converter. The converter will be first developed. Then, the control strategy of the proposed converter will be developed. The main tasks of this project include modeling, analyzing, simulating, and finally understanding the performance of the grid-connected high-power converter applied for high-power wind energy conversion system.

1.4 Objectives

The main tasks include:

- Literature review about high-power offshore wind power converter and its control strategies.
- Define and analyze scientific problems and state the reasons for decisions made in this project.
- Develop the model of offshore wind power converter.
- Develop a proper control strategy for offshore wind power converter.
- Analyze operation performance of offshore wind power converter.
- Simulate and verify the proposed solution.
- Experimental verification using the digital platform in the laboratory.
- Experimental analysis based on relevant industrial codes.

Chapter 2

State-of-the-Art

2.1 Grid Code for Wind Power

The grid code for wind power is a technical standard developed by power system operators to ensure the safe and reliable connection of wind farms to the grid, including voltage, frequency, etc. As wind power penetration increases, these codes are more and more important for grid stability maintenance. The codes of wind power grid are explained as follows:
1. Voltage Control:

- Dynamic Reactive Power Support: The wind farm needs to provide dynamic reactive power regulation to maintain the voltage stability. For instance, reactive power needs to be injected quickly, when the voltage drops.
- Range of Power Factor: WTs are typically required to operate between 0.95 lead and 0.95 lag for grid voltage regulation.

2. Frequency Response:

- Primary Control: The wind farm is required to adjust its output when the frequency of the grid fluctuates. For instance, reserve capacity can be retained through load reduction operations.

3. Active Power Control:

- Operation with Limited Power: When the grid is congested, the operator can remotely adjust the wind power output.
- Limit of Ramp Rate: In order to avoid negative impact on the power grid, the limit of power's changing speed needs to be set.

4. Harmonics and Power Quality:

- To avoid interfering with other devices, the limit of current harmonic distortion rate is supposed to be set. For instance, the THD should be lower than 5%.
- In addition, Denmark has one of the highest wind power penetration rates in the world, and its grid codes, developed by Energinet, have the following characteristics:

a. Frequency Control Flexibility:

- Single Frequency Modulation Participation: Since 2016, Denmark has required new wind farms to have a single frequency modulation capability, which needs to respond to frequency changes within 2s.
- Overfrequency Cutting Protection: When the frequency exceeds 52Hz, the machines need be cut in stages to prevent equipment damage.

b. Power Quality Optimization:

- Harmonic Restriction: IEC 61400-21 Standard requires WTs to pass the tests before being connected to the power grid to ensure that the harmonic distortion rate meets the requirements.
- Flicker Suppression: There are strict limits on the voltage flicker caused by wind farm start-stop and wind speed fluctuations.

c. System Services under High Penetration:

- VSG Technology: Some wind farms simulate the inertia response of traditional synchronous generators to improve the stability of system.
- Black-start Capability: Some offshore wind farms require the ability to start up and help to restore power after a grid breakdown.

2.2 Offshore Wind Farm

Offshore wind farm is a renewable power facility that generates electricity from offshore wind power resources, where the wind energy can be converted into electricity and delivered to the land-based power grid. Its components mainly include WTs, offshore bases that support the WTs, submarine cables and substations.

At present, the main challenge is that when the machines are connected to power grids, long-distance HVDC transmission technology is required, so the requirements for power grid are very high. Nowadays, Europe (especially Denmark and the United Kingdom) is the leader in this field, and the typical examples are Horns Rev in Denmark and Hornsea 2 in the United Kingdom. Also, China is growing rapidly in this field, with a cumulative installed capacity of more than 30 GW by 2022.

The offshore wind farms are mainly applied in grid-connected power generation, offshore power supply and so forth. Figure 2.1 shows the multiple-converter wind power grid-connected converter system. In addition, floating wind power and intelligent operation and maintenance are the future development trends in this field.

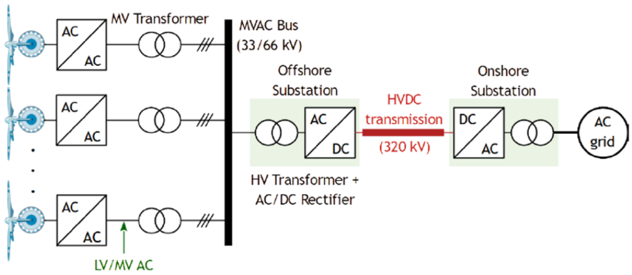

Figure 2.1: The diagram of multiple-converter wind power grid-connected converter system

2.3 Wind Turbine

Wind Turbine (WT) is the core that convert wind energy into electricity, and its structure is complex and highly integrated. In this sub-chapter, its main components and their functions are described in detail.

2.3.1 Rotor

The rotor is the core of capturing wind energy and is composed of blades and hub. The rotor converts wind energy into mechanical energy by rotating the blades. For optimal aerodynamic efficiency, the number of blades is typically 3. The blade is made of lightweight high-strength materials (such as glass fiber, carbon fiber composite, etc.), and with a streamlined airfoil design to maximize wind energy capture. The hub can connect the blade and main shaft together. Figure 2.2 shows the model of rotor.

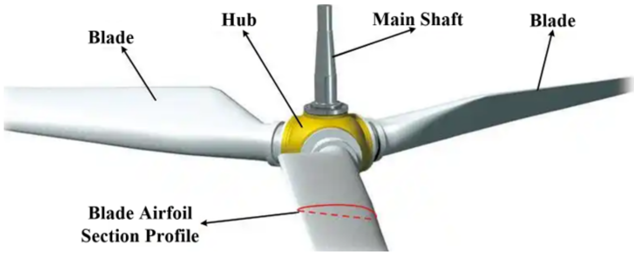

Figure 2.2: The diagram of rotor in WT

2.3.2 Nacelle

The nacelle is usually located on top of the tower and is also the control center of the WT, whose basic diagram is shown in Figure 2.3. The core components inside the nacelle are main shaft, gear box, generator, converter, brake system, etc.

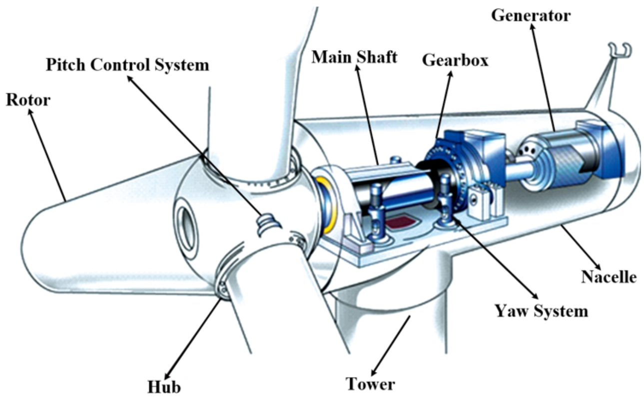

Figure 2.3: The diagram of nacelle in WT

The main shaft transmits the mechanical energy of the rotor. The gearbox (only in non-direct-driven WT) increases the low speed to the high speed required by the generator; however, direct-driven WT does not need gearbox, and the maintenance cost can be reduced. Generators that convert mechanical energy into electrical energy mainly include DFIG and PMSG - DFIG requires gearbox, with low cost but complex maintenance; PMSG is first choice of direct-driven WT, with high efficiency and reliability. The converters can convert the unstable AC output by generator into electric energy with stable frequency and voltage to ensure grid compatibility. The braking system is to stop the wind wheel rotation in the emergencies, and the braking methods include mechanical braking and aerodynamic braking.

2.3.3 Tower

The tower is used to support the rotor and nacelle, and is usually 80-160 meters high. The main types of towers are steel barrel towers, concrete towers and mixed towers. The mixed towers use steel and concrete at the same time, which can guarantee both strength and economy.

2.3.4 Auxiliary Systems

The auxiliary system of WT mainly includes yaw system, pitch system, cooling system and monitoring system. The pitch system is the most important, which adjusts the pitch angle through hydraulic or electric mechanism, controls the power output and prevents overspeed. Figure 2.4 in Chapter 1 briefly describes the basic principles of the pitch system.

Figure 2.4: The diagram of transformer in wind farm

2.3.5 Power Transmission Components

Power transmission components mainly include transformers and cables. The transformer can boost the low voltage coming from the generator to the grid voltage, as shown in Figure 2.5.

2.4 The Generator

As mentioned in 2.3.2, the generators mainly include DFIG and PMSG. In this subchapter, these two type of generators are introduced in detail.

2.4.1 Double-Fed Induction Generator

The variable-speed WT using the DFIG has gained the attention of the market owing to its low installation cost, the relatively small power capacity of the converter, and the high ability of energy transfer at various wind speeds. Many reviews on the fundamentals of the DFIG wind turbine are valuable [14][15][16][17][18].
DFIG is an asynchronous generator which is widely used in wind power generation systems. The core feature of it is that both the rotor and stator are connected to the grid through converters (the stator is directly connected to the grid, and the rotor is connected through a back-to-back converter). In this way flexible control of speed and power is achieved.
DFIG is a common term that can be used to describe an electrical machine with the following characteristics:
1 Cylindrical stator that has in the internal face a set of slots (typically 36-48), in which are located the three phase windings, creating a magnetic field in the airgap with two or three pairs of poles.
2 A cylindrical rotor that has in the external face a set of slots, in which are locate the three phase windings, creating a magnetic field in the air gap of the same pair of poles as the stator.
3 The magnetic field created by both the stator and rotor windings must turn at the same speed but phase shift to some degrees as a function of the torque created the machine.
4 As the rotor is a rotating part of the machine, to feed it, it is necessary to have three slip rings. The slip ring assembly requires maintenance and compromises the system reliability, cost, and efficiency.
Many new wind farms will employ wind turbines based on DFIG, which offer several advantages when compared with fixed-speed generators [19][20][21][22]. These advantages, including speed control, reduced flicker, and four-quadrant active and reactive power capabilities, are primarily achieved via control of a rotor side converter, which is typically rated at around 30%-35% of the generator rating for a given rotor speed variation range of ±25%. When DFIG is applied in wind power-based grid-connected converter system, Figure 2.5 shows the diagram of multi-machine power system with DFIG [23].

2.4.2 Permanent-Magnet Synchronous Motor

The PMSG-based wind farms usually combine direct-drive technology to directly convert the mechanical energy of wind turbines into electrical energy, which is one of the mainstream technologies of offshore and onshore wind power. Its main advantages include:

- High Efficiency: Permanent magnet can be without external excitation, where the energy loss is reduced and the wind power conversion efficiency is more than 95%.
- Low Maintenance Costs: Gearbox is unnecessary and mechanical transmission fault points are eliminated, since gearbox failures account for more than 30% of traditional WT failures.
- High Reliability: It can be with simpler structure, which is more suitable for harsh environments.
- Wide Speed Operation: Flexible adjustment can be achieved through full power converter which adapts to wind speed fluctuations, where power generation can be increased.
- Low Noise: It is with no gearbox mechanical noise and small impact on the surrounding environment.

However, it also has certain limitations:

- High Initial Cost: Permanent magnets rely on rare earth materials (such as neodymium, dysprosium), and the material cost accounts for 40%-60% of the generator cost.
- Volume and Weight: The diameter of the direct-drive generator is large (for instance, the diameter of the 10 MW model exceeds 6 meters), which increases the burden of the tower and the infrastructure.
- Demagnetization Risk: High temperature or strong vibration may cause demagnetization of permanent magnets, requiring complex cooling systems (liquid / air cooling) protection.
- Rare Earth Dependence: The supply chain is affected by geopolitics, and there are still risks of supply interruption.
- Recycling Challenges: The immature recycling technology of permanent magnets may cause resource waste and environmental pollution.

When PMSG is applied in grid-connected converter system, its diagram is shown in Figure 2.6 [24]. With PLL, the system is operating in grid-following mode.
As shown in both Figure 2.5 and 2.6, there are 2 converters operating. Both rotor-side converter in Figure 2.5 and MSC in Figure 2.6 are adopted to ensure decoupling control of stator-side active and reactive power, and control the generator with a wide speed-range operation. As for the GSCs in both Figure 2.5 and 2.6, they are adopted to keep the DC-link voltage constant, and control reactive power

flow between the GSC and the grid.

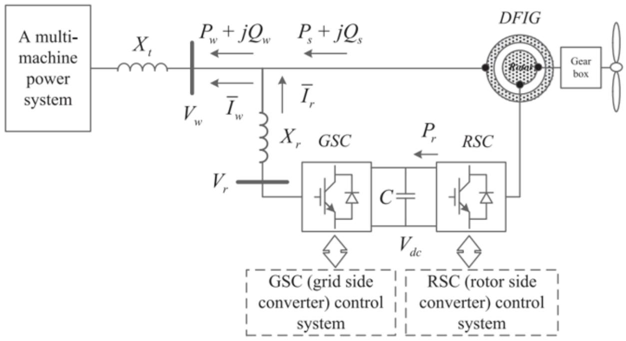

Figure 2.5: The diagram of multi-machine power system with DFIG

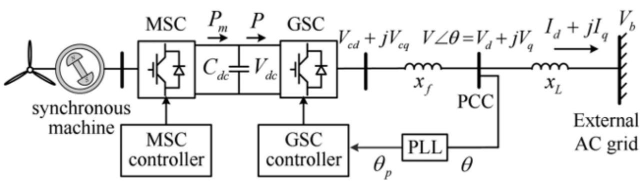

Figure 2.6: The rationale of SPWM technique

2.5 PWM

PWM is a modulation method to generate an expected voltage by pulses which has equal height but unequal width. PWM module converts the digital signal to the equivalent analog amount by adjusting the duty cycle of the periodic pulse signal (the proportion of the high level time to the cycle). Its core is to control the energy transfer through fast switches to achieve precise regulation of voltage, current or power.

Various PWM control methods have been proposed since the concept of multilevel converter was proposed at the beginning of 1980s'. According to the classification of waveform generation, PWM technologies mainly inculde SPWM and SVPWM.

2.5.1 Sinusoidal Pulse Width Modulation

SPWM module generates a modulated signal that is close to sinusoidal wave to reduce the harmonic distortion, which has the advantage of high output waveform quality. As shown in Figure 2.7, sinusoidal wave is divided into N components, while the components are expressed by a series of pulses. It means the switch-on time of power electronic device simulates the sinusoidal variation characteristics. The SPWM technique is commonly used in converters and AC loads.

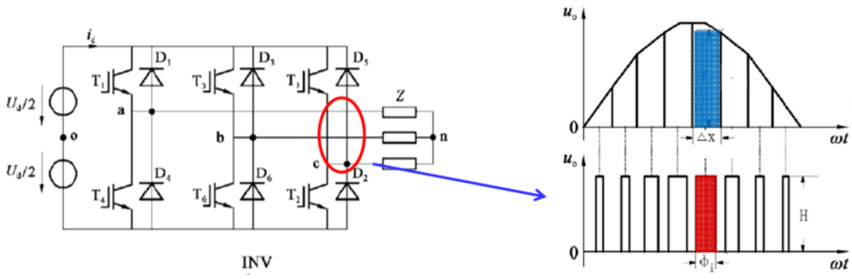

Figure 2.7: The diagram of PMSG-based grid-connected converter system

2.5.2 Space Vector Pulse Width Modulation

As shown in Figure 2.8, SVPWM takes the ideal flux circle of the stator of the three-phase symmetrical motor as the reference standard, and forms PWM wave through the switching of different switching modes of the three-phase converter to track the exact flux circle with the actual flux vector. 6 non-zero voltage vectors and 2 zero voltage vectors are used to synthesize the desired voltage vector. The non-zero voltage vector corresponds to different switching states of the inverter, while the zero voltage vector corresponds to states where all switches are off or all switches are on. The desired output voltage vector is synthesized by switching different voltage vectors alternately.

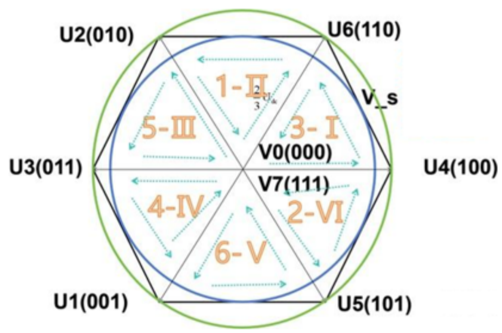

Figure 2.8: The rationale of SVPWM technique

SVPWM is to optimize the switching sequence through vector synthesis, improve the voltage utilization rate, has the advantages of high efficiency and fast dynamic response, and is often used in three-phase motor frequency conversion control and high-power scenarios.

2.6 Coordinate Transformation

In motor control and power electronic converter control, coordinate transformations, including abc-dq and abc-$\alpha\beta$, are used to convert a three-phase AC system (abc coordinate system) to an equivalent rotating or stationary coordinate system to simplify mathematical models, achieve decoupling control, and improve dynamic response performance. Its core is to convert the time-varying AC quantity into direct flow (dq coordinate system) by mathematical transformation, which is convenient for controller design.

2.6.1 Definition of Coordinate System

abc coordinate system: It is three-phase stationary coordinate system, which directly corresponds to the actual current or voltage of the three-phase winding of the motor (phase A, B, C).
$\alpha\beta$ coordinate system: It is two-phase stationary coordinate system, using Clarke Transformation (3 $\rightarrow$ 2 phase) to project the triphasor onto the orthogonal two-phase stationary axis (α axis, β axis).
dq coordinate system: It is two-phase rotating coordinate system, the $\alpha\beta$ coordinate system is synchronously rotated around the rotor magnetic field by the Park Transformation (static $\rightarrow$ rotation), so that the d axis is aligned with the rotor flux direction, and the q axis is orthogonal to the d axis.

2.6.2 Processes of Coordinate Transformation

Clarke Transformation (abc $\rightarrow$ $\alpha\beta$): It converts the three-phase stationary coordinate system to a two-phase stationary coordinate system, eliminating the neutral component (assuming three-phase equilibrium), as shown in (2.1). It is to project a three-phase current / voltage onto an orthogonal two-phase plane, preserving amplitude and phase information.

$$\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \tag{2.1}$$

Park Transformation ($\alpha\beta \rightarrow$ dq): It converts the stationary $\alpha\beta$ coordinate system into a dq coordinate system that rotates synchronously with the rotor (θ is angle of rotor magnetic field), as shown in (2.2). It eliminates the time variability of the AC quantity by rotating, so that the d axis corresponds to the magnetic field component and the q axis corresponds to the torque component, to achieve decoupling control.

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} \tag{2.2}$$

2.6.3 Characteristics of Coordinate Transformation

- Decoupling Control: In the dq coordinate system, the d-axis controls the magnetic field (excitation current), and the q-axis controls the torque (torque current), to achieve independent regulation.
- Time-varying to Static: AC quantity (such as sinusoidal current) is represented as direct flow in dq coordinate system, simplifying PID controller design.
- Fast Dynamic Response: Direct adjustment of dq current allows fast tracking of torque and flux requirements.
- Dependent on Angle θ: The rotor position needs to be accurately obtained (such as an encoder or observer), and errors can cause control failure.

2.7 Maximum power point tracking (MPPT)

Maximum Power Point Tracking (MPPT) is a dynamic optimization technique used to extract the maximum available power from variable energy sources such as solar energy and wind power. Its core is to make the energy output power always at the maximum power point (MPP) by adjusting the load impedance or operating point.

2.7.1 MPPT in Solar PV System

The characteristic curves of solar PV panels, including P-V curve and I-V curve, are shown in Figure 2.9[25]. I_{sc} is short-circuit current, and V_{oc} is open-circuit voltage. I_{mpp} and V_{mpp} comprise the M_{pp} of PV panel M_{pp}, which makes output power of PV panel P_{pv} reach the maximum power P_{max}.

2.7.2 MPPT in Wind Power System

The characteristic curves of WTs are shown in Figure 2.10 [18].
The cp-λ characteristic curve is first shown in the left side of Figure 2.10. C_p is power coefficient and is tip speed ratio, where the pitch angle $\beta 1 < \beta 2 < \beta 3 < \beta 4 < \beta 5 (\beta 1 = 0)$. $\beta 1$ makes C_p reach its maximal value $C_{p_{max}}$, when $\lambda = \lambda_{max}$.
Once β=0, the correlation between output power of WT PWT and rotor speed of WT ω_r is shown in the right side of Figure 2.10 with different wind speed V1<V2<V3<V4<V5. PWT can reach its maximal value $Pmax_i (i = 1, 2, \ldots, 5)$, when ω_r is equal to corresponding ω_{ri} for the MPPT of WT.

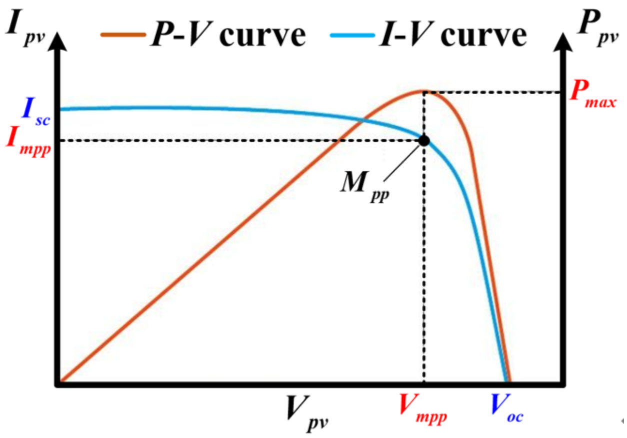

Figure 2.9: The characteristic curves of solar PV panels

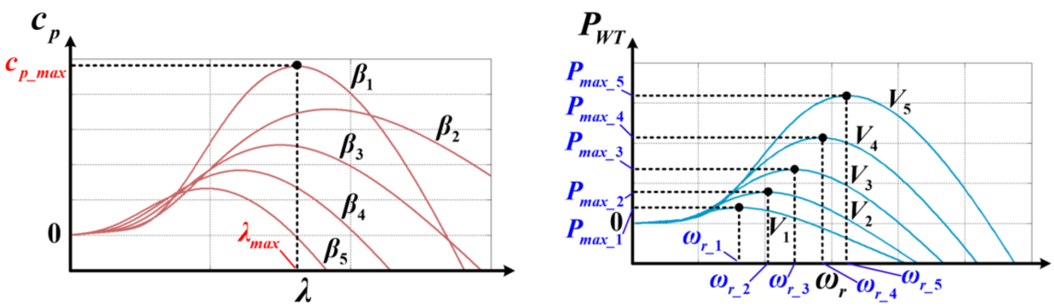

Figure 2.10: The characteristic curves of WT. Left: The cp- characteristic curve. Right: The P-r characteristic curve (=0)

Chapter 3

System Design

3.1 System Design

The aim of this chapter is to design a MW-class wind power converter with control system.
The mechanical power generated by wind turbine can be represented as follows.

$$P_m = \frac{1}{2}\rho_{\text{air}} A C_p(\lambda, \beta)\sigma^3_{\text{wind}} \tag{3.1}$$

The wind speed v_{wind} is in [m/s], the mechanical power is in [Nm/s], ρ is the air density in $[kg/m^2]$, and the area is described by A and is in $[m^2]$. The power coefficient Cp is dependent on β.
The tip speed ratio is determined as follows:

$$\lambda = \frac{\omega_R R}{V_{\text{wind}}} \tag{3.2}$$

Where ωR describes the angular speed of the wind turbine rotor and is in [rad/s].
The power coefficient varies according to the tip speed ratio and the pitch angle, hence it is not constant. It can be given by the following equation

$$C_P = 0.5176\left(\frac{116}{\lambda_0} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_0}} + 0.0068 \tag{3.3}$$

The λ_0 can be expressed as follows.

$$\frac{1}{\lambda_0} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3.4}$$

3.2 Design of Grid-side Converter

In this section, the design of the grid-side converter is given, including rectifier, DC-link capacitor and inverter. Hardware design depends upon multiple factors such as the instantaneous current and voltage of IGBTs, harmonic requirements, system reliability, dynamic current, and thermal capacity of the semiconductor, etc. The following assumptions are given in this design.

- Power devices are selected according to voltage and current requirement.
- The filter is sized according to the harmonic content and the active and reactive power requirement.
- Switching frequency is given according to typical datasheet of power device.

In this case, the DC-link voltage used in industrial applications is defined as 15000 V. The filter sizing depends on various factors of the systems, such as harmonic requirement, the volume of the system, and active and reactive power transfer between the system and grid. In this project, L filter is considered. The major advantage of using an L-filter is that being a single component in the system without the resonance as LCL filter. The drawback is that its volume, where a higher value of the inductor is needed to filter the required harmonic content. This drawback is compensated by an LCL filter which is known for better harmonic content reduction. The volume of the filter is reduced drastically as the smaller values of the inductor are used.
The system is validated in four stages:
1.PLL and frames transformations: An operational point of no grid current is simulated, and then the voltages and currents are registered and compared to their theoretical values. 2.Power system, open-loop test: Three operational points are calculated and simulated. Relevant voltages and currents are registered and compared to their theoretical values. 3.Current control: The current control loop is tested for three reference values. 4.DC-link control: The DC voltage control loop is tested for two values of input power on the DC-link. For the first three tests, the machine-side converter is modeled as a constant voltage source. For the last test, the machine side converter is modeled as a controlled power source, to mimic the power injection from the wind turbine.

Chapter 4

Hardware Platform

This section describes the hardware-in-loop platform based on PLECS RT box. With the hardware-in-the-loop testing, the system can easily run through thousands of possible scenarios to properly exercise the controller without the cost and time associated with actual physical tests. This test always validates the designed control system when implemented in the real system. The RT-box is a real-time simulator designed for power converter control. The RT box is available in several variants with different performance levels, for this project, RT-box 1 is used.
Figure 4.1 shows the picture of this RT-box and test environment in this project. The RT-box is connected to the laptop in lab. The machine side converter is modelled as DC voltage source, simulation is uploaded to RT-box in single task mode since both controller and plant are running on the same time step and core. PWM signals are generated though the digital inputs and Digital outs of RT-box using the PWM capture block in the software. The controller′ output varies the reference signal of the modulation stage according to the requirement of the power delivery and the voltage.

Figure 4.1: Hardware-in-the-Loop Testing for PLECS Simulation

Chapter 5

Simulation and Experiment Verification

5.1 Simulation Analysis

In this section, simulation verification is given for a 2 MW wind power converter in a permanent-magnet synchronous generator (PMSG). The simulation model is developed in PLECS software as shown in Figure 5.1. The stator of the PMSG is directly connected to a three-level neutral-point clamped (NPC) back-to-back converter. The grid side of the converter is connected to a step-up star-delta transformer, which feeds the generated power into the 10 kV medium voltage network.

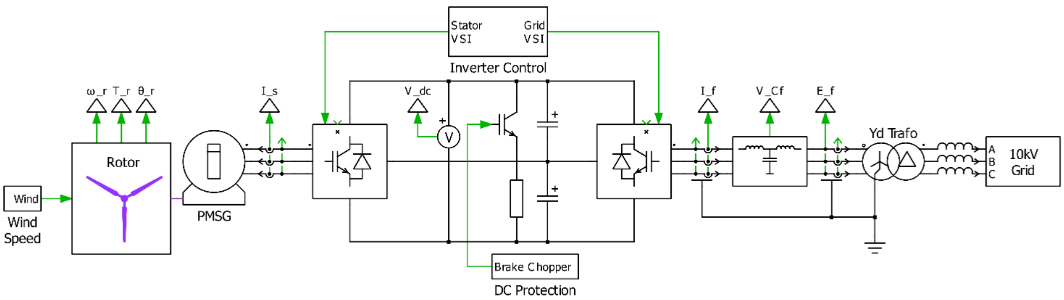

Figure 5.1: Hardware-in-the-Loop Testing for PLECS Simulation

The mechanical physical domain of the wind turbine is controlled by a maximum power point tracking (MPPT) strategy. The wind speed is increased from below the rated wind speed to above the rated wind speed. During this period, the machine-side converter controls the stator current of the PMSG, by controlling the electromagnetic torque, adjusting the speed of the rotor, to implement the maximum power tracking. The corresponding relationship between maximum power and rotor speed is shown in Figure 5.2. To keep the PMSG operated within a stable range, the converters are operated by using 3-level space-vector pulse-width modulation (SVPWM). The simulation model of the machine-side converter is shown in Figure 5.3.

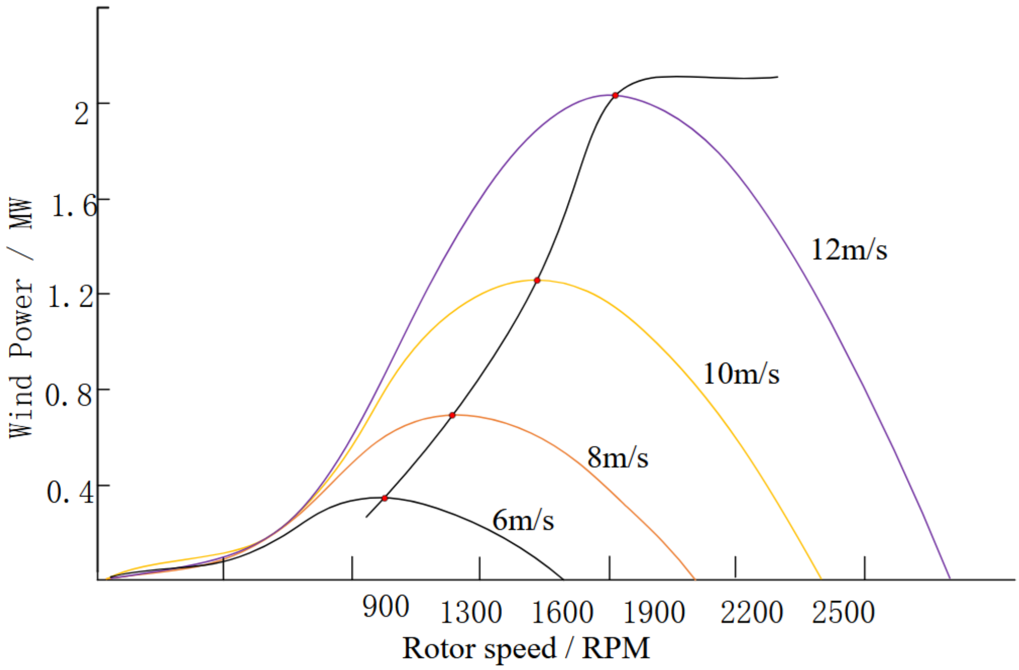

Figure 5.2: The corresponding relationship between maximum power and rotor speed.

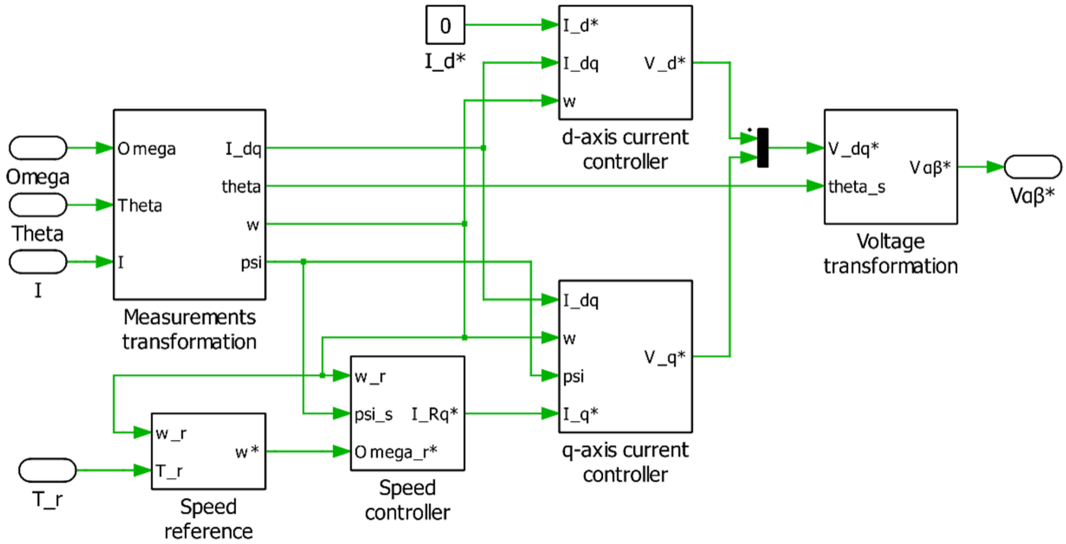

Figure 5.3: The control diagram of the machine-side converter

For the grid-side converter, it controls the voltage of the DC bus. Then, the grid-injected power is dominated by the output current. The stability of the DC bus voltage is crucial for grid power quality. The deviation of the overall voltage or the neutral point voltage will cause the distortion of the output waveform of the grid-side converter. Therefore, a brake chopper is applied to limit the rise of the DC voltage. Furthermore, the neutral point voltage balancing strategy is performed in the grid-side converter. The DC bus voltage is expected to be maintained at 1500 V. The simulation model of the grid-side converter is shown in Figure 5.4.

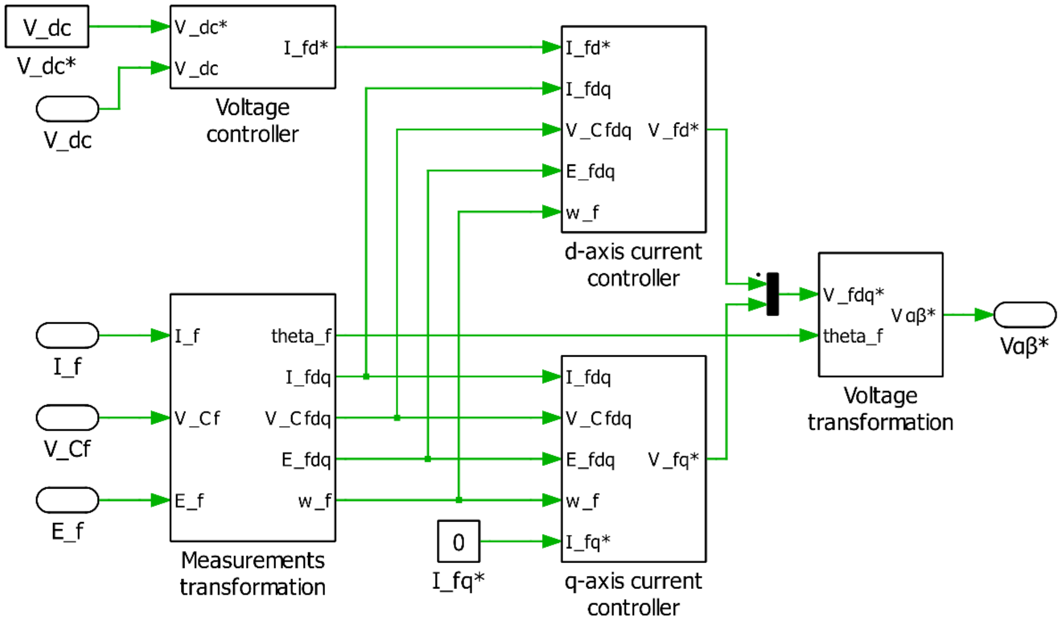

Figure 5.4: The control diagram of the grid-side converter

A. The simulation verification of the grid-connected power

In this Simulation verification, the wind speed is gradually increased from 6 m⁄s to 14 m⁄s. From Figure 5.2, the rated wind speed for the wind turbine is 12 m⁄s. Therefore, the simulation results below and above the rated wind speed are both obtained. The performance of the machinic parts is shown in Figure 5.5, while the performance of electrical parts is shown in Figure 5.5

In Figure 5.5, wind speed increases by 2 m⁄s at every 50 seconds. Under the rated wind speed, the machinic torque increases first to speed up the rotor, then the electromagnetic torque increases to boost the current. The MPPT wind power is converted by the PMSG to electrical power. However, above the rated wind speed, the wind turbine is controlled to capture constant wind power to protect the system.

In Figure 5.6, to keep the DC bus voltage stable, the grid-side converter increases its output current to inject the MPPT power into the power grid. It can be seen that the d-axis current is increased while the q-axis current keeps constant. the gird power is increased as increase of wind speed. The DC bus voltage has a small transient process when the wind power is inserted in, which is controlled at its rated value. This shows the effectiveness of the control strategy. Since the DC bus voltage is well-controlled, the output voltage and current maintain good sinusoidal forms throughout the whole dynamic process.

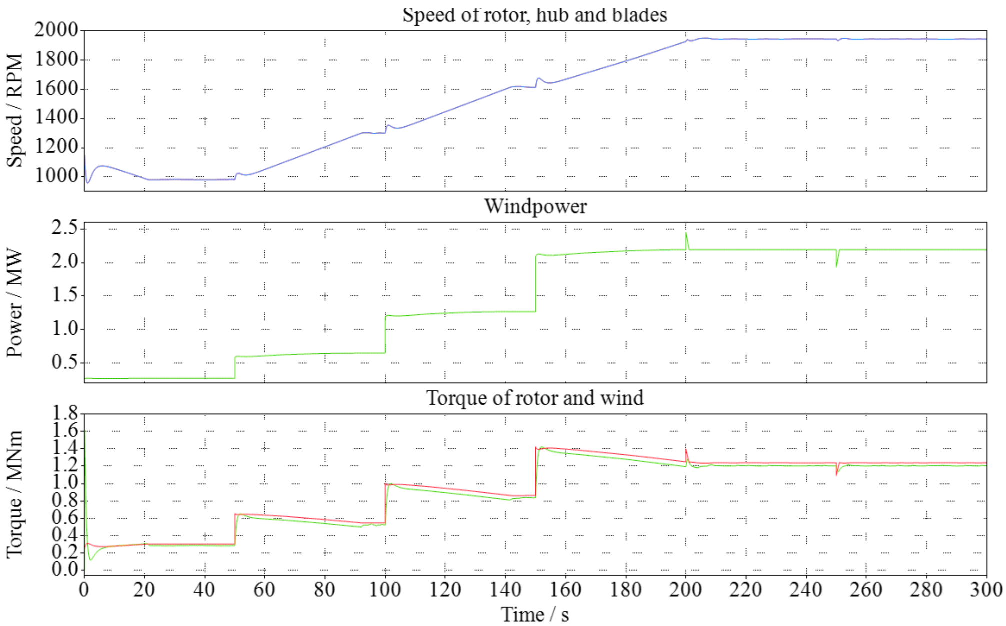

Figure 5.5: The Performance of the Machinic Parts

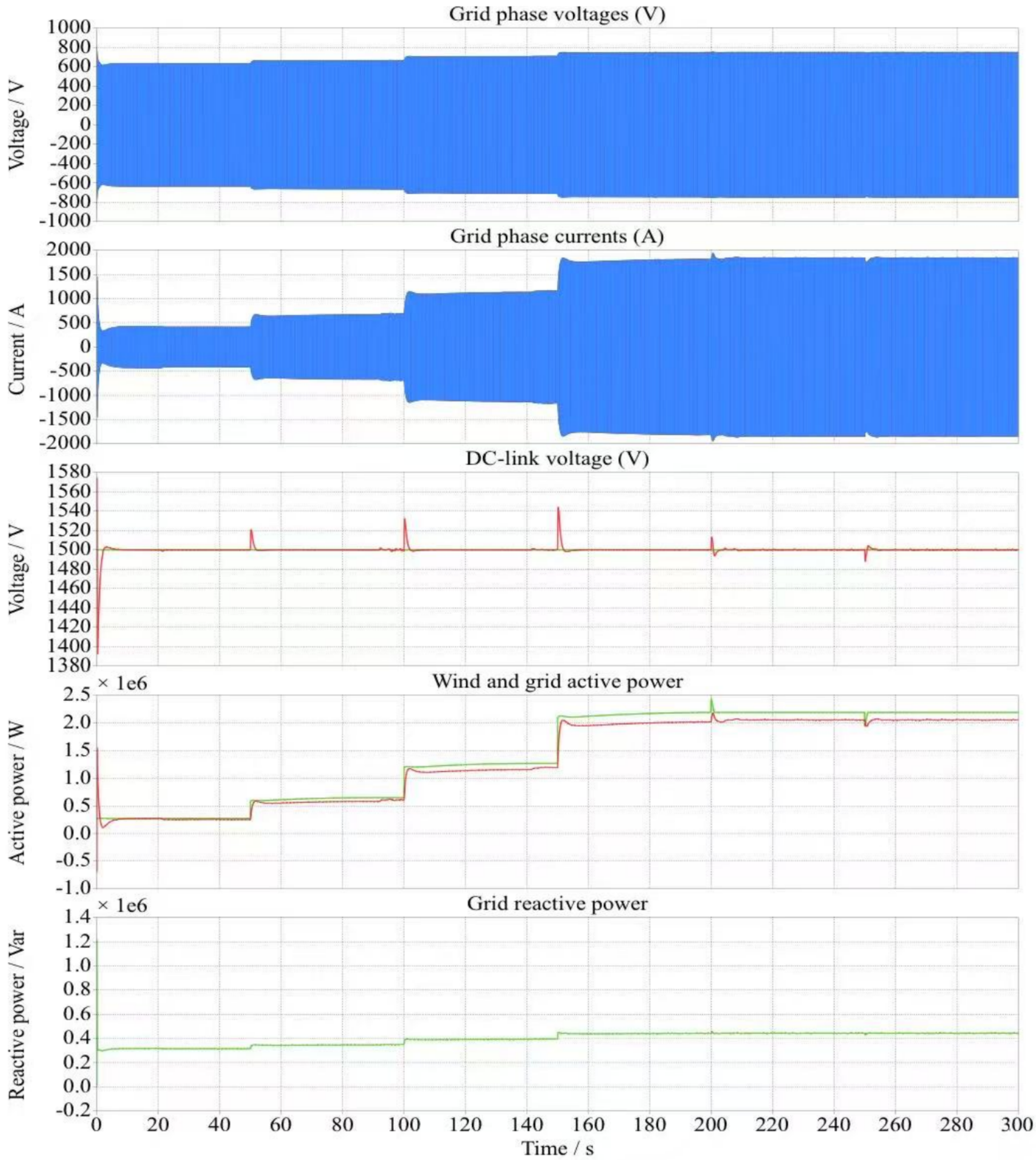

Figure 5.6: The performance of the electrical parts

B. The simulation verification of the neutral point voltage control
In Figure 5.7, the effectiveness of the neutral-point voltage balancing strategy is rigorously validated through a transient disturbance test. At 200 seconds, an intentional voltage drop is introduced to the lower DC-link capacitor for a short duration of 0.03 seconds, simulating asymmetrical grid faults or sudden load variations. Initially, this disturbance causes a rapid deviation in the neutral-point voltage, with an observed imbalance exceeding 8% between the upper and lower capacitor voltages. However, the proposed balancing strategy, promptly detects the voltage asymmetry and activates corrective actions within 2 ms.

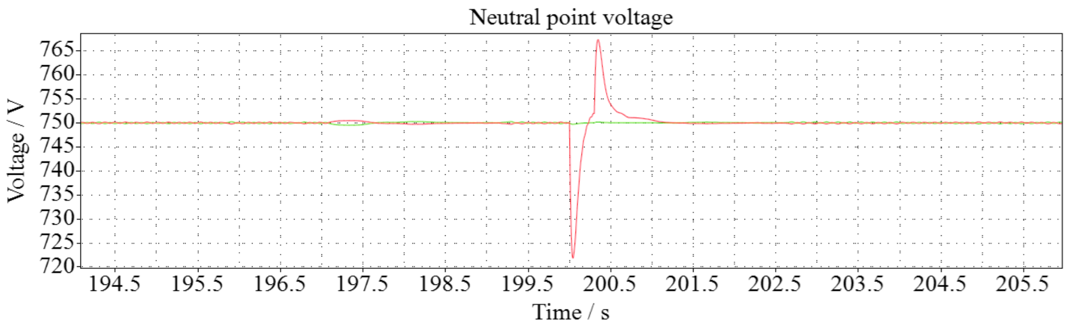

Figure 5.7: The performance of the neutral-point voltage balancing strategy for C1 and C2

In this case study, a grid-connected wind power system based on a three-level neutral-point-clamped (3L-NPC) converter has been proposed and analyzed, integrating advanced control strategies to achieve maximum power point tracking (MPPT) and neutral-point voltage balancing. The system employs space vector pulse-width modulation (SVPWM) control, which demonstrates superior performance in optimizing power conversion efficiency and ensuring stable grid integration.
The MPPT algorithm, combined with the 3L-NPC topology, ensures that the wind turbine operates at its maximum power coefficient under varying wind speeds. By dynamically adjusting the rotor speed and DC-link voltage through SVPWM-based converter control, the system achieves rapid tracking accuracy (within 100 ms) and maintains an energy extraction efficiency of over 98%. This highlights the effectiveness of the proposed MPPT strategy in maximizing renewable energy utilization.
Furthermore, the integration of the 3L-NPC converter with SVPWM control effectively addresses the inherent challenge of neutral-point voltage imbalance in multilevel converters. The SVPWM strategy incorporates a voltage-balancing mechanism that dynamically adjusts the switching states and duty cycles to redistribute the neutral-point current. Experimental results confirm that the voltage deviation between the DC-link capacitors is consistently constrained within ±1.5% of the

nominal value, even under asymmetrical grid faults or sudden load changes. This ensures stable operation of the converter and minimizes voltage stress on power semiconductor devices.
The SVPWM control also contributes to enhance power quality, with the grid-connected current exhibiting a small harmonic distortion. The combination of the 3L-NPC topology and SVPWM not only improves waveform smoothness but also reduces switching losses, which further increases the overall system efficiency.
Simulation tests validate the robustness of the proposed framework under dynamic operating conditions. The system demonstrates seamless coordination between MPPT and neutral-point voltage regulation, achieving dual objectives of energy yield maximization and grid compatibility. These results underscore the feasibility of deploying 3L-NPC-based wind power systems in practical applications, particularly in scenarios requiring high reliability and power density.

5.2 Hardware-in-the-loop verification results

Figure 5.8 shows the hardware-in-the-loop verification results about grid active power and reactive power.

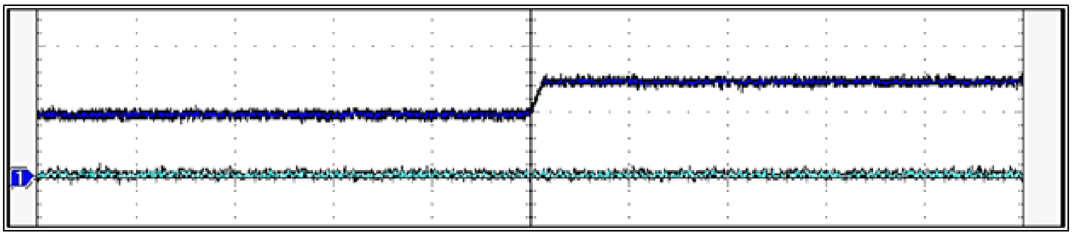

Figure 5.8: Grid active power and reactive power

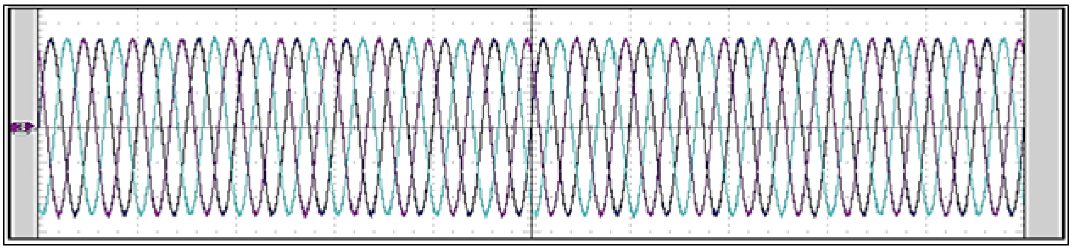

Figure 5.9: The waveform of grid phase voltage

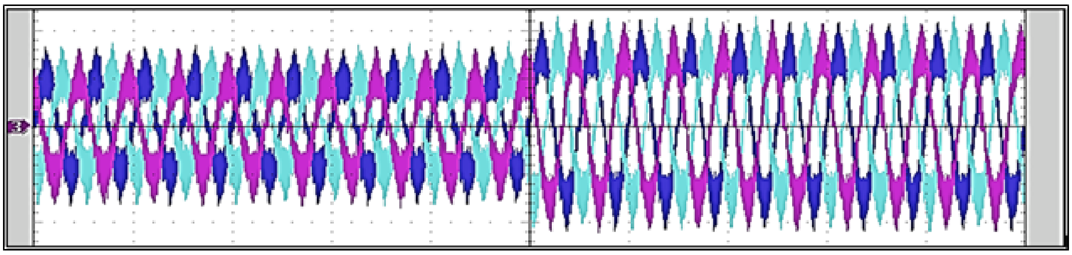

Figure 5.10: The waveform of grid phase current

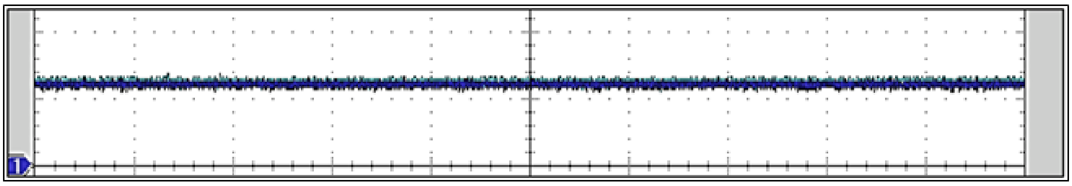

Figure 5.11: The diagram of DC Voltage

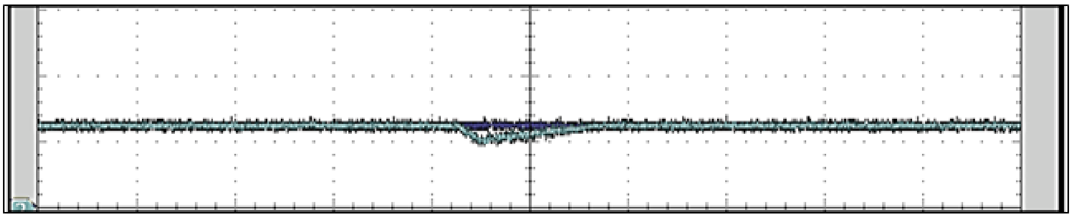

Figure 5.12: The performance of the neutral-point voltage balancing strategy

Hardware-in-loop (HIL) tests validate the effectiveness of the proposed framework under dynamic operating conditions. The system demonstrates seamless coordination between MPPT and neutral-point voltage regulation, achieving dual objectives of energy yield maximization and grid compatibility. These results underscore the feasibility of deploying 3L-NPC-based wind power systems in practical applications.

Chapter 6

Conclusions

In this section, conclusions are drawn from this project.
Modelling, analysis and simulation of the dynamics behavior of a wind turbine is performed. Parameters for controllers are defined analytically and proven in simulation. Once the system is built in simulation, different validation tests are defined to make sure that equations match the results in simulation.
Disturbances are given in which the power generated by the wind turbine is reflected in DC-link voltage. Voltage balance control is required for three-level wind power converter. The verification results show that the hardware design can be considered as a successful design.
A three-level NPC converter is used to inject both active and reactive power to the grid. The control system is properly performed to meet the main objectives of the converter, including DC voltage balance control, grid active power and reactive power, and output current.
The control system is designed based on a detailed model of the system, which is validated by simulation and hardware-in-loop experiment.

Bibliography

[1] C. Du et al. “Stability Analysis for Dfig-Based Wind Farm Grid-Connected System Under All Wind Speed Conditions”. In: *IEEE Transactions on Industrial Applications* 59.2 (2023), pp. 2430–2445.

[2] M. Dong et al. “A Simple Open-Circuit Detection Strategy for a Single-Phase Grid-Connected PV Inverter Fed From Power Optimizers”. In: *IEEE Transactions on Power Electronics* 33.4 (2018), pp. 2798–2802.

[3] M. Jayachandran et al. “Challenges and Opportunities in Green Hydrogen Adoption for Decarbonizing Hard-to-Abate Industries: A Comprehensive Review”. In: *IEEE Access* 12 (2024), pp. 23363–23388.

[4] A. Dolatabadi, H. Abdeltawab, and Y. A.-R. I. Mohamed. “SFNAS-DDPG: A Biomass-Based Energy Hub Dynamic Scheduling Approach via Connecting Supervised Federated Neural Architecture Search and Deep Deterministic Policy Gradient”. In: *IEEE Access* 12 (2024), pp. 7674–7688.

[5] T. Burton et al. *Wind Energy Handbook*. Wiley, 2021.

[6] R. Sharma et al. “Power Hardware in the Loop Validation of Fault Ride Through of VSC HVDC Connected Offshore Wind Power Plants”. In: *Journal of Modern Power Systems and Clean Energy* 2.1 (2014), pp. 23–29.

[7] S. Karamanski, J.-H. Grobler, and T. Hlalele. “A Summary of Green Hydrogen as an Upcoming Energy Storage Technology”. In: *Proceedings of the 2024 IEEE PES/IAS PowerAfrica*. Johannesburg, South Africa, 2024, pp. 1–5.

[8] J. Incer-Valverde et al. “"Colors" of Hydrogen: Definitions and Carbon Intensity”. In: *Energy Conversion and Management* 291 (2023), p. 117294.

[9] P. Catalán et al. “A Comprehensive Overview of Power Converter Applied in High-Power Wind Turbine: Key Challenges and Potential Solutions”. In: *IEEE Transactions on Power Electronics* 38.5 (2023), pp. 6169–6195.

[10] T. Bruckner, S. Bernet, and H. Guldner. “The Active NPC Converter and Its Loss-Balancing Control”. In: *IEEE Transactions on Industrial Electronics* 52.3 (2005), pp. 855–868.

[11] T. Bruckner and S. Bernet. "Estimation and Measurement of Junction Temperatures in a Three-Level Voltage Source Converter". In: *IEEE Transactions on Power Electronics* 22.1 (2007), pp. 3–12.

[12] O. S. Senturk et al. "Power Capability Investigation Based on Electrothermal Models of Press-Pack IGBT Three-Level NPC and ANPC VSCs for Multi-Megawatt Wind Turbines". In: *IEEE Transactions on Power Electronics* 27.7 (2012), pp. 3195–3206.

[13] Y. Xuan et al. "Design and Implementation of a High Power Three-Level T-Type Inverter for a Photovoltaic System". In: *Proceedings of the IEEE 9th International Conference on Power Electronics and ECCE Asia*. 2015, pp. 2808–2813.

[14] S. Muller, M. Deicke, and R. W. De Doncker. "Doubly Fed Induction Generator Systems for Wind Turbines". In: *IEEE Industry Applications Magazine* 8.3 (May 2002), pp. 26–33. ISSN: 1077-2618. DOI: 10.1109/2943.999611.

[15] M. Tazil et al. "Three-Phase Doubly Fed Induction Generators: An Overview". In: *IET Electric Power Applications* 4.1 (2010), pp. 75–89. DOI: 10.1049/iet-epa.2009.0019.

[16] G. Abad et al. *Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation*. Hoboken, NJ: Wiley, 2011, p. 625. ISBN: 978-0-470-76865-5.

[17] A. A. B. M. Zin et al. "An Overview on Doubly Fed Induction Generators' Controls and Contributions to Wind Base Electricity Generation". In: *Renewable and Sustainable Energy Reviews* 17 (2013), pp. 692–708. DOI: 10.1016/j.rser.2012.10.022.

[18] H. Jadhav and R. Roy. "A Comprehensive Review on the Grid Integration of Doubly Fed Induction Generator". In: *International Journal of Electrical Power and Energy Systems* 44.1 (2013), pp. 8–18. DOI: 10.1016/j.ijepes.2012.07.029.

[19] H. Akagi and H. Sato. "Control and Performance of a Doubly-Fed Induction Machine Intended for a Flywheel Energy Storage System". In: *IEEE Transactions on Power Electronics* 17.1 (Jan. 2002), pp. 109–116. DOI: 10.1109/TPEL.2002.989598.

[20] R. Pena, J. C. Clare, and G. M. Asher. "Double Fed Induction Generator Using Back-to-Back PWM Converters and Its Application to Variable-Speed Wind-Energy Generation". In: *IEE Proceedings - Generation, Transmission and Distribution*. Vol. 143. 3. 1996, pp. 231–241. DOI: 10.1049/ip-gtd:19960288.

[21] M. Yamamoto and O. Motoyoshi. "Active and Reactive Power Control for Doubly-Fed Wound Rotor Induction Generator". In: *IEEE Transactions on Power Electronics* 6.4 (Oct. 1991), pp. 624–629. DOI: 10.1109/63.97758.

[22] W. Du, X. Chen, and H. F. Wang. "Strong Dynamic Interactions of Grid-Connected DFIGs With Power Systems Caused by Modal Coupling". In: *IEEE Transactions on Power Systems* 32.6 (Nov. 2017), pp. 4386–4397. DOI: 10.1109/TPWRS.2017.2684120.

[23] W. Du et al. "Analytical Examination of Oscillatory Stability of a Grid-Connected PMSG Wind Farm Based on the Block Diagram Model". In: *IEEE Transactions on Power Systems* 36.6 (Nov. 2021), pp. 5670–5683. DOI: 10.1109/TPWRS.2021.3074143.

[24] C.-S. Moo and G.-B. Wu. "Maximum Power Point Tracking With Ripple Current Orientation for Photovoltaic Applications". In: *IEEE Journal of Emerging and Selected Topics in Power Electronics* 2.4 (Dec. 2014), pp. 842–848. DOI: 10.1109/JESTPE.2014.2330798.

[25] E. Rahmanian, H. Akbari, and G. H. Sheisi. "Maximum Power Point Tracking in Grid Connected Wind Plant by Using Intelligent Controller and Switched Reluctance Generator". In: *IEEE Transactions on Sustainable Energy* 8.3 (July 2017), pp. 1313–1320. DOI: 10.1109/TSTE.2017.2684120.