Modelling and Simulation of DFIG for wind energy applications using PWM converters

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Abstract

Modelling and Simulation of DFIG for wind energy applications using PWM converters

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This research work focuses on Double Fed Induction Generator Modelling and Simulation in wind energy conversion system applications. DFIG is one of the most common machines in modern wind power generation because of its capability to operate efficiently for a wide range of wind speeds. The design of the system consists of two back-to-back connected PWM converters through a dc link. In this scheme the stator of DFIG is connected to the grid directly, while rotor connected to the grid through two back-to-back converters and DC Link. A 2 MW DFIG system is modelled and simulated in the specialized power electronics tool PLECS. This work significantly demonstrates the ability to maintain grid stability which has been achieved by simulating the system under three different speeds for both regular and fault conditions. The simulation demonstrates that the system can keep normal grid parameters, manage energy transmission, and smooth transition between sub-synchronous, synchronous and super-synchronous zones, even during disturbances like a three-phase fault.

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DEDICATION

I dedicate this work to my daughter

Chapter 1. INTRODUCTION

The increasing demand for energy, coupled with environmental challenges such as global warming and the depletion of fossil fuels, demands a search for and adoption of sustainable energy solutions. Renewable energy sources such as wind, solar, and biomass have emerged as viable alternatives due to their ability to produce energy with minimal environmental impact. Of the above, wind energy is now considered a clean and rich resource; it contributes significantly to the reduction of greenhouse gas emissions and enables sustainable development [13][14]. Technological advances in wind energy conversion systems (WECS) have consequently enabled the efficient harnessing of wind energy. The DFIG is one of the most important innovations that has enabled variable-speed operation and effective capture of energy over fluctuating wind conditions. Because they can operate at partial power conversion through back-to-back converters, they are energy-efficient and cost-effective for large-scale applications [4][8]. This research is focused on the design, modeling, and simulation of a DFIG system equipped with back-to-back PWM converters in the rotor circuit. A DC-link between the rotor and grid-side converters will ensure seamless energy transfer and storage to enable stable grid operations. For the grid-side converters, vector-controlled schemes are implemented to enhance system performance for fluctuating wind conditions [4][5].

1.1 Background and Motivation

Global energy consumption has increased at a tremendous rate, hence exhausting conventional energy resources rapidly and giving rise to ecological concerns. Renewable energy technologies present a viable path for overcoming these challenges. Wind energy is one of the world's fastest-growing renewable energy technologies. From 2001 through 2023, installed global wind power capacity increased exponentially, reflecting increased dependence on this source of clean energy [16][17].

Despite such growth, many challenges persist in the optimization of energy conversion and in maintaining grid stability in varying wind conditions. Therefore, it has motivated research into advanced systems such as DFIGs, capable of providing flexibility and efficiency in capturing and converting energy accordingly [10][7].

1.2 Thesis Organization

The thesis is organized into the following chapters:

Chapter 1: Introduction

This chapter provides the background and motivation for the research. This chapter outlines the importance of wind energy as a renewable source, along with the contribution made by DFIGs within modern WECS. It states the problem statement and elaborates on the scope of the study.

Chapter 2: Renewable Energy and Wind Power Development

The chapter provides an overview of wind energy source growth and significance within renewable energy sources. It discusses PV Energy and Wind Energy as these two are highly demanded renewable energy sources. A description of the wind turbine technologies and their historical evolution focuses on the transition to advanced generator systems, such as DFIGs.

Chapter 3: Generators Used in Wind Energy Conversion Systems

This chapter introduces the different types of generators used in variable-speed wind turbines, such as Squirrel Cage Induction Generators (SCIG), Wound Rotor Induction Generators (WRIG), Permanent Magnet Synchronous Generators (PMSG), and DFIGs. It also compares these technologies and discusses the suitability of the DFIG for variable-speed wind turbines.

Chapter 4: Power Converter Topologies

This chapter provides discussions on power converters applied in a wind turbine and their integration into VSCs and CSCs for advanced topologies, as well as new topologies including back-to-back PWM converters. More important, through this chapter, it shows its importance with respect to reliable grid integration and effective power conversion.

Chapter 5: DFIG-Modelling and Simulation

This chapter details the mathematical modeling of DFIG systems, including their mechanical and electrical components. The chapter introduces the dq-axis transformation and explains the dynamic equations governing DFIG behavior. Control strategies for the Rotor Side Converter (RSC) and Grid Side Converter (GSC) are also presented, along with their implementation in PLECS.

Chapter 6: Simulation Results

This chapter presents the simulation results of a 2 MW DFIG system operating under various conditions, including transitions between sub-synchronous, synchronous, and super-synchronous speeds. It presents the performance of the system during normal and fault conditions to show its robustness and capability for fault ride-through.

Chapter 7: Conclusion

This chapter summarizes the key findings of the research, emphasizing the advantages of DFIG systems in modern wind energy applications. It also suggests directions for future work to enhance the efficiency and reliability of wind energy systems.

Chapter 2. RENEWABLE ENERGY SOURCES

For the past few decades, energy demands have gradually increased, especially for electrical power and environmental issues, and this has become a challenging issue for the world. Furthermore, pollution is growing parallel with the energy demand while conventional energy sources such as fossil fuels are rapidly depleting. Over the last few decades, researchers have been conducting studies to improve energy efficiency [1]. This has led to the discovery of various alternatives for renewable energy, a combination of natural sources used for electrical power generation. These natural sources are sunlight, geothermal heat, wind, tide, water, and various forms of biomass. These sources are free of cost and reduce the greenhouse effect. Renewable energy is energy that comes from a source that will not run out. It is natural, self-replenishing, and usually has a low or zero carbon footprint. Examples of renewable energy sources include wind power, solar power, bioenergy (organic matter burned as a fuel), and hydroelectric, including tidal energy.

In the last few years, renewable energy has experienced one of the most significant growth areas, with a percentage of over 30 % per year, compared with coal and lignite energy growth. The European Community (the EU) aims to reach 45 % in 2030, but the EU-27 energy is only 17 % of world energy. With 22 % of the energy share, the US has adopted similar goals under the pressure of public opinion concerned with environmental problems and overcoming the economic crisis. However, the policies of Asia and Pacific countries, with 35 % of the energy share, will probably be more critical in the future energy scenario. Countries like China and India continuously require more energy (China's energy share has increased by 1 point yearly since 2000). The need for more energy in emerging countries and the environmental concerns of the US and the EU increases the importance of renewable energy sources in the future.

2.1 PV ENERGY DEVELOPMENT

Negative climate changes, contamination of the countryside, worldwide population growth, urbanization, and other factors have caused an increase in temperature and environmental problems. The modern world operates with energy from fossil fuels at volatile prices, contributing to greenhouse gas emissions and other pollutants. Most scientists agree that the Earth is warming faster than ever due to the enormous amount of greenhouse gases that humans are releasing into the atmosphere [2]. Increasing global energy consumption results in the depletion of fossil fuel resources and increases greenhouse gas (GHG) emissions, contributing to global warming. Greenhouse gases are components of the Earth's atmosphere, and due to their physicochemical properties, they can retain solar energy within the Earth's atmosphere. These gases directly impact the greenhouse effect as they absorb infrared radiation from our planet and prevent energy from being released into outer space, increasing the atmosphere's temperature and the Earth's surface.

The world is looking for new renewable energy sources, and PV is becoming more critical in solving these climate change issues. It is believed that PVs, wind, and other renewable energy sources will represent a significant portion of the future energy mix. The ability to develop renewable energy sources will decrease the price volatility in the electricity market. PV consumption has been increasing due to the replacement of fossil fuels for energy. Although PVs were not the largest producer of renewable energy in 2020, their role and share of the market will increase with the 2030 and 2050 targets. In a PV installation, the light unit, i.e., a photon, after contact with the silicon contained in the PV module, produces an electron movement. Accordingly, electricity is generated. An inverter that converts direct current into an alternating current is a device needed to use the generated energy. The PV modules can be installed not only in buildings but also in fields. This flexibility in installation means that PVs have a chance to become the leading source of power generation [3]. Solar and wind-assisted heat pump to meet the building air conditioning and electric energy demand in the presence of an electric vehicle charging station and battery storage.

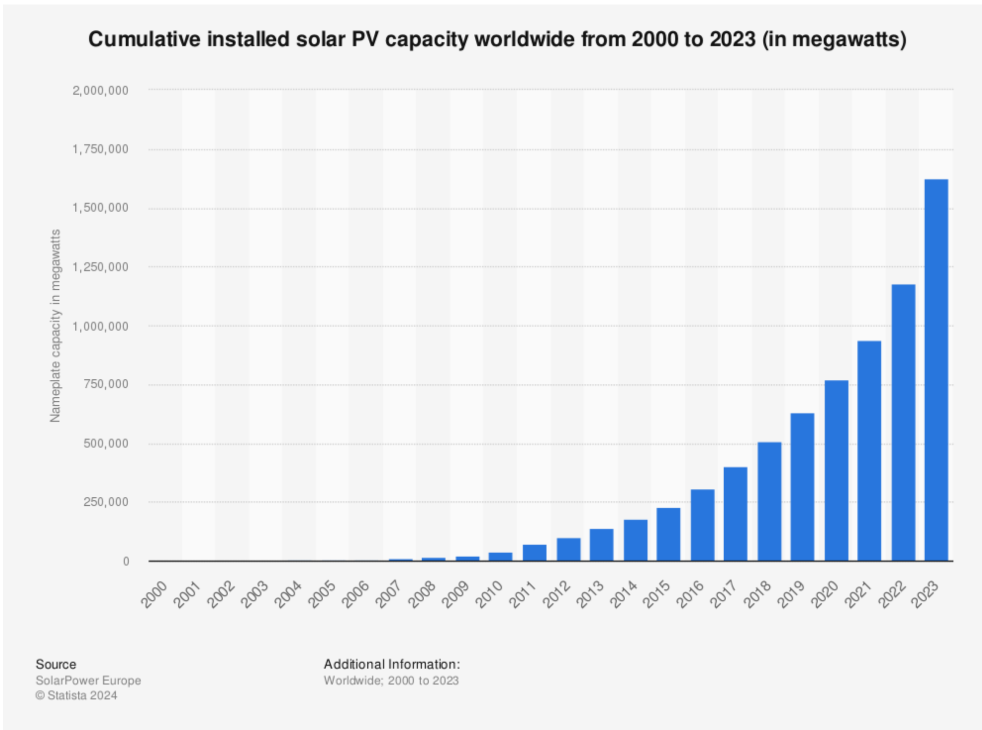

Figure 2.1 Cumulative Installed Solar Power Capacity [17]

2.2 WIND ENERGY DEVELOPMENT

Wind power, or wind energy, is a form of renewable energy that harnesses the power of the wind to generate electricity. It involves using wind turbines to convert the kinetic energy of moving air into the turning motion of blades, which is then transformed into electrical energy.

Wind power is one of the fastest-growing methods of producing renewable energy, making it crucial as the world shifts toward cleaner, more sustainable energy sources. With increasing concerns about climate change, the depletion of fossil fuels, and environmental damage, wind power offers a clean, efficient, and abundant energy solution.

Using the wind to generate power is not a new idea. People have used windmills for tasks like grinding grain or pumping water since the 7th century in places like Persia and the Middle East. This idea spread to Europe, where it also became essential for agriculture. However, it was not until the 1800s, when electricity became more common, that people started thinking about wind as a way to generate electrical power instead of using fossil fuels [10].

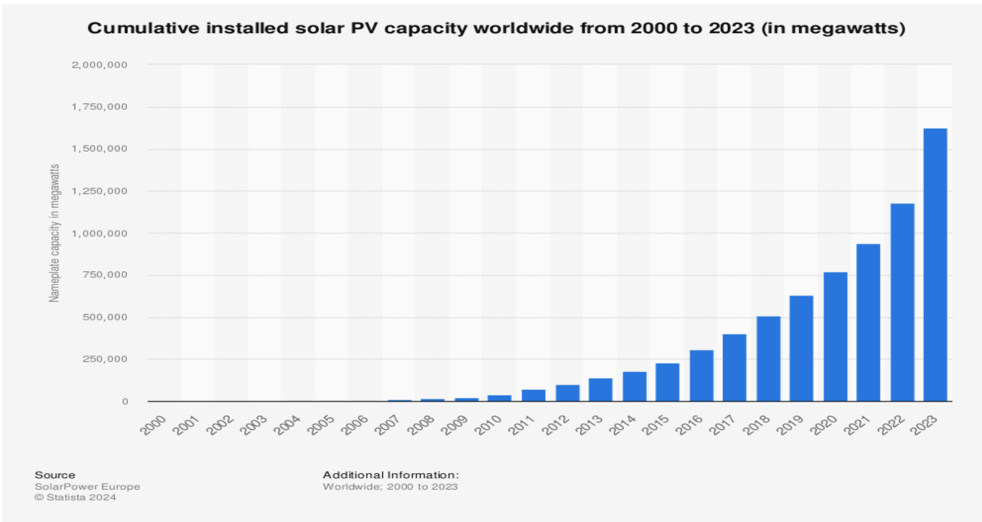

Figure 2.2 Cumulative Installed Wind Power Capacity [17]

2.2.1 *Historical Background*

In the 1900s, engineers developed wind turbines to capture wind energy more efficiently. The oil shortages in the 1970s made people more interested in renewable energy, which led to significant investment in wind power [11][15]. Today's wind turbines, with their modern designs and advanced technology, can produce large amounts of electricity, comparable to the amount generated by traditional power plants that run on fossil fuels [13][16].

Wind turbine system technology is still the most promising technical energy technology it started in the 1980s with a few tons of kilo watt power production per unit today multi megawatts size winter beds are being installed reference one to four and they are used advanced power generators [15] [16].There is a widespread of wind turbine systems in the distribution networks as well as there are more and more wind power stations which are connected to the transmission networks Denmark for example has a high power capacity penetration more than 30% of wind energy in major areas of the country on today 25% of the all electrical energy consumption is covered by wind energy the aim is to achieve 100 percent non fossil based power generation system in 2050 [15] [16].

Initially wind power did not have any serious impact on the power system control but now due to its size wind power has to play a much more active path in grid operations and control [13] [3].

The technology used in wind turbines was originally based on a squirrel cage induction generator connected directly to the grid power. variations in the wind were almost directly transferred to the electrical grade by using this technology as the speed is fixed furthermore no dynamic control of the active and reactive power exists except for it a few bypass capacitor banks which ensured unity power factor at the point of common coupling [4][5].

As the power capacity of the wind turbine increases regulating the frequency and the voltage in the grid become even more important. During the last decade it has become necessary to introduce power electronics as an intelligent interface between the wind turbine and the grid. power electronics is changing the basic characteristics of the wind turbine from being an energy source to being an active power source for the grid the electrical technology used in the wind turbine is not new it has been discussed for several decades but now the cost per kilowatt of a new wind power plant is comparable and even lower than coal power plants hence solutions with power electronics are very attractive. These innovations transformed the basic characteristics of wind turbines from passive energy sources to active contributors to grid stability and operations [8] [16]. While the electrical technology used in wind turbines has been under discussion for decades, the current cost per kilowatt of new wind power plants is now comparable to, or even lower than, that of coal power plants, making power electronics solutions highly attractive [8] [16].

2.3 Conclusion

This chapter focused on the increasing importance of renewable energy sources, particularly advances in solar and wind energy systems, as important means of addressing increasing global demand while taking environmental challenges into consideration. Solar power, becoming increasingly flexible in installation and highly contributory to reducing greenhouse gas emissions, continues to forge ahead as a sustainable energy source. In the same fashion, wind energy has grown into a key technology to provide clean, efficient, and abundant power generation. Though highly relevant, solar and wind are the two significant contributors that shape the future of renewable energies, this study focuses specifically on Wind Energy Conversion Systems (WECS). It performs the modeling and simulation of the wind energy system, particularly focusing on DFIG, which may enable efficient and flexible energy generation under variable conditions of wind speed. This study is expected to contribute toward the development of a reliable, advanced wind energy technology contributing to a sustainable energy future.

Chapter 3. GENERATORS IN WIND ENERGY CONVERSION SYSTEMS

In Wind turbine systems generator is a major part, it converts mechanical energy into the electrical energy. As the wind blows turbine rotates which in turn connects with the shaft of the generator through the gearbox. There are mainly five types of generators used in Wind turbine systems.

1. Squirrel cage Induction generators
2. Wound Rotor Induction Generators
3. Permanent magnet Induction Generators
4. Synchronous Generators
5. Double fed Induction Generators

3.1 Squirrel cage Induction Generators

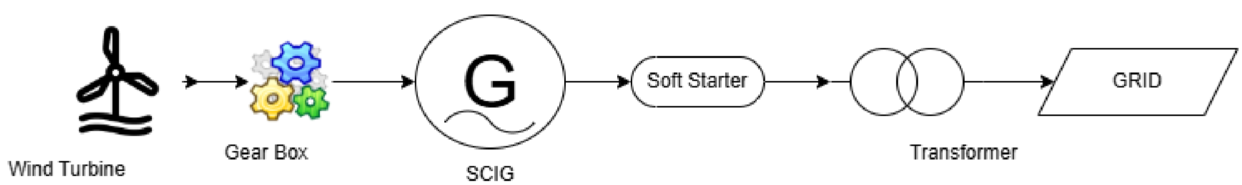

Figure 3.1 Single Line Diagram of Squirrel Cage Induction Generator in WECS.

These are simple in design and reliable generators. Mostly used in small wind turbine plants. These are easy to maintain and robust construction. That is why in the early years of Wind power development they used Squirrel cage Induction motors [27]. Squirrel cage induction generators (SCIGs) are widely used in wind power plants, particularly in smaller or older wind turbines. They are famous for their robustness, simplicity, and low cost. SCIGs are a popular choice for converting wind energy into electrical energy. Unlike synchronous generators, SCIGs operate at a slightly variable speed, because of this they are well suited to fluctuating wind conditions. We often encounter fluctuating wind conditions in wind energy applications [28]. Below are the structure, operation, advantages, and limitations of SCIGs in the context of wind power generation.

3.1.1 *Structure, Principle of Operation, Advantages and Disadvantages*

SCIGs name came from the structure of the rotor. It resembles a squirrel cage. The rotor consists of conducting bars, usually made of aluminum or copper, that are short-circuited by end rings, forming a continuous conducting loop. The stator is the stationary part of the generator. It contains three-phase windings connected to the grid or load.

In operation, an external source, usually connected to the grid, is needed to provide the magnetizing current that creates a rotating magnetic field in the stator. This rotating field induces currents in the rotor bars. The currents in the rotor in turn produce a secondary magnetic field. The interaction between the stator's rotating magnetic field and the induced magnetic field in the rotor produces torque, causing the rotor to spin. When the rotor speed is greater than the synchronous speed of the magnetic field, the generator begins to produce electricity by converting mechanical energy from the wind turbine into electrical energy [5] [11].

One key feature of SCIGs is that they operate at a speed slightly lower than synchronous speed, referred to as "slip." This slip allows a small degree of speed variation, accommodating the wind's fluctuating nature to some extent without requiring complex control systems [25].

SCIGs have been used in many small and old wind turbine systems because of their simplicity, strength, and low maintenance cost. Their operational cost is low as they are brushless and durable in construction. SCIGs can be directly connected to the grid, which further simplifies the design of the turbine by avoiding sophisticated conversion components [27]. However, they have several setbacks: a narrow range of operational speeds, dependence on reactive power provided by the grid, and energy losses due to slip that reduce their efficiency compared to other advanced technologies such as Doubly-Fed Induction Generators. Despite these setbacks, SCIGs still fit within niche applications in this market, including hybrid and off-grid wind systems, based on their reliability and simplicity [11][5].

3.2 WOUND ROTOR INDUCTION GENERATORS

WRIGs are most widely usen in wind power plants, ranging from medium to large-scale wind turbines. The capability for operation at variable speed and efficiently handling fluctuating wind conditions has made WRIG an important agent in the renewable sector. In contrast to the squirrel cage type of induction generators, a wound rotor induction generator has a rotor with windings that are extendable to allow external control, thus giving more flexibility during power generation. The following overview explains how WRIGs work, including various advantages and disadvantages, and how they fit into today's wind power systems.

3.2.1 *Structure, Principle of Operation, Advantages and Disadvantages*

The name itself suggests that WRIGs have windings on the rotor, unlike the squirrel cage rotor, which has short-circuited bars. Its rotor is wound with insulated copper wire in the form of a three-phase winding similar to that of the stator in the case of a WRIG. These windings are connected to external resistors or converters via sliprings. That allows rotor current control and provides better speed adjustment [5][7].

For operation, the rotor is rotated by turbine which is driven by the wind. It creates rotating magnetic field in the stator windings connected to the grid. A particular feature of WRIG is that current in the rotor winding can be controlled from the outside, normally through power electronics. This feature enables the WRIGs to vary their slip—a quantity defined as the difference between rotor speed and synchronous speed over a wider range, allowing them to efficiently operate under different wind speeds condition [4][9][11]. Since the control is done on the rotor current, the output power can be optimized according to wind conditions. Hence, the WRIGs are appropriate for applications that include variable speed from wind [8][12].

WRIGs offer a number of advantages that make them quite suitable for modern wind power applications. Due to the active rotor resistance can be controlled externally, either by using external resistors or converters which in turn control the currents. WRIGs are capable of variable speed operation [15]. This feature allows generator to adapt to fluctuating wind conditions, optimizing energy production in regions characterized by variable wind patterns. Another advantage of WRIG is that it improves power quality, which is very much necessary for grid stability when it comes to large-scale wind farms [19]. Their wider range of speed reduces mechanical stress on the components of the turbines and hence increases durability while reducing wear due to sudden wind gusts [13][19].

Besides, the converter ratings are lower in WRIGs than in completely variable-speed systems such as DFIGs, which makes them more efficient with reduced system complexity. One of the drawbacks of the WRIG is the regular maintenance required for slip rings and brushes, adding to operational costs and difficulties in offshore or remote locations. Moreover, the need for reactive power to generate the magnetic field further complicates and makes the system more costly by requiring grid support or, alternatively, additional compensating mechanisms, while their efficiency remains low compared to DFGs, thus making these solutions less favored in the large-scale wind farms [5][9].

Despite this, WRIGs are suited to medium-sized turbines and hybrid systems, offering a cost-effective solution when not all the benefits of variable-speed operation are required. Advancements in power electronics, control technologies, and rotor designs, together with improvements in slip rings and reactive power management, will further improve the reliability and efficiency of WRIGs and widen their applications to offshore and remote wind farms where reliability and robustness are paramount [5][9][17].

3.3 Permanent Magnet Induction generators

Permanent magnet induction generators are the ones whose magnetic field is created by permanent magnets. By contrast to conventional induction generators excited from external sources, PMIGs use the self-inherent magnetic field of permanent magnets mounted on the rotor, therefore they are self-exciting and efficient. They find an extensive application in various renewable energy sources and, above all, in wind power converting due to their very high efficiency, reliability, and capability of generating power within a wide range of variations in the wind speed [19][21].

3.3.1 *Structure, Principle of Operation, Advantages and Disadvantages*

Most PMIGs structurally resemble other types of induction generators, with permanent magnets fixed on the rotor. The stator contains the coils of the conductive material-usually copper-wound around in a very specific manner to most efficiently induce current. Now, the magnetic field is provided by permanent magnets made of rare-earth materials, instead of electromagnetic excitation due to an external current. Such magnets establish a fixed magnetic flux which, interacting with the rotating stator, induces an EMF in rotation. That will enable PMIGs to generate power at much lower speeds, thus allowing their use in regions with variable wind conditions [17].

In this case, turbine blades turned by wind in turn rotate the rotor of the turbine. The cutting of the magnetic field created by the rotor across the stator windings creates an alternating current in the stator coils, which is directly fed to an inverter or connected to the grid. It is, of course, without the need for any kind of excitation system, which reduces losses of energy and, out of course, increases efficiency, making PMIGs ideal for a variable speed application.

3.4 Synchronous Generators

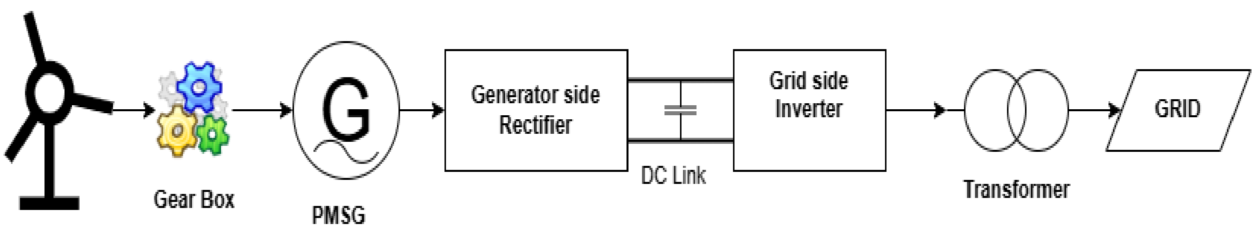

Figure 3.2 Single Line Diagram of PMSG Connected to WECS

Structure and Working Principle of Synchronous Generators:

Basically, a synchronous generator consists of two main parts, the stator and the rotor. The stator is the stationary part of the generator and is made up of windings around which electric current is induced. The rotor, which rotates inside the stator, is normally mounted with either electromagnets or permanent magnets in order to develop a magnetic field. By the rotation of the rotor, which changes the mechanical energy into electrical energy of constant frequency synchronized with the speed of the rotor, a current on the stator windings is induced. Therefore, synchronous generators are characterized by this constant frequency operation, which enables stable grid integration [2].

In a lot of applications, wind power has synchronous generators connected directly to the turbine shaft, this is what is referred to as direct drive. The major benefit of such a configuration is that this gearbox is eliminated, thus bringing down mechanical complexity and raising efficiency. In these configurations, the rotational speed of the rotor is low or precisely the rotational speed of the turbine. Variable frequency output from the generator normally needs power electronics, like inverters, that can provide a constant frequency matching that of the grid and hence ensure synchronism with the grid frequency [19]. It is due to this ease of integration with the grid that synchronous generators have been especially popular for large-scale wind power applications, particularly in offshore environments where reliability becomes so crucial.

3.4.1 *Types of Synchronous Generators used WECS, Advantages and Disadvantages*

Synchronous generators used in wind power plants can be categorized into two main types:
Permanent Magnet Synchronous Generators (PMSGs): PMSG deploys permanent magnets on the rotor for magnetic field creation so that no external power source is required to excite the rotor. PMSGs are very efficient and promise reduced maintenance due to the absence of slip rings and brushes [20]. This efficiency and reliability make PMSGs quite feasible for offshore wind farms, where access for maintenance is difficult and expensive.

Electrically Excited Synchronous Generators (EESGs): EESGs incorporate electromagnets on the rotor excited by an externally provided DC source to generate the magnetic field. Compared with PMSGs, these generators provide more controllable magnetic fields and normally higher cost-effectiveness since there is no expensive rare-earth magnet present. They require slip rings and brushes for current supply to the rotor, Thus, compared to EESGs, higher maintenance is required [4].

Synchronous generators have a number of advantages that make them very suitable for wind power applications, especially for offshore and large wind farms. They offer stable output frequency, thus simplifying grid integration by reducing the need for extensive frequency regulation equipment, something very welcome for large wind farms where reliability is a major issue. Besides, synchronous generators operate excellently in direct drive systems, with no use for gearbox mechanisms that are prone to mechanical abrasion, hence increasing efficiency and reducing maintenance-one key advantage in offshore locations, where maintenance is considerably costly and difficult to attend to [4]. Being able to provide reactive power support assures grid voltage stability and has made them vital tools in integrating large wind farms into the grid by offsetting fluctuations in power output and preventing voltage sags in the process [20]. Besides that, their robustness for harsh environmental conditions also comes from fewer moving parts and robust construction, which makes them even more suitable for offshore wind farms. Despite the advantages described above, synchronous generators have some drawbacks, including high initial costs, especially for Permanent Magnet Synchronous Generators, whose magnets are made of rare-earth materials that are quite expensive. They also require advanced control systems and power electronics for frequency and voltage matching in variable wind conditions, increasing technical complexity and costs[24]. Besides, thermal management is a challenge in high-power applications, requiring additional cooling systems that further add to the maintenance and operational requirements. Continuous innovation in power electronics, development of magnet alternative materials, and active thermal management should guarantee a shift toward economic sustainability with improved environmental profiles, yet future improvements will come from innovation-advanced systems within the increasing demand for wind energy applications.

3.5 DOUBLE FED INDUCTION GENERATOR

The Doubly fed induction generators are one of the predominant technologies in wind energy generation, keeping in view the features of variable speed and effective conversion of wind energy into electrical power. While the conventional induction generator has the possibility to connect to the stator only, the DFIGs have both the stator and the rotor connected to the grid [4][3].

This special attribute in control enables a wide range of speeds, with the essential needs of energy capture at variable wind conditions. DFIGs come with power electronic converters that make the generator produce output power with high quality and stability at fluctuating wind conditions. Hence, they are found to be highly efficient and reliable among modern wind farms [16][22][25].

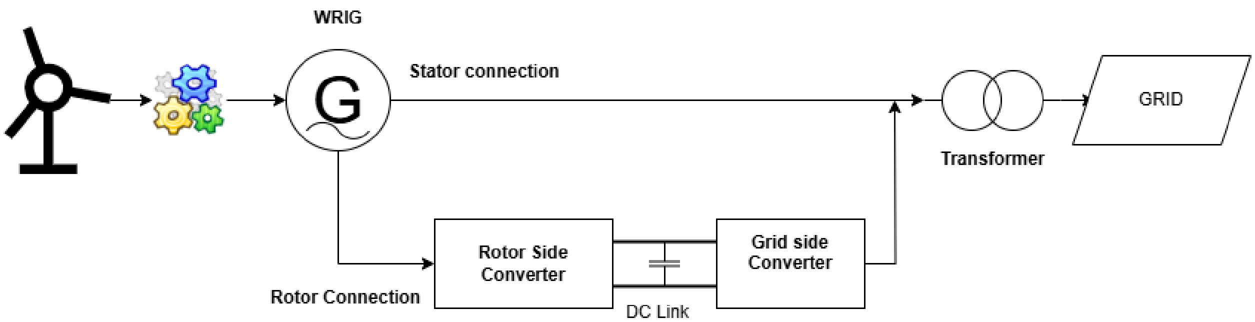

Figure 3.3 Single Line Diagram of Double Fed Induction Generator

Their novelty is that DFIGs have a wound rotor that is connected to the grid via slip rings and power converters. The stator is directly connected to the grid, while the rotor is connected through a bidirectional power converter, it consists of rotor side converter (RSC) and grid-side converter (GSC) [4]. This in turn allows operation of the DFIG at both super-synchronous and sub-synchronous speeds. This means that the converters deal with only a fraction-25-30%, in most cases-of the total power handled by the generator, hence making DFIGs more efficient than full-conversion systems.

With every variation in wind speed, there is a corresponding variation in rotor speed. The power converter controls the rotor current, which makes the speed control flexible and efficient. This enables the generator to maintain a constant frequency output to the grid at variable rotor speeds. This configuration makes the DFIG able to respond to turbulence in wind speeds and hence helps to capture more energy from the wind at the same time as keeping stability and reliability. DFIGs operate in four quadrants; therefore, they can generate and absorb reactive power, which is essential for grid stability and to reduce the need for additional reactive power compensation [5][29].

3.5.1 *Advantages of DFIGs in Wind Power Applications*

DFIGs have several significant advantages, making them widely adopted in wind power generation:

Variable-Speed Capability: DFIG has the capability to run over a range of speeds. In fact, this enhances its capability to capture the energy within the wind. Its operability over such a range provides better ability in areas of variable wind conditions, thus enabling the turbine to adapt and maximize output throughout different wind speeds[17]

High Efficiency: Since DFIGs only control a fraction of the total power through their converters, very high efficiency in energy conversion can be realized. It is the reason that makes the cost and size of the power electronics more feasible since partial power conversion is required in comparison to a full-power converter system such as PMSG [4].

Improved Grid Compatibility**:** The DFIG can provide active and reactive power due to its capability, which has a number of stabilizing effects on the grid. Large-scale wind farms have higher demands on the grid, therefore reactive power control of DFIG will dampen voltage fluctuations within the network without any additional equipment, apart from supporting grid stability [16].

Reduced Mechanical Stress: Due to the variable speed operation of DFIG, there is reduced mechanical stress on the turbine mechanical components since, in such a turbine, operation is based on varying the rotor speed according to changes in the wind rather than fixed rotor speed. It prolongs life for the turbine components, reduces maintenance costs, and increases overall reliability [4].

3.5.2 *Limitation and future scope of DFIG*

Despite their advantages, DFIGs have a few limitations:

Complexity and Cost: The complexity, in that the DFIG requires a dual power converter system along with slip rings, makes it more complicated than the simple fixed-speed generators. Such systems require additional maintenance on slip rings and converters that raise both operational costs and complexity, especially in offshore applications where access for maintenance may become restrictive [24]

Sensitivity to Grid Faults: DFIGs are very sensitive to grid faults, including voltage dips. The rotor currents may increase at low voltage and may cause damage to power electronics. Additional protection systems, such as crowbar circuits for the converters, may be required during fault conditions in order to protect converters from such changes, increasing cost and system complexity.

Dependence on Power Electronics: DFIG wind turbines producing electrical energy under variable speed rely heavily on power electronic converters. Furthermore, in addition to possible susceptibility of power electronics to environmental conditions, specialized maintenance, or protection may be needed; exposure to salt and moisture at offshore wind farms increases the possibility of component degradation.

DFIGs have become one of the most cost-effective, efficient, and adaptable machines in onshore and offshore wind farms all over the world. They are very popular in large-scale wind farms because of their reliable and flexible power output. The fact that DFIGs efficiently handle variable wind speeds means they are best suited for regions of varying wind conditions, hence making the projects more economically viable [29].

However, in the near future, improvement in power electronics and control systems could relieve some of the drawbacks now occurring in DFIG. For example, fault-tolerant converters with improved rotor protection mechanisms against grid disturbances can reduce the maintenance needs of DFIGs [22]. Furthermore, additional studies in the development and design of alternative materials for slip rings could increase the operational life span of DFIGs and thus make the turbines more competitive in renewable energy production. With holistic demand on renewable energy starting to increase, DFIG would remain the cornerstone for wind power generation, striking a fine balance among cost, efficiency, and grid compatibility.

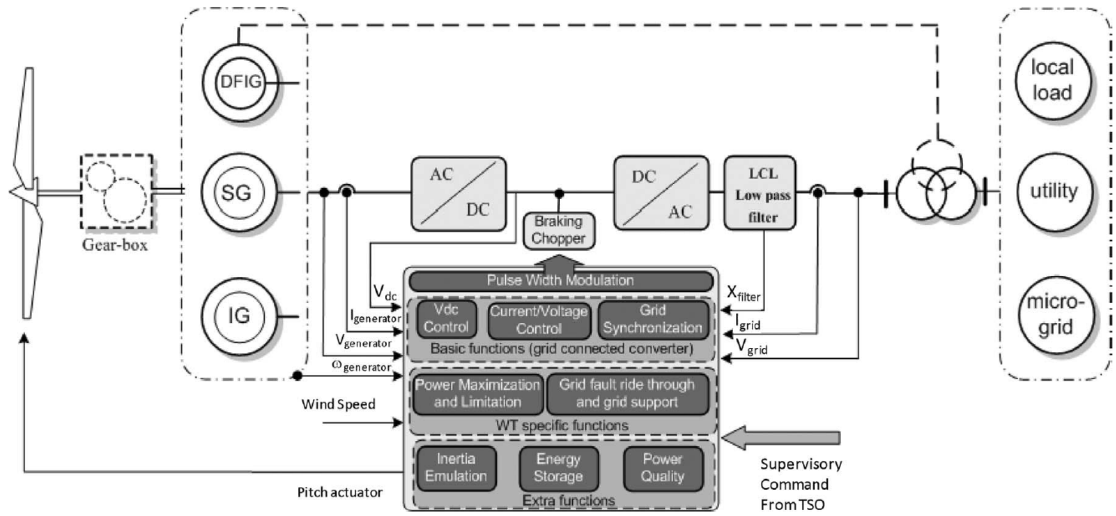

Figure 3.4 Different type of Generators Connected to the WECS. [24]

The wind energy conversion system is demonstrated here with a variety of generator options for grid integration: it depicts, on one hand, an SG whose stator is directly connected to the grid through a full-rated power converter to facilitate variable speed and precise control. Another choice would be a DFIG that couples the rotor to the grid using a partial-rated converter as a compromise in terms of both cost and performance. Last but not least is the induction generator, the one most commonly used with fixed speed: it consists of a gearbox boosting turbine speed, AC/DC/AC converters for converting power, and an LCL filter that minimizes harmonic content. Further, it can include PWM for voltage/frequency control, grid synchronism, and brake chopper to dissipate any surplus energy. It also points out the special functions of power maximization and grid stability, with the possibility of additional features such as inertia emulation and energy storage, showing the system's adaptability to varying loads and grid demands.

Table 1 Comparison of different generators used in WECS [13]

Feature	SCIG	WRIG + Variable Rotor Resistance	DFIG	SG (Synchronous Generator)	PMSG (Permanent Magnet Synchronous Generator)
Power Converters	<1% of rated	Partial	Partial	Full	Full
Converter capacity	N/A	Small	Reduced	Full	Full
Soft Starter	Yes	Yes	Yes	Yes	Yes
Speed Range	<1% of rated	<10% of rated	± 30% of rated	Full (100% of rated)	Full (100% of rated)
Gear box requirement	Yes	Yes	Yes	Yes	Yes
Aero Dynamic Power Control	Pitch	Pitch	Pitch	Pitch	Pitch
Grid side reactive compensation	Yes	Yes	Yes	No	No
Active Power Control/ MPPT	N/A	Limited	Yes	Yes	Yes
Maintenance requirement	++(Low)	+(Moderate)	0 (moderate)	0(Moderate/High)	0(Low)
Efficiency Rating	Low	Low-Reduced	Good	Good	Good

3.6 Conclusion

This chapter presents different types of generators used in wind energy conversion systems and discusses the special features, advantages, and limitations of each. Of these, the DFIG is far superior owing to its high capability on variable speed, high efficiency at partial power conversion, and active-active-reactive power control. Advanced control of DFIG through power converters makes it easy to integrate into the grid even with fluctuating wind conditions, and hence is preferred for large-scale and offshore wind farms. While other generators, such as SCIGs and WRIGs, try to impress with their simplicity and robustness, PMIGs and SGs impress with their efficiency and reliability, DFIG presents a balance between cost and performance, meeting the increased demand for alternative sources of energy. This paper will focus on DFIG, taking into consideration its excellent adaptability and advanced control features that can enhance the efficiency of wind energy conversion and the stability of the grid.

Chapter 4. GRID POWER CONVERTER TOPOLOGIES

The major demands that power converter topologies should meet in wind turbine systems are as follows: high reliability with limited maintenance, compact size/weight, and low power losses. AC/AC conversion in these systems can be either direct or indirect. In indirect conversion, the AC/DC and DC/AC transformations are done by two converters interconnected by a DC link. In contrast, direct conversion is without any DC link.

First, it provides de-coupling of the grid with the generator by managing the asymmetry and other power quality challenges. On the contrary, indirect conversion requires a big amount of energy storage [22] in the DC link that may cause thermal stresses, probably shortening its life span and simultaneously increasing the cost. The decoupling effect of the DC link due to an indirect conversion may offer advantages in the case of low voltage rise through but also provides inertia for smoothing power transfer from the generator to the grid.

The main advantage of direct conversion, as realized in the matrix converter topology, is its one-stage power conversion without any intermediate energy storage. This, among many advantages, comprises reduced thermal stress on power devices, lower switching losses than two-level back-to-back VSI, and improved harmonic performance on the generator side, which may possibly lead to an even lower switching frequency. The advantages listed above are supplemented by some serious documented disadvantages. These are the unreliability of the technology, higher component count, with more conduction losses, and control is bound to get more complicated. Besides, the designing of the grid filter is also a bit cumbersome in nature, with no unity in voltage transfer ratio. This structure is particularly attractive for an offshore wind turbine, where maintenance is difficult and where the lack of DC link storage is often the least reliable part of converters. For their utilization with doubly fed induction generators, matrix converters have been patented.

4.1 SINGLE CELL CONVERTER TOPOLOGY

Generally, these topologies are divided into voltage stiff (voltage-fed or voltage-source) and current-stiff (current-fed or current-source) configurations, with names VSC and CSC, respectively. The Z-source converter, being the third alternative, has an impedance network of capacitors and inductors on the DC side[24]. Depending on the principal direction of power flow, they are called either rectifiers or inverters. If it allows for a bidirectional flow of power, such converters are called bidirectional. On the other hand, they can be classified as phase-controlled-using thyristors and natural commutation synchronized with grid voltage-or PWM-based, using forced-commutated devices. In this respect, grid converters act mainly as inverters in the case of distributed power generation systems. While it can also be used for both the direction of power flow, they are useful in DC link pre-charging.

The AC output voltage of a VSC cannot exceed the DC input voltage; hence, it is basically a buck (step-down) inverter for DC/AC conversion and a boost (step-up) rectifier for AC/DC conversion. When the available DC voltage is low, such as that coming from direct-driven synchronous generators with a diode bridge rectifier, it is necessary to have an additional DC/DC boost converter to increase the DC voltage to an appropriate level for operating on the grid [25]. This additional stage adds system cost and reduces overall efficiency. In any phase leg of the inverter, the upper and lower switches cannot be turned on at the same time, intentionally or due to EMI noise, since this will create a "shoot-through" event that may destroy the switches. It is prevented by introducing a dead time between switch transitions, so as not to have any overlap between the upper and lower switch turn-on times; such dead time may result in waveform distortion. In order to reduce the current ripple and harmonic standards a high-order output filter is necessary, which would add to power losses and control complexity.

4.1.1 *Voltage source converter*

In a VSC, the main converter circuit is fed from a relatively large capacitor connected to a three-phase bridge. Typically, the circuit has six switches, each composed of a power transistor combined with a free-wheeling diode so that a current can flow bidirectionally while voltage is blocked unidirectionally [26]. Both passive AC and DC parts, like capacitors and inductors, are required in the VSC systems for energy storage, filtering, and other applications. Conventionally, the VSC operates with a DC capacitive storage element instead of DC inductive storage, where the capacitor is charged to a certain voltage level with the view of ensuring functionality of the VSC. By switching, the VSC regulates AC current to control the DC voltage, which is an important part in active rectifiers or filters. Since the AC active power converted into DC by the

VSC varies with the amplitude of the AC current, as seen from power balance. Thus, changes in AC active power result in changes of DC power, which charges or discharges the DC capacitor. This is an inter-related process wherein the DC capacitor charge, AC current control, and DC voltage regulation all draw on the energy storage capability of the capacitor. The need for PWM makes filtering at both the DC side and AC side necessary. Passive elements charge and discharge in every switching cycle, thereby smoothing the AC currents and stabilizing the DC voltage. This filtering is central to the control process, since dynamic behavior of both AC current and DC voltage controls depends upon the time constants of two-stage filtering. In general, design involves a trade-off between good filtering and fast response dynamics [27].

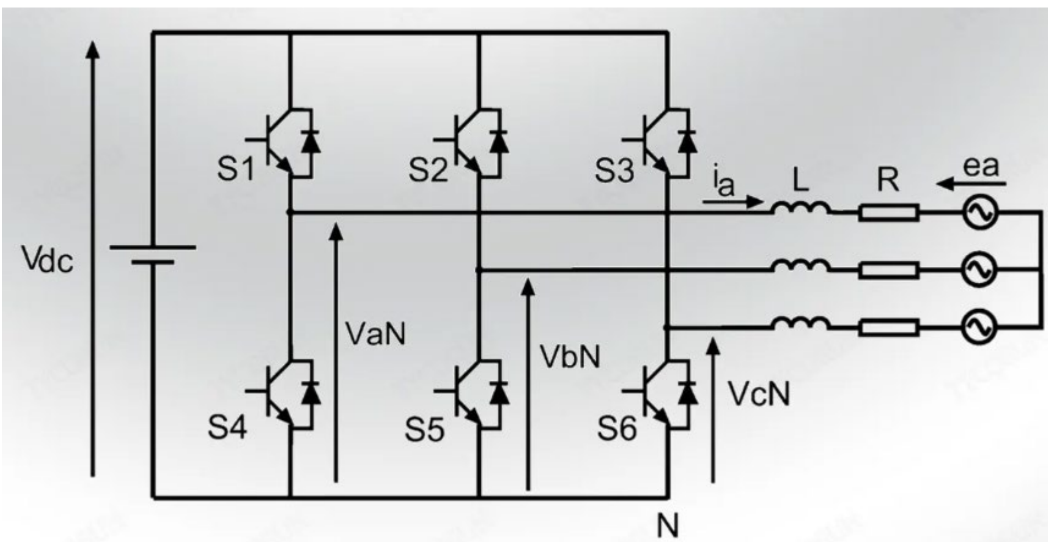

Figure 4.1 Voltage Source Converter [29]

The AC output voltage of a VSC cannot exceed the DC input voltage; hence, it is basically a buck (step-down) inverter for DC/AC conversion and a boost (step-up) rectifier for AC/DC conversion. When the available DC voltage is low, such as that coming from direct-driven synchronous generators with a diode bridge rectifier, it is necessary to have an additional DC/DC boost converter to increase the DC voltage to an appropriate level for operating on the grid [25]. This additional stage adds system cost and reduces overall efficiency. In any phase leg of the inverter, the upper and lower switches cannot be turned on at the same time, intentionally or due to EMI noise, since this will create a "shoot-through" event that may destroy the switches. It is prevented by introducing a dead time between switch transitions, so as not to have any overlap between the upper and lower switch turn-on times; such dead time may result in waveform distortion. In order to reduce the current ripple and harmonic standards a high-order output filter is necessary, which would add to power losses and control complexity.

4.1.2 *Current Source Converter*

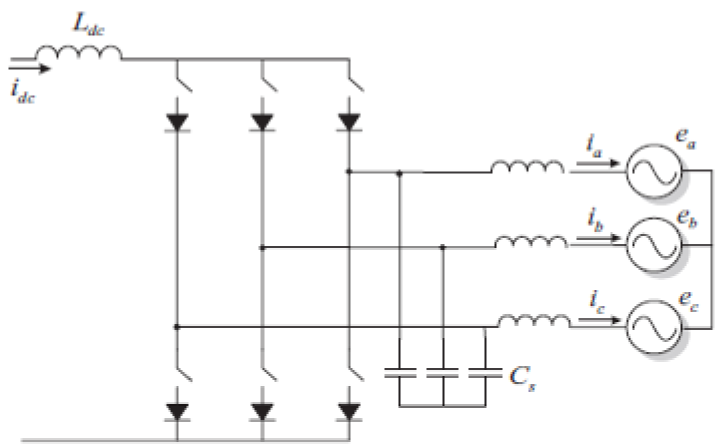

Figure 4.2 Current Source Inverter [29]

The conventional CSC is less employed. It operates with a DC current source, usually furnished by a large inductor fed by source. Its power circuit is built of six switches, mostly semiconductor devices such as GTOs and SCRs or transistors with series diodes able to conduct the current in one direction and block voltages in both directions[20]. The CSC needs a stiff DC current source from either the generator side or the grid side converter. The grid side converter usually controls the DC link current, based on the assumption of a stiff grid condition. In fact, however, the actual DC current depends on the power imbalance on both sides. Generator power changes, often due to fluctuating wind speed, cannot be compensated immediately by controls at the grid side, and thus the DC link current will overshoot or undershoot, which may have impacts on system stability [29].

The main characteristics of the CSC are as follows:

Input voltage AC output must be higher than the initial DC voltage feeding the DC inductor. Due to this fact, the CSC can act as a boost inverter for DC/AC conversion and as a buck rectifier for AC/DC conversion, which is suitable for grid converter applications. Selection: At least one upper and one lower switch must remain gated continuously to prevent the open circuit of DC inductor. If this happens, then component failure could occur. In fact, this danger of open-circuit due to EMI noise is one of the most important reliability issues for CSCs. Safe current transfer could be guaranteed by having some overlap time, but the waveform distortion will result from this action.

The major switches in CSCs must have the capability to withstand reverse voltage, and thus a series diode also must be added to high-speed high-performance transistors such as IGBTs. In this configuration, it narrows the adoption of lower cost and high-efficiency IGBT modules and IPMs. Single-cell power converter solutions based on VSC or CSC topologies applied to medium and high-power wind turbines are reviewed in the following section [29].

4.2 Medium Power Converters

Medium-power wind turbine systems, typically in the range of 2 MW, are still very popular in the market. For this power level, single-cell topologies using only six switches arranged in a bridge configuration provide a very good design compromise. Such a configuration can be used in both full-power and partial-power configurations, for example, in doubly fed induction generators or converters using only below-rated wind speed [4]. In all cases, both capabilities for power injection control and harmonics are enhanced by using forced-commutated converters.

Among them, VSI is one of the best choices, mainly when implemented on the generator side for a typical back-to-back configuration, as shown in the figure below

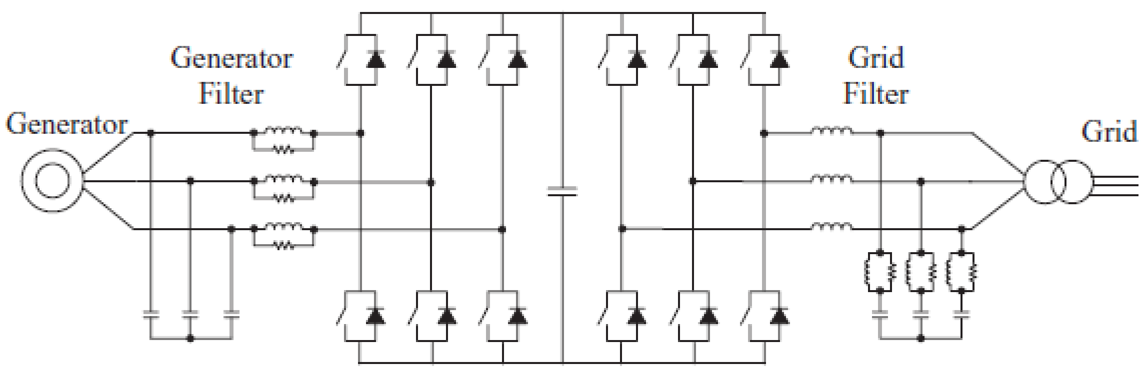

Figure 4.3 Two Level Back-to-Back PWM Converter VSI [29]

That two-level back-to-back VSI is now mature, using off-the-shelf integrated power devices, but is often restricted in very high-power applications by its switching and conduction power losses [3]. One alternative to this configuration is the Current Source Converter (CSC) shown in Figure 4.4, which has three significant advantages:

1.Accompanying would partially be done by exploiting cable lengths and, where necessary, optimization of cable layout. This assumption holds good if the generator and the first converter are inside the nacelle and the grid-side CSC is located at the bottom of the tower. In the case of

2.wind farms, there is a possibility to use a DC grid, and then DC cables can be long enough to provide the necessary inductance [16][22]

3.The inherent protection of the DC link inductor against short-circuit faults makes the realization of fault ride-through capabilities, as dictated by grid codes, easier [19][27].

A small filter at the AC side is enough for harmonic standards. This makes compliance with harmonic requirements much easier [19].

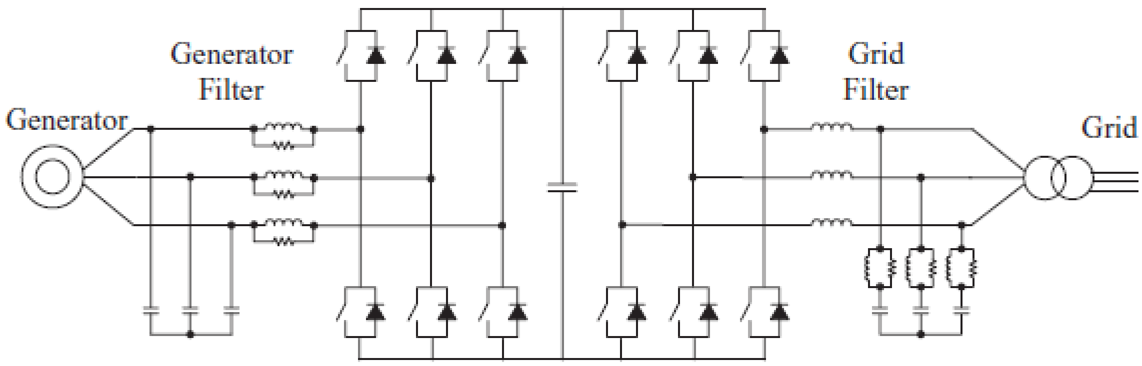

Figure 4.4 Two level Back-to- Back PWM converter CSI [29]

4.3 HIGH POWER CONVERTERS

For power ratings of more than 2 MW, multilevel converter topologies are commonly applied, as in the three-level voltage source converter. This concept allows the application of lower-rated semiconductor devices and decreases harmonic distortions on the grid, resulting in either smaller switching losses or a reduced grid filter [18][19]. However, the conduction losses remain significant since several devices connected in series carry the grid current, and a more sophisticated control system is required for balancing the DC link capacitors [22].

4.4 CONCLUSION

Chapter 4 discussed different grid power converter topologies essential for wind turbine systems. The major requirements for such power converters were underlined, including high reliability, compactness, and low power losses. Among others, the following converters have been reviewed for performance, advantages, and limitations for specific applications in wind energy systems: voltage source converters, current source converters, and matrix converters.

It was also shown in this chapter that the most promising topologies of medium-power converters will likely find wider use in wind turbine systems with a rating around 2 MW. They make a compromise between efficiency and cost and performance for full-power and partial-power variable-speed configurations. Among the two, the PWM-based converters, particularly the two-level back-to-back PWM converter, are found highly efficient and reliable for medium-power applications.

The PWM converters will be used in this thesis as the medium-power converter topology. They allow good efficiency in power injection control and give an excellent harmonic performance, thus becoming a suitable choice for studying and modeling wind energy systems.

Chapter 5. MATHEMATICAL MODELLING OF DOUBLE FED INDUCTION GENERATOR

This chapter presents the dynamic model of the different parts of the DFIG-based wind turbine and its mechanical part for analyzing the dynamic performance of the system under specified operating conditions and for designing the control system. The work starts by considering the basic mathematical equations describing the relation between voltages and fluxes in the machine as the basis for the development of the dynamic model [4] [19].

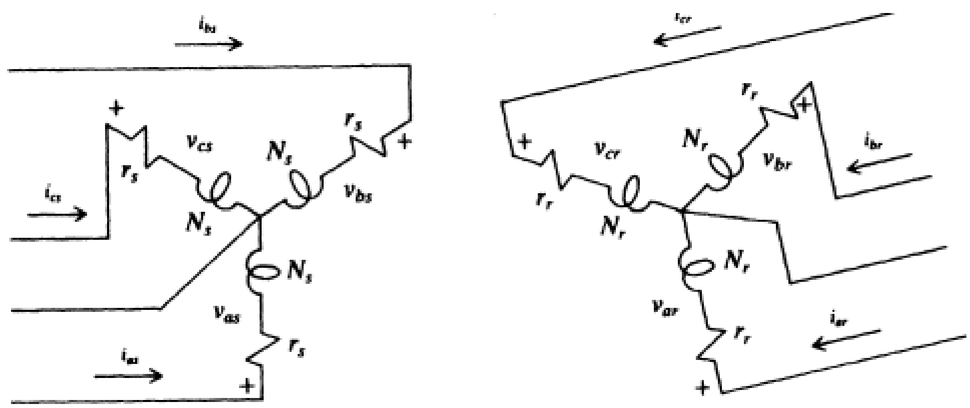

Figure 5.1 Three phase Y connected symmetrical Induction Machine [29]

$$v_{as} = r_s i_{as} + \rho\lambda_{as} \tag{1}$$

$$v_{bs} = r_s i_{bs} + \rho\lambda_{as} \tag{2}$$

$$v_{cs} = r_s i_{cs} + \rho\lambda_{as} \tag{3}$$

$$v_{ar} = r_r i_{ar} + \rho\lambda_{as} \tag{4}$$

$$v_{br} = r_r i_{br} + \rho\lambda_{as} \tag{5}$$

$$v_{cr} = r_r i_{cr} + \rho\lambda_{as} \tag{6}$$

Where:

r_s is the stator resistance

r_r: Rotor resistance referred to the stator.

v_{as}, v_{bs}, v_{cs} = stator phase voltages

i_{as}, i_{bs}, i_{cs} = stator phase currents

v_{ar}, v_{br}, v_{cr} = rotor phase voltages referred to the stator

i_{ar}, i_{br}, i_{cr} = rotor phase currents referred to the stator

$\lambda_{as}, \lambda_{bs}, \lambda_{cs}$ = stator phase fluxes

$\lambda_{ar}, \lambda_{br}, \lambda_{cr}$ = rotor phase fluxes referred to the stator

The above equations can be written in simple form as

$$v_{abcs} = r_s i_{abcs} + \rho \lambda_{abcs} \tag{7}$$

$$v_{abcr} = r_s i_{abcr} + \rho \lambda_{abcr} \tag{8}$$

For a linear magnetic systems flux linkages can be expressed as

$$\begin{bmatrix} \lambda_{abcs} \\ \lambda_{abcr} \end{bmatrix} = \begin{bmatrix} L_s & L_{sr} \\ (L_{sr})^T & L_r \end{bmatrix} + \begin{bmatrix} i_{abcs} \\ i_{abcr} \end{bmatrix} \tag{9}$$

5.1 DQ ANALYSIS

DQ analysis is a method that converts the occurring alternating quantities in rotating field machines such as electric currents, induced voltages, or flux linkages to constant quantities. This confers advantages to the analysis and control of electric machines. The name comes from the direct axis (d-axis) and quadrature axis (q-axis) of the associated coordinate system [2] [16] [28] [41].

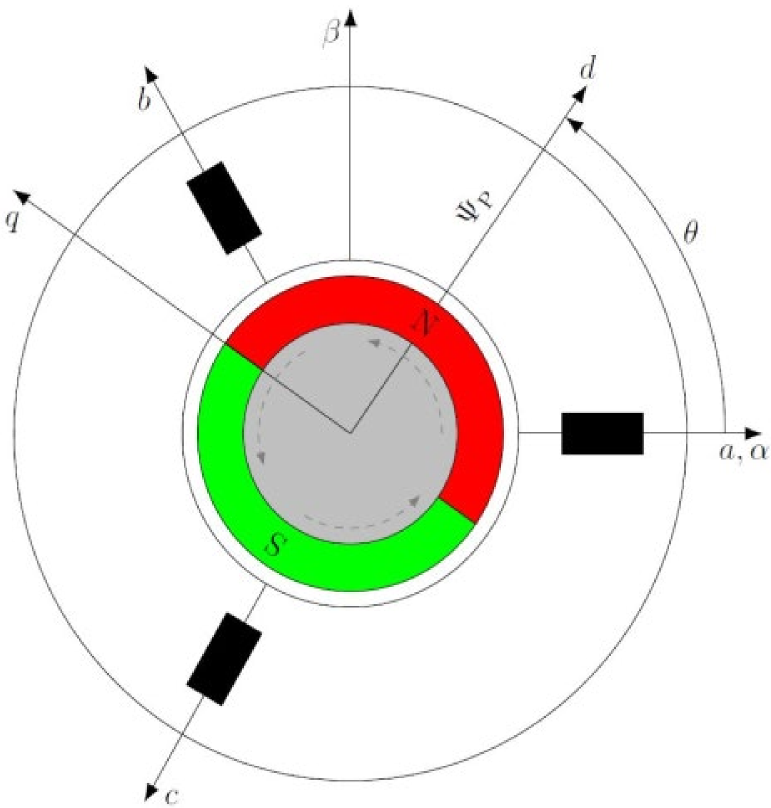

Figure 5.2 Coordinate systems of Induction Machine [29]

The diagram illustrates some of the coordinate systems used with rotating field machines Induction machines, particularly. These coordinate systems simplify the analysis of three-phase systems, which have axes offset by 120 degrees, into simpler, orthogonal two-phase systems with axes offset by 90 degrees [4][19].

The Clarke transformation is performed to transform the three-phase abc system into the two-phase αβ system fixed to the stator, and then the Park transformation rotates the moving αβ system synchronously with the rotor to result in the dq system fixed to the rotor [4][19].

The rotor flux linkage and rotor angle are also displayed: ΨP, and θ, respectively. These are vital components in the DQ analysis, a mathematical approach toward rotating field machines for the purpose of their analysis and control [9].

Voltage Equations in the Synchronous Reference Frame

In a DFIG system, the voltage equations can be analyzed using the q-d synchronous reference frame, which simplifies the analysis by converting three-phase currents and voltages into two orthogonal components (q and d axes).

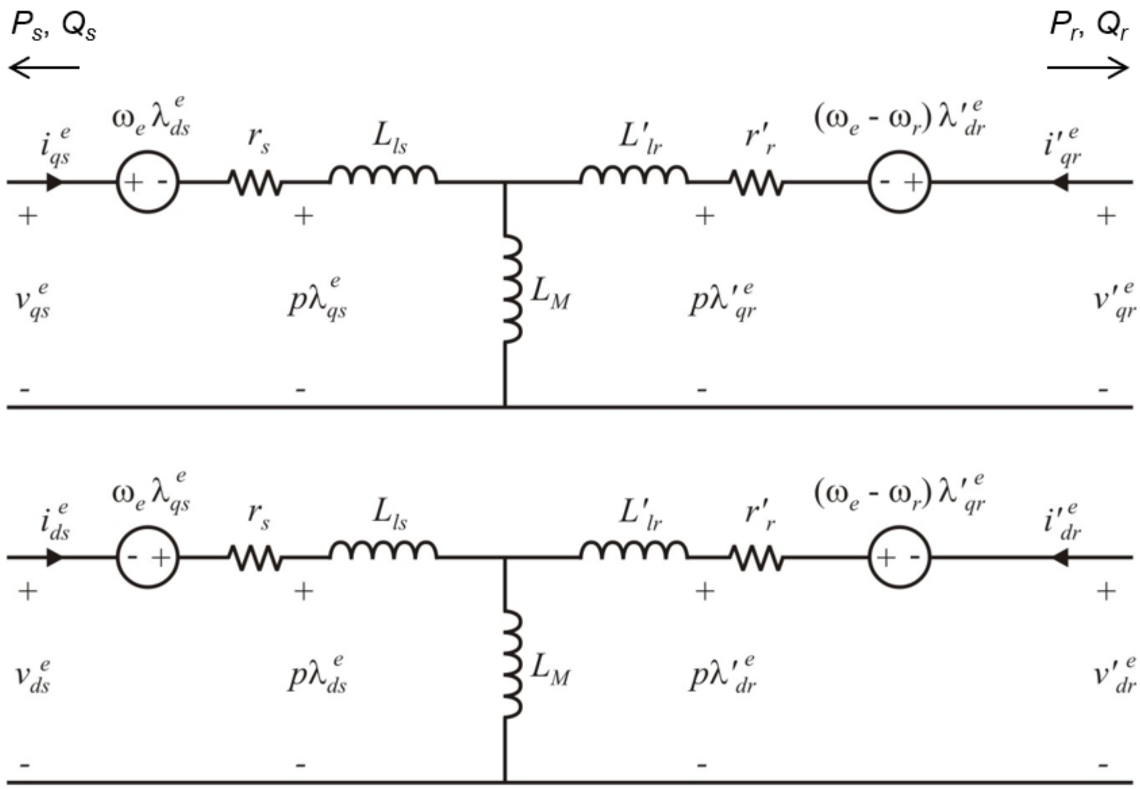

Figure 5.3 Induction Machine q-d equivalent circuit in stationery reference frame [32]

The stator voltage equations in the synchronous reference frame are:

$$V_{qs}^e = r_s I_{qs}^e + w_e \lambda_{ds}^e \quad (10)$$

$$V_{ds}^e = r_s I_{ds}^e - w_e \lambda_{qs}^e \quad (11)$$

$$\lambda_{qs}^e = L_{ss} I_{qs}^e + L'_{lr} I'^e_{qr} \quad (12)$$

$$\lambda_{ds}^e = L_{ss} I_{qs}^e + L'_{lr} I'^e_{dr} \quad (13)$$

Where:

- V_{qs}^{e} and V_{ds}^{e} are the q-axis and d-axis components of the stator voltage.
- r_s is the stator resistance.
- I_{qs}^{e} and I_{ds} are the q-axis and d-axis components of the stator current.
- w_e is the synchronous angular speed.
- $\lambda_{qs}^{e}$and λ_{ds}^{e} represent the q-axis and d-axis flux linkages.
- L_{ss} is the stator inductance.

Substituting Flux linkage equations into voltage equations

$$V_{qs}^{e} = r_s I_{qs} + w_e L_{ss} I_{ds}^{e} + w_e L'_{lr} I'^{e}_{dr} \tag{11}$$

$$V_{ds}^{e} = r_s I_{ds} - w_e L_{ss} I_{qs}^{e} - w_e L'_{lr} I'^{e}_{qr} \tag{12}$$

By Solving for stator Currents:

$$\begin{bmatrix} I_{qs}^{e} \\ I_{ds}^{e} \end{bmatrix} = \begin{bmatrix} r_s & w_e L_{ss} \\ -w_e L_{ss} & r_s \end{bmatrix} \begin{bmatrix} V_{qs}^{e} - w_e L_m I'^{e}_{dr} \\ V_{ds}^{e} - w_e L_m I'^{e}_{qr} \end{bmatrix} \tag{13}$$

In the Synchronous reference frame $V_{qs}^{e} = \sqrt{2}\, V_s$, $V_{ds}^{e} = 0$

Substituting these values in equation (11) and (12)

Assuming that $w_e L_{ss} \gg r_s$

$$I_{qs}^{e} = -\frac{L_m}{L_{ss}} I'^{e}_{qr} \tag{14}$$

$$I_{ds}^{e} = \frac{\sqrt{2}\,V_s}{w_e L_{ss}} - \frac{L_m}{L_{ss}} I_{dr}^{\prime e} \tag{15}$$

The RSC controls the active and reactive power exchanged between the rotor and the grid in a DFIG-based wind turbine system. By using decoupled control strategies in the synchronous reference frame, the RSC enables independent control of active and reactive powers.

5.1.1 *Rotor Side Converter Control*

The RSC controls the active and reactive power exchanged between the rotor and the grid in a DFIG-based wind turbine system. By using decoupled control strategies in the synchronous reference frame, the RSC enables independent control of active power and reactive power [4][13]. By ignoring the power losses, the active power can be expressed as a function of the d-axis and q-axis stator voltages and currents [23].

The stator real power Ps and reactive power Qs are given by:

$$P_s = -\frac{3}{2}\left(V_{qs}^{e} I_{qs}^{e} + V_{ds}^{e} I_{ds}^{e}\right) \tag{16}$$

$$Q_s = \frac{3}{2}\left(V_{qs}^{e} I_{ds}^{e} - V_{ds}^{e} I_{qs}^{e}\right) \tag{17}$$

In the Synchronous reference frame

$$V_{qs}^{e} = \sqrt{2}\,V_s \ , V_{ds}^{e} = 0. \tag{18}$$

By substituting (18) in (16) and (17)

$$P_s = -\frac{3}{2}\left(\sqrt{2}\,V_s I_{qs}^{e}\right) \tag{19}$$

$$Q_s = -\frac{3}{2}\left(\sqrt{2}\,V_s \ I_{ds}^{e}\right) \tag{20}$$

Substituting (14),(15) in (16) and (17) stator active and reactive power in terms of rotor currents

$$P_s \approx \frac{3}{2}\ \frac{\sqrt{2}}{L_{ss}} V_s L_m I_{qr}^{\prime e} \tag{21}$$

$$Q_s \approx \frac{3}{2}\ \frac{\sqrt{2}}{L_{ss}} V_s L_m I'^{e}_{dr} - \frac{3\,V_s^2}{w_e L_{ss}} \tag{22}$$

This shows that the real power is directly controlled by the q-axis rotor current I_{qr} and similarly reactive power is controlled by d axis rotor current I_{dr}[4][20]. In general, a PI controller is used in PLECS simulation for the control of the rotor currents Iqr and Idr to achieve the desired active and reactive power flows [27].

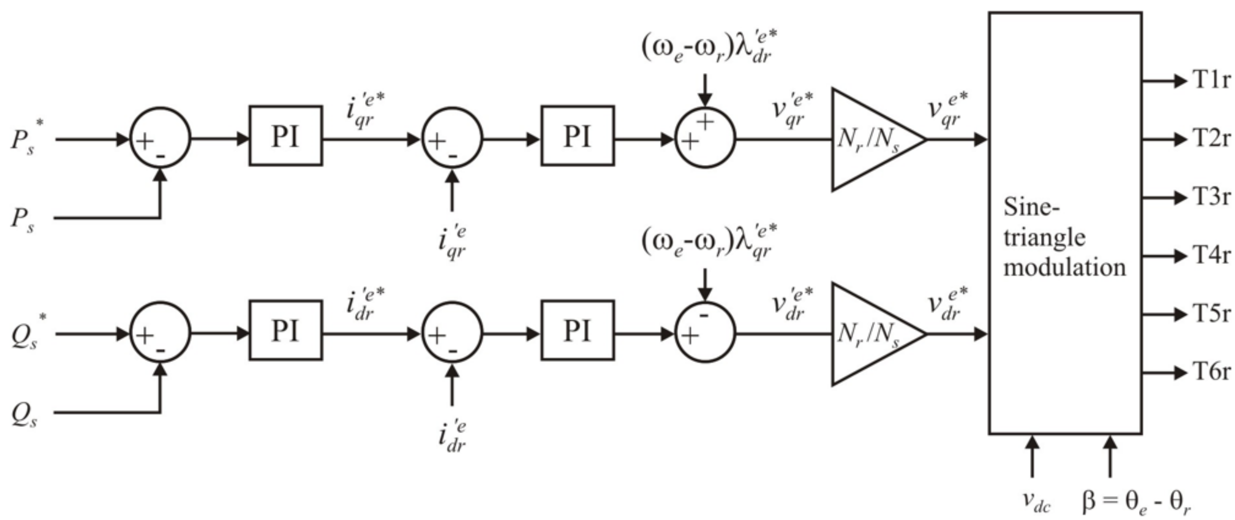

Figure 5.4 Rotor Side Converter Control (RSC) [35]

The figure represents the control block diagram for a Doubly-Fed Induction Generator (DFIG) system, which is commonly used in wind energy conversion systems. This schematic illustrates the implementation of control for managing the active (Ps) and reactive (Qs) power of the generator for optimum performance of grid stability, using two separate control loops [4] [29].

The active power loop compares the desired active power Ps* with the actual measured power Ps. The difference is processed by a PI controller that generates a reference current component iqre* to correct the error. Similarly, the reactive power loop compares the desired reactive power

Qs* and the measured value Qs to feed a PI controller generating the corresponding reference current component idre* [13][34]

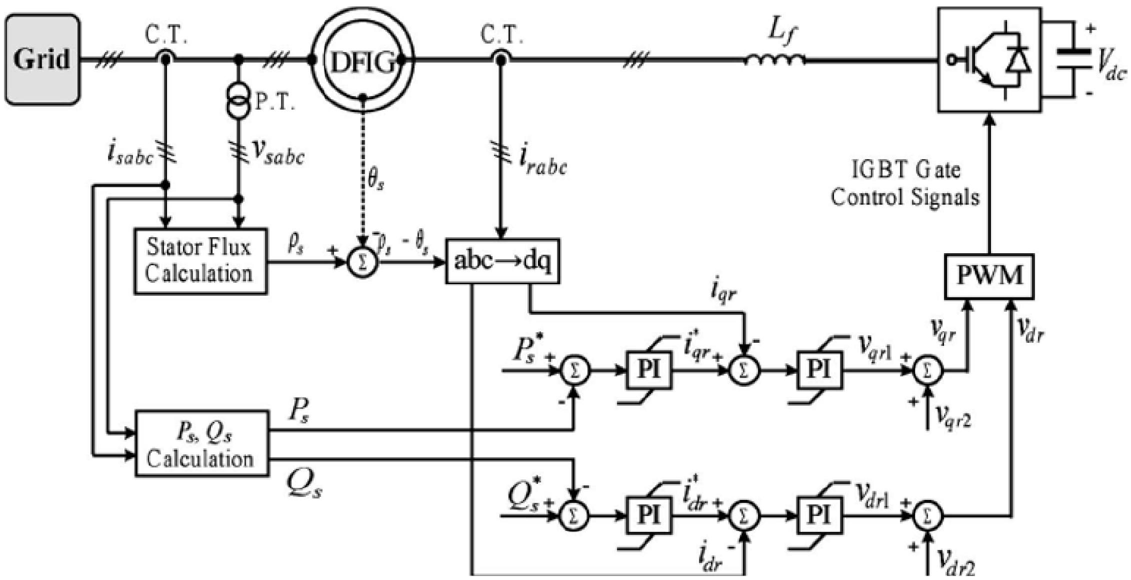

Figure 5.5 Double Fed Induction Generator Rotor Side Converter Model [39]

These reference currents are then compared with the actual rotor currents, and the resulting error is again subjected to PI controllers. This stage produces reference voltage signals, V_{qr}^{e*} and V_{dr}^{e*}, which become very important for the control of the rotor-side converter. Further refinement of the control process is obtained by the inclusion of compensation terms that take into consideration the dynamic coupling effects between the various axes of the machine [27].

At the end, the voltage signals are gained with the rotor-to-stator turns ratio (Nr/Ns) and pass through a sine-triangle modulation block, which develops actual switching signals for the six IGBT switches, from T1r to T6r inside the rotor-side converter. Using this elaborate control circuit, the DFIG can safely uncouple the active and reactive power controls, thereby enabling an idealized flow of power to the grid

5.1.2 *Grid Side Converter Control*

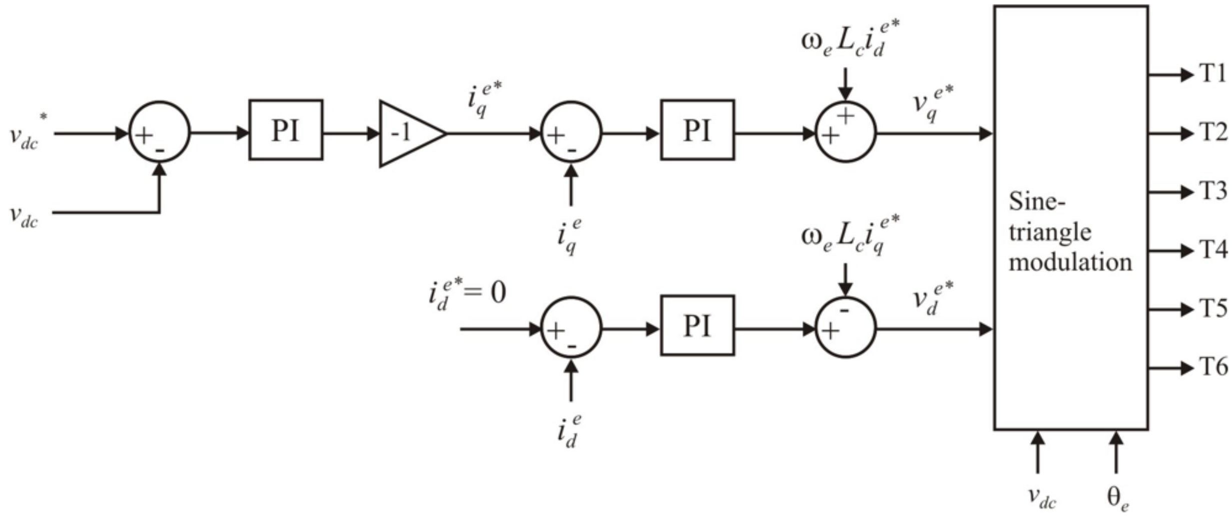

Figure 5.6 Grid Side Converter Model [39]

This figure explains the GSC control system of a DFIG setup in detail. The GSC plays a very important role in maintaining DC-link voltage and thus ensuring an uninterrupted power exchange between the DFIG and the grid. The grid voltage-oriented vector control approach is applied to enable independent active and reactive power control[27]. Two key purposes of this strategy are as follows:

Maintain a stable DC-link voltage: It attains an active power flow control and continuously compares the desired set DC-link voltage, Vdc*, to the measured one, Vdc. The error in the difference is fed to a PI controller, which now provides a reference q-axis current, I_q^{e*}.This reference current is then compared with the actual q-axis current, I_q^e , and the resulting error is processed via another PI controller to produce the q-axis voltage V_q^{e*}. A compensation term is added in order to take into consideration the dynamic coupling effects within the system [27].

Control reactive power flow: To minimize the size and cost of the GSC, the reactive power flow is typically maintained at zero. This is achieved by setting the reference d-axis current (I_d^{e*})to zero. Thus, the difference between reference and actual I_d^{e*} is considered by a PI controller for generating v_d^{e*}[4].

The final voltage references are then passed to the $v_d^{e*}$and v_q^{e*}which are then sent to a sine-triangle modulation block. This block produces six accurate switching signals for all IGBT switches in the GSC, ensuring proper control in the operation of the converter. The described control approach allows the GSC for optimum performance by maintaining stability in the DC-link voltage, handling the reactive power, and synchronizing effectively with the grid. In consequence, it ensures higher efficiency and costs reductio [19] [29].

5.2 WIND POWER CHARACTERISTICS

Before the presentation of the results of the simulation, here discussing some fundamental characteristics of wind turbines and the inherant variability of wind energy. Wind energy is naturally unpredictable, with fluctuating speeds that directly affect the performance and efficiency of wind turbines. This variability demands advanced control strategies to ensure optimal energy capture and system stability under varying conditions. Understanding the power coefficient, tip speed ratio, and pitch angle provides a base for the development of control systems for variable-speed wind turbines. As such, this discussion was important to set the grounds for the interpretation of simulation results and to highlight the significance of robust control methodologies in systems related to wind energy.

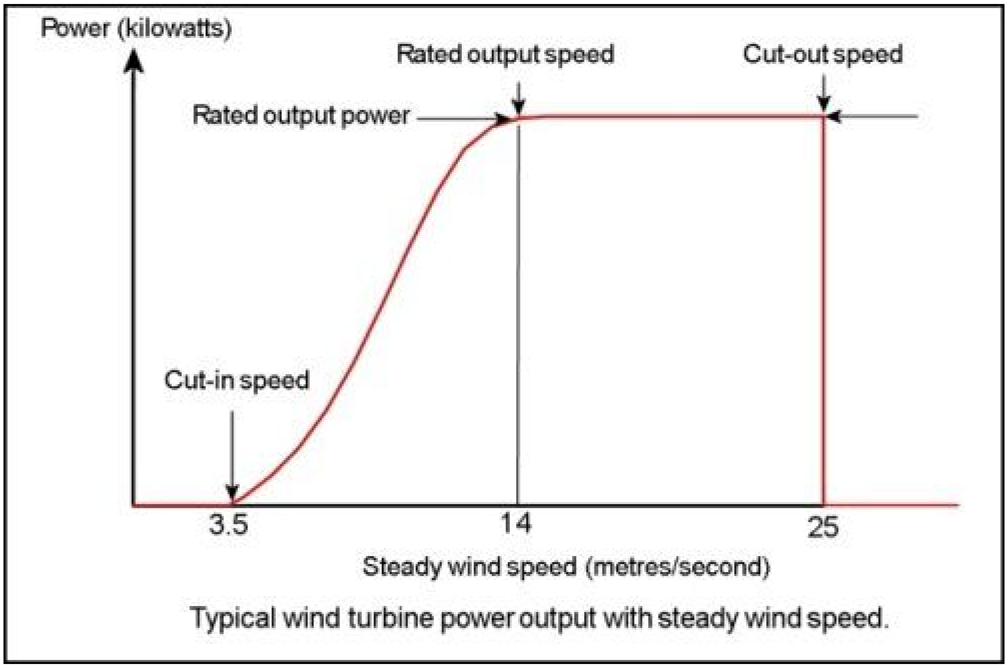

Figure 5.7 Typical Power Curve of Wind Turbine

The power curve in Figure 5.7 expresses the relationship between rotational speed and power output. At low wind speeds, turbines operate below optimal rotational speeds, generating low power. As wind speed increases to the rated wind speed, the turbine adjusts its rotational speed to achieve maximum C_p .Beyond the rated wind speed, the power output is limited by pitch control to avoid over-speeding and to protect the turbine.

The Power Coefficient Cp essentially describes the efficiency with which a wind turbine could convert the kinetic energy from the wind into mechanical energy. In essence, it shows the possibility of catching energy by a wind turbine. Its theoretical value for the upper limit is now called the Betz Limit and equals 59.3%. The limit obtained by the German physicist Albert Betz; it is claimed that only 59.3% of the kinetic energy contained in wind could be converted to the mechanical power generated by the rotor of a wind turbine. Considering real conditions, the Cp value usually ranges between 35% and 45%, depending on type and operating conditions of modern wind turbines [6][10].

5.2.1 *Power vs Rotational Speed of wind turbine*

Mechanical power in the wind turbine is closely related to its rotational speed. Higher wind speeds require an optimization of rotational speed, since maximum power needs to be captured efficiently without damaging the turbine structure [29].

The power available in the wind (Pwind) can be given as:

$$\text{Pwind}=1/2\rho A v_w^3 \qquad (23)$$

This equation expresses the fact that wind power is proportional to the cube of the wind speed, and as such a small increase in wind speed will provide a large increase in available power. The actual power captured by the turbine is a fraction of Pwind defined by Cp, and given by:

$$C_p\ (\lambda, \beta) = \frac{Pmech}{Pwind} \qquad (24)$$

$$Pmech = C_p\ (\lambda, \beta)\ X\ 1/2\rho A v_w^3 \qquad (25)$$

The output power of a wind turbine therefore depends on the rotational speed of the blades as well as on the wind speed [4].

Chapter 6. SIMULATION RESULTS

The DFIG control scheme includes a rotor coupled with the grid via a back-to-back converter configuration made of Rotor Side Converter and Grid Side Converter. The converters in these are using a two-level SPWM method to reach independent active/reactive power control while attaining stable grid integration.

The RSC plays a leading role in the control of both active power (Ps) and reactive power (Qs) generated. The three-phase rotor currents ($Iabc$)are transformed into the dq-reference frame to isolate their active (i qr) and reactive (i dr) components. This makes active power control straightforward, because (iqr) controls active power directly, while (i dr) controls the reactive power. Reference values for these currents are compared with the measured currents, and the resulting errors are processed by Proportional-Integral (PI) controllers to generate the control voltages (vdr and vqr). These voltages are then transformed back into the three-phase (abc)frame to yield the required rotor voltages which are fed to the SPWM converter. The converter generates gate signals for the six IGBTs in the RSC, which enables precise control of the rotor voltages. This ensures optimal capture of energy from the wind while enhancing power quality by compensating for reactive power and filtering harmonics. The reactive power reference (Qref) is set to zero in usual grid-connected cases to maintain unity power factor. The GSC is responsible for maintaining the DC-link voltage ($v$dc) constant regardless of the magnitude and direction of the rotor power. This it does by transforming grid voltages and currents into the dq-reference frame and regulating the DC-link voltage with PI controllers. The control voltages are given by $v$de and vqe.

The generated signals by the PI controllers are transformed back to the three-phase (a,b,c) frame and used by the SPWM converter for the control of the IGBTs in the GSC. Besides keeping the DC-link voltage, the GSC provides reactive power compensation, ensuring grid stability and improving power quality.

The transient and dynamic performance of the Doubly Fed Induction Generator integrated with the grid, under normal operating conditions as well as during the disturbance, such as three-phase line-to-line fault is done. The analysis performed considers both mechanical and electrical parameters for a better explanation of the system behavior. In turn, the mechanical parameters include rotor speed and torque that reflect the dynamic response of a wind turbine and generator during condition variations, which are supposed to provide insight into the energy conversion efficiency and stability. The simulation employs vector control methods for both the RSC and GSC to offer decoupled control of active and reactive power. Such a setup allows the independent control of the mechanical and electrical parameters, hence making this system very adaptable to disturbance and varying wind speeds.

In this way, by studying transient and steady-state behaviors of the named above parameters, the simulation would be able to make proper judgment on the effectiveness of the control strategy, robustness of the DFIG system, and its capability of maintaining stability and power quality under fault conditions. It would therefore give the results for the identification of critical points for improving performance optimization.

The simulation focuses on a 2 MW Doubly-Fed Induction Generator (DFIG) connected to a 10 kV grid operating at a frequency of 50 Hz.

The machine is configured with the following key parameters:

stator resistance (Rs) of 0.022 Ω

rotor resistance (Rr′) of 0.00026672 Ω

stator leakage inductance (Lls) of 1.2 mH

rotor leakage inductance (Lr') of 7.3946 μH

and magnetizing inductance (Lm) of 2.9 mH.

The number of pole pairs is set to 2, with a turn’s ratio of 0.3846. The machine has a rotor inertia (JJ) of 75 kg·m² and a friction coefficient (F) of 0.8106 N·ms. Switching frequency is 10k.

I performed simulations on the PLECS demo model[to evaluate the system's performance under both normal and faulty conditions. These simulations were done to see the behavior of the system in both normal and faulty conditions of the system for better understanding of its capability.

Case 1: Transition to Synchronous Speed

The rotor of the DFIG in case 1 is initially rotating at sub-synchronous speed, which is below the grid frequency. It then smoothly accelerates up to synchronous speed, where the rotor's speed matches the grid frequency. This is a typical operating scenario for a wind turbine, where the rotor speed varies in accordance with changing wind conditions. This simulation specifically looks at the capability of the control system to maintain stability during this acceleration phase and ensure a smooth transition to synchronous operation, which is crucial for efficient energy transfer to the grid.

Case 2: Transition to Super-synchronous Speed and Fault Response

The second case takes the evaluation a step further. The rotor starts at a synchronous speed but accelerates beyond the super-synchronous state. This scenario is common when the wind turbine needs to capture maximum energy from high winds. To add another layer of complexity and assess the system's robustness, a three-phase fault is introduced. This fault simulates a severe grid disturbance, which can significantly disrupt the power flow and potentially destabilize the system. The work in this part is based on the fault ride-through capability study of the DFIG, an important feature for maintaining grid stability during disturbances.

I simulated these two cases in order to analyze the system's performance for a wide range of operating conditions. Rotor speed, DC-link voltage, active and reactive power, stator voltages and rotor currents were monitored and evaluated with key parameters. This gives a comprehensive insight into the stability and robustness of the DFIG system to ensure its reliable operation during normal and extreme situations.

These scenarios, one after another, are performed in this example to analyze the system performance and stability under different operating conditions of the system.

6.1 CASE-1 SIMULATION RESULTS

Initial Operating Conditions: In the initial phase of the simulation, the generator operates at a rotational speed of 151 rad/s, sub synchronized with the grid frequency. The active power dynamics of the rotor, stator, and total are shown in fig 6.1. For the initial periods of time, the rotor is running at sub-synchronous speed; thus, the power needs to flow into the rotor circuit from the grid for magnetization and control (negative rotor power, shown in red). In that period, most of the active power is fed to the grid by the stator.

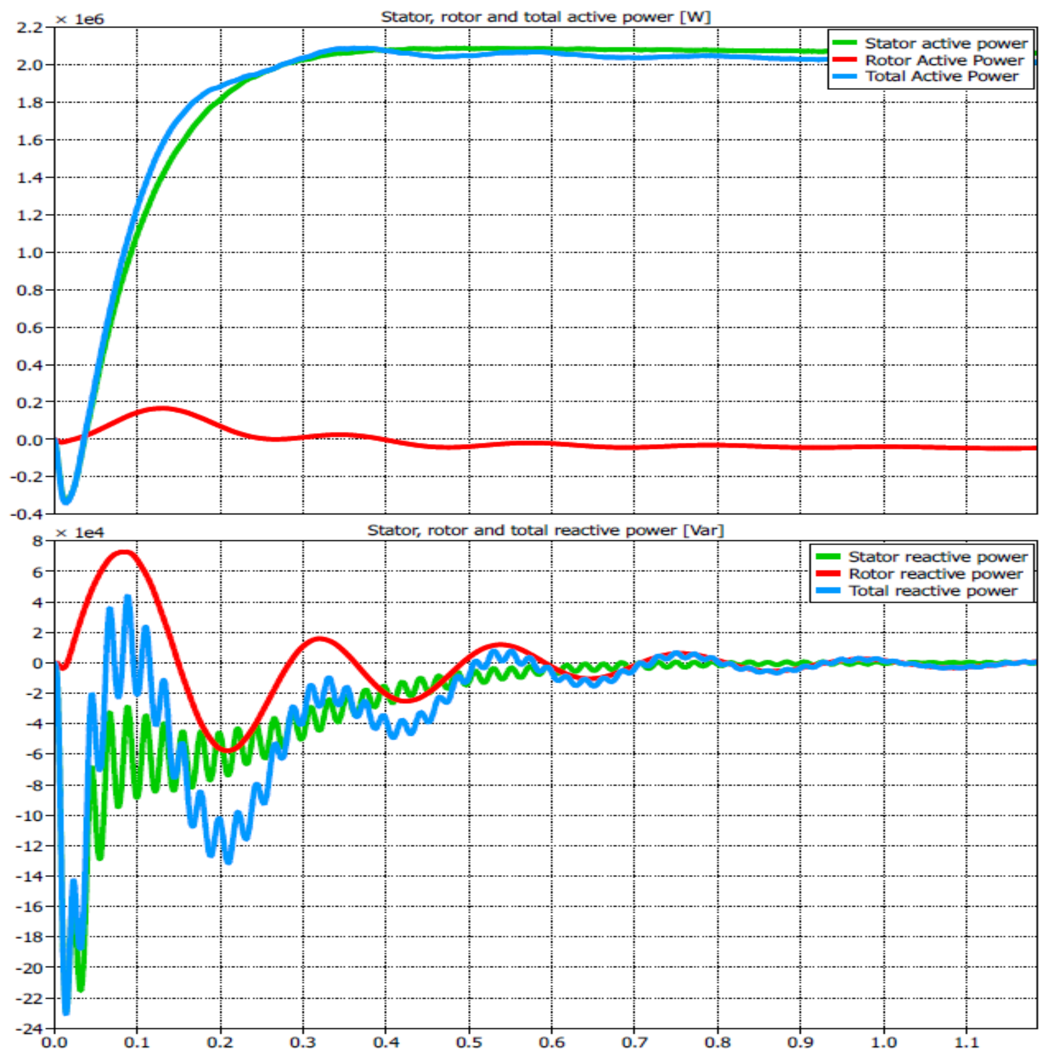

Figure 6.1 Power Flow Initial transients

From figure 6.2, the grid phase voltages are sinusoidal and balanced, meaning that synchronization with the grid has been achieved and the quality of power is assured. Grid (stator) phase currents have small transients at the beginning and reach a steady state with fast damping. In Figure 6.4, Rotor phase currents are highly oscillatory due to electromagnetic coupling;

however, they get stabilized when the rotor picks up its desired speed, which reflects strong rotor-side control. In figure 6.5 the DC-link voltage exhibits initial fluctuations caused by converter dynamics but stabilizes rapidly, ensuring reliable energy exchange. Overall, the system's control strategy effectively mitigates transient effects, maintaining stable operation and smooth energy conversion in wind energy systems.

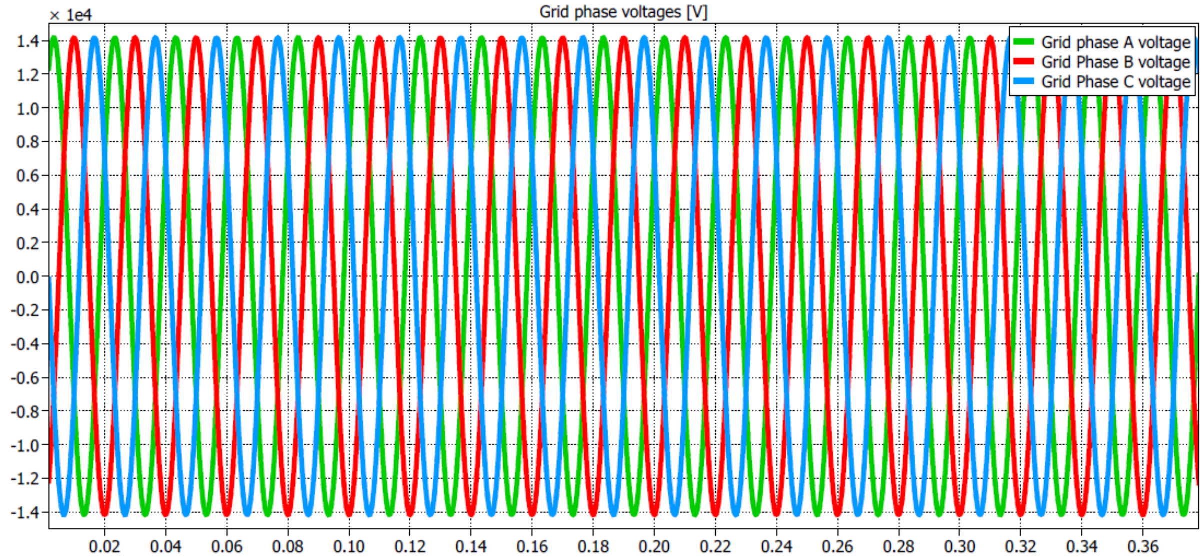

Figure 6.2 Grid Phase Voltage during Initial Transients

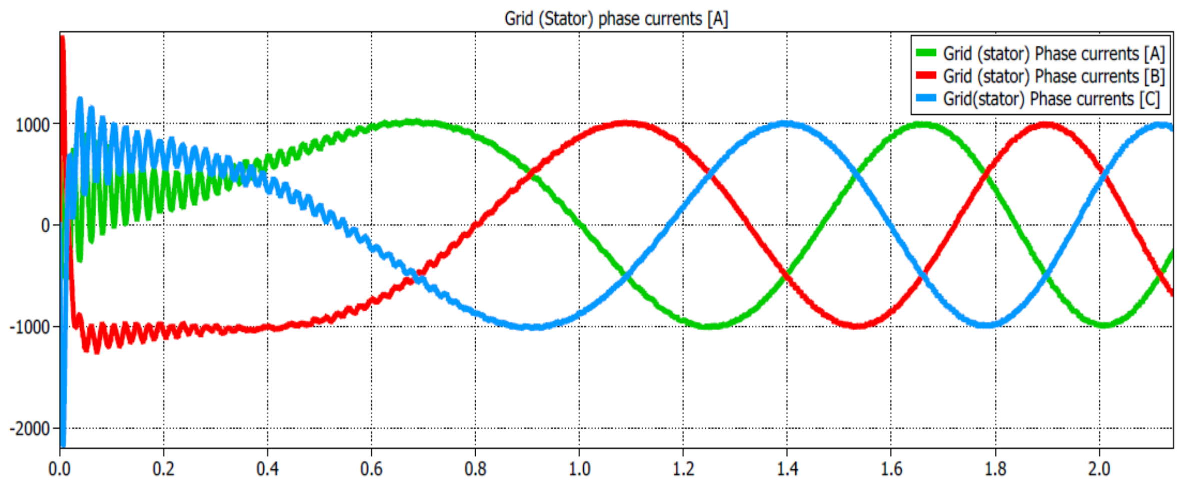

Figure 6.3 Grid phase currents during Initial transients

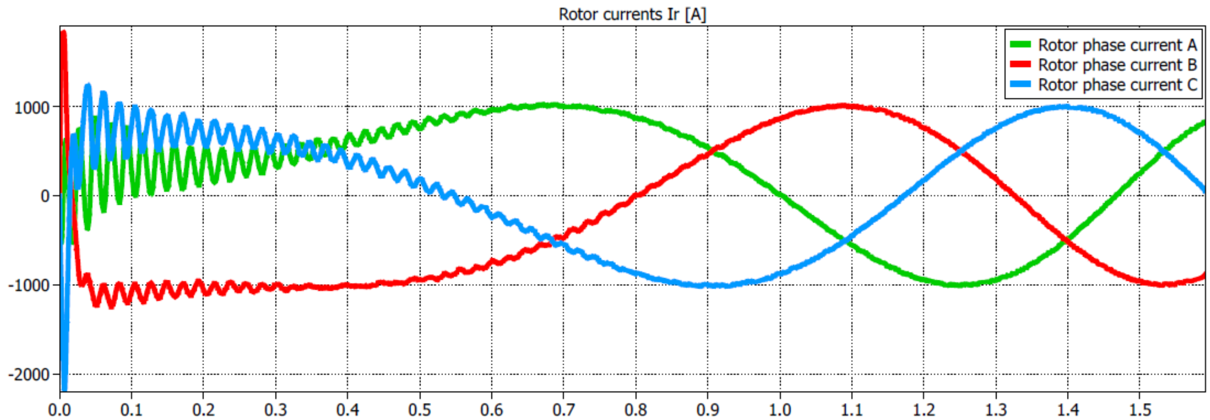

Figure 6.4 Rotor currents during Initial transients

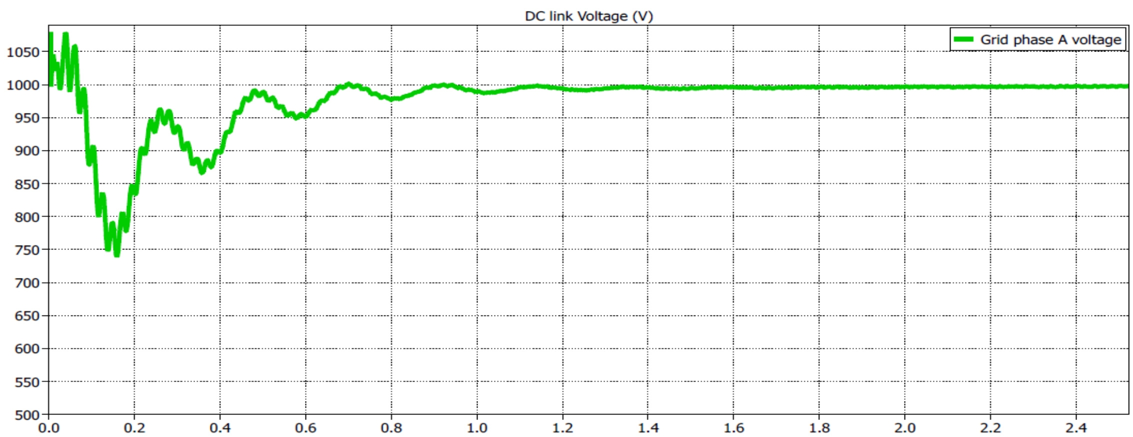

Figure 6.5 DC Link Voltage during Initial transients

When the rotor accelerates towards synchronous speed at t=4 seconds, the active power (Figure 6.3) of the rotor approaches zero, which means that the energy exchange in the rotor circuit is reduced. During synchronous speed, the stator keeps supplying most of the active power-green curve, while the total active power-blue line-manages to stabilize at a higher level, reflecting efficient energy conversion. Oscillations in the rotor reactive power dampen down as the rotor reaches synchronous speed. The total reactive power is seen to settle around zero, which is indicative of the minimal exchange of reactive power and therefore a well-operating DFIG system under synchronous conditions.

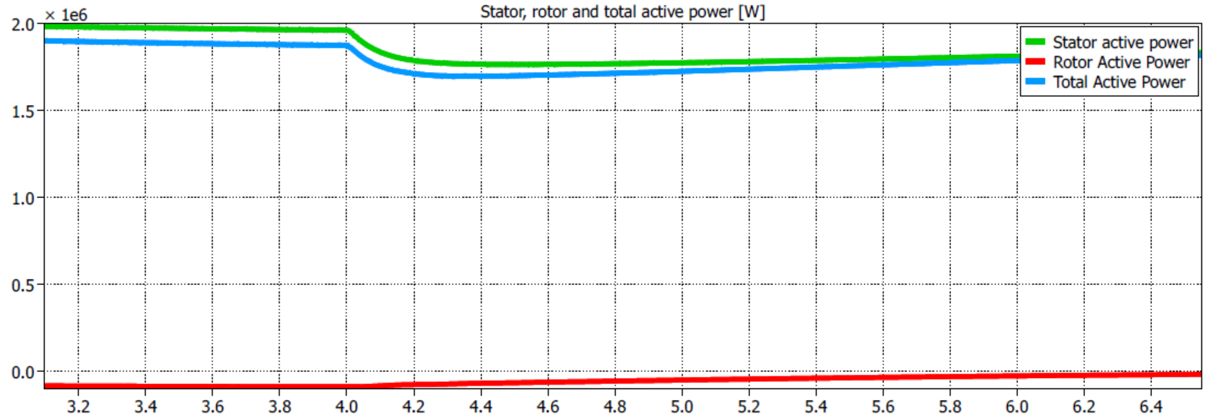

Figure 6.6 Active Power during Sub Synchronous to Synchronous transition

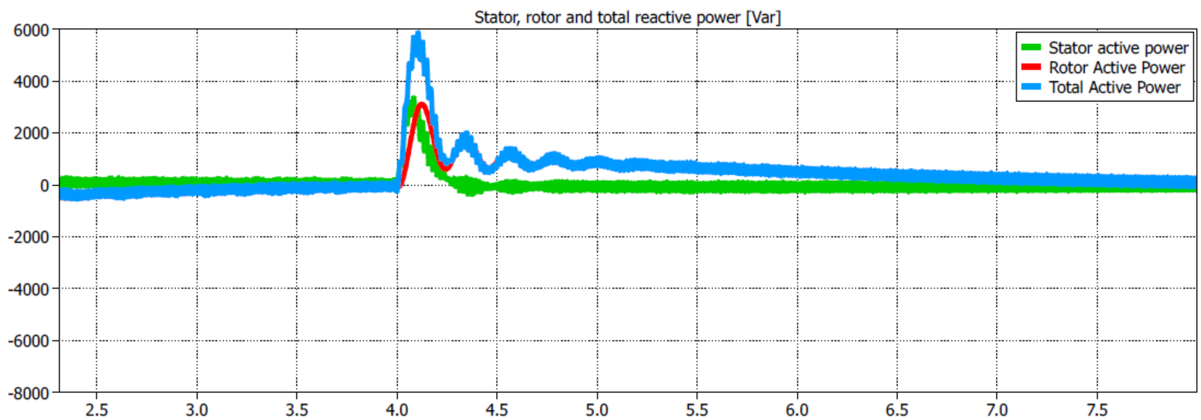

Figure 6.7 Reactive Power during Sub Synchronous to Synchronous transition

The figures 6.8,6.9,6.10,6.11 show the performance of grid phase voltages, grid (stator) phase currents, rotor phase current, and DC-link voltage during the transition of the rotor speed from sub synchronous to synchronous in a DFIG system. The grid phase voltage is balanced and sinusoidal during the transition, reflecting stable grid synchronization. In this case, the grid (stator) phase currents reflect a reduction in magnitude while the rotor is accelerating, thus indicating an effective redistribution of power between the rotor and stator. The rotor phase currents also stabilize at a reduced magnitude, which implies that the rotor-side converter has effectively controlled the electromagnetic coupling. The DC-link voltage has minor fluctuations during the speed change but quickly stabilizes to ensure reliable operation of the power converters. From figure 7.2 we can see that frequency of the rotor currents are increased.

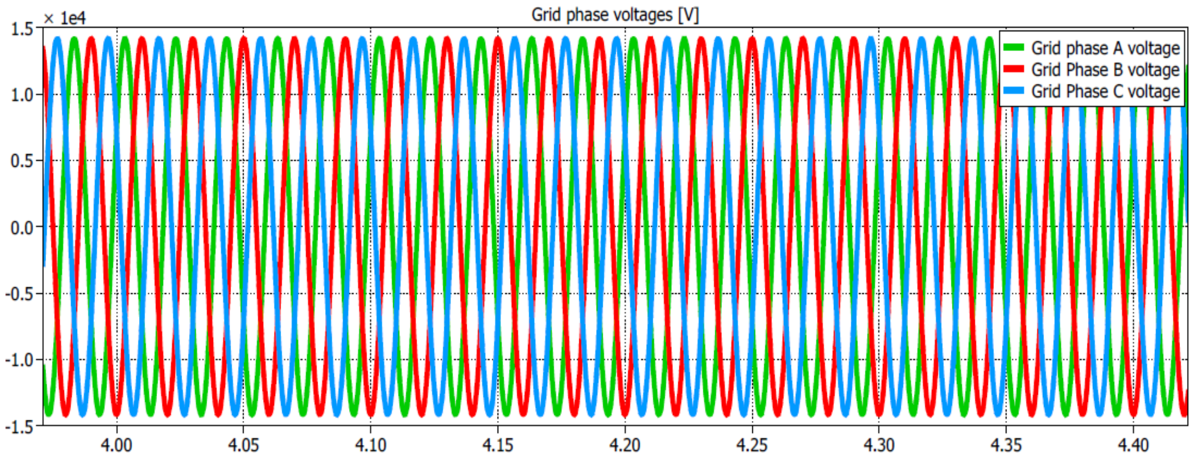

Figure 6.8 Grid phase Voltage transition from sub synchronous to synchronous

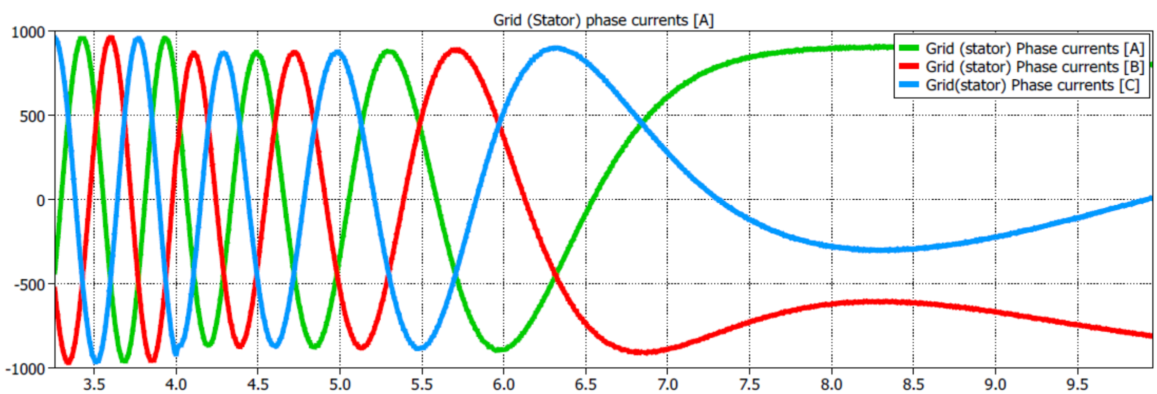

Figure 6.9 Grid stator phase currents Sub Synchronous to Synchronous transition

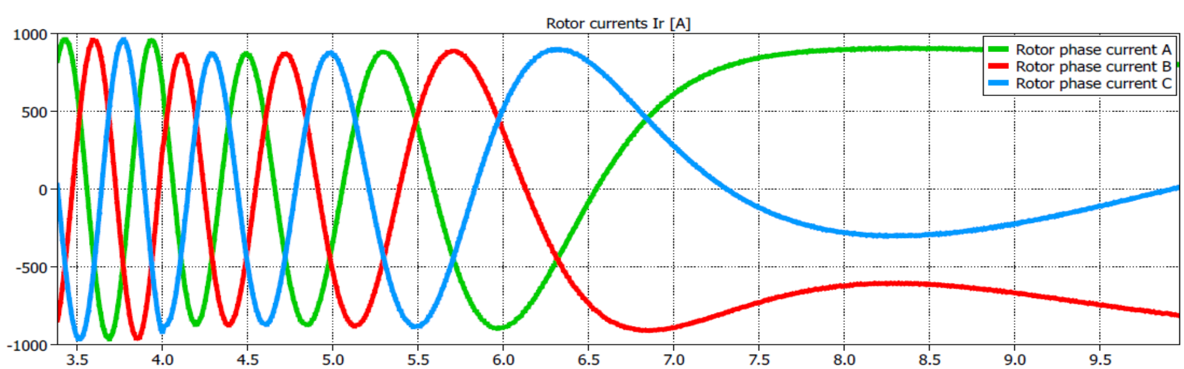

Figure 6.10 Rotor currents during Sub Synchronous to Synchronous transition

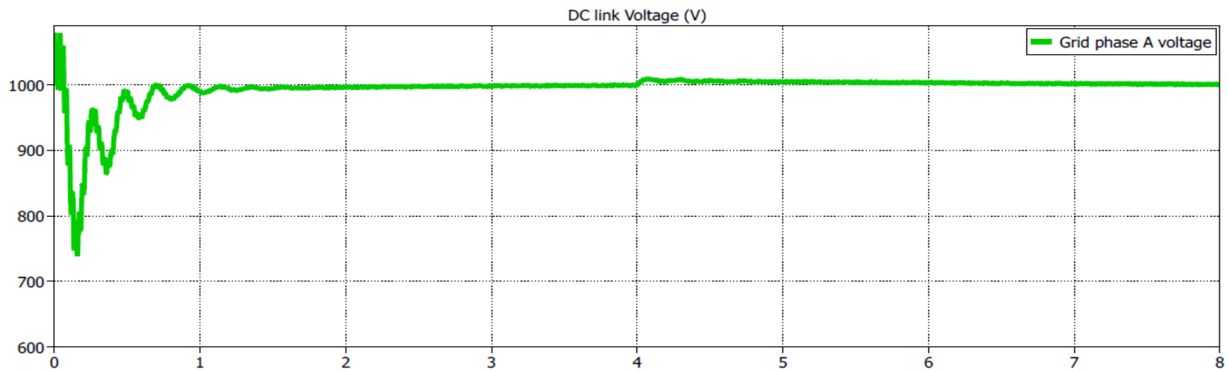

Figure 6.11 DC Link voltage during Sub Synchronous to Synchronous transition

6.2 CASE-2 SIMULATION RESULTS

I simulated the second case, where the rotor starts at synchronous speed and accelerates to super-synchronous speed. Additionally, a three-phase fault was introduced to assess the system's robustness under severe grid disturbances. I observed the below parameters to know fault riding capability, stability during faulty conditions.

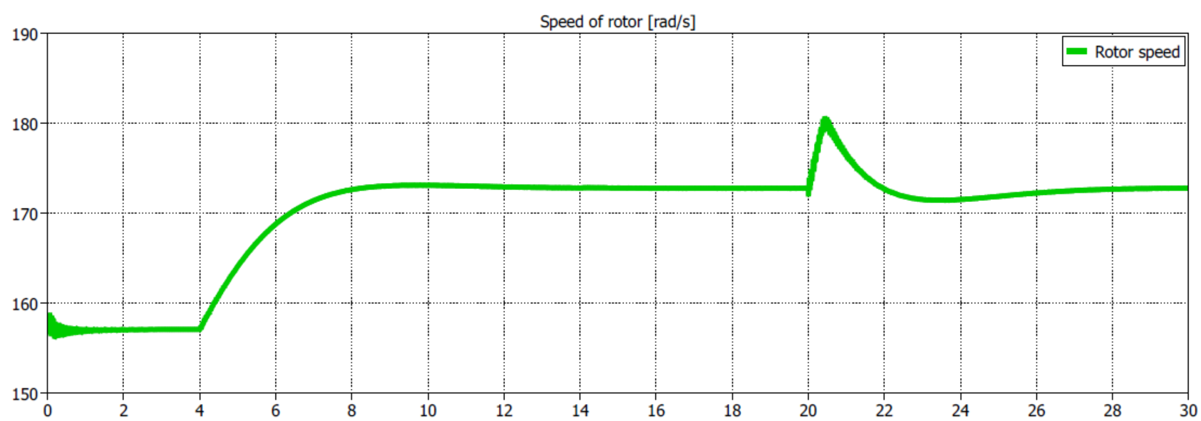

Figure 6.12 Speed of the rotor in Rad/Sec

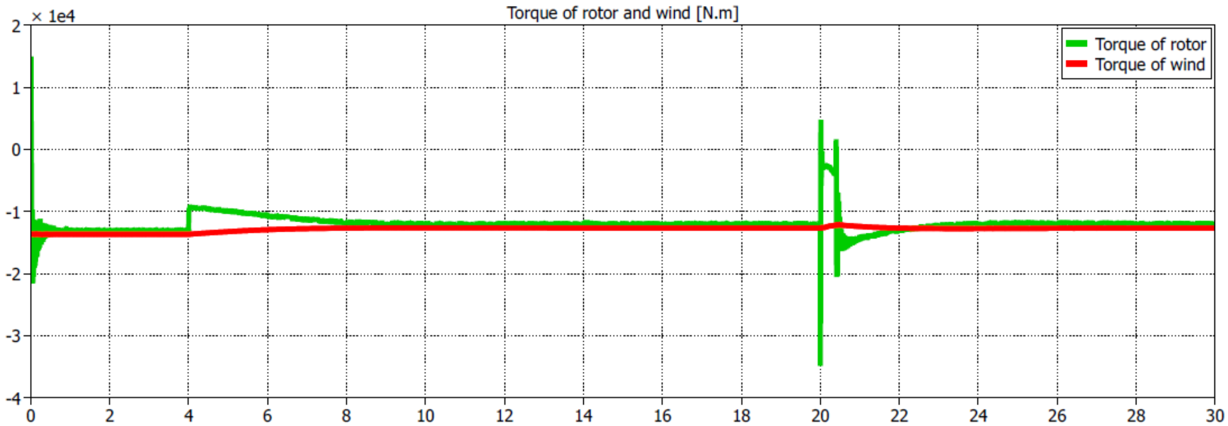

Figure 6.13 Torque of the rotor and wind in Rad/Sec

The 6.12 graph plots the rotor speed in rad/s versus simulation time. The initial value of the rotor speed is about 151 rad/s, representing stable operation at sub synchronous speed. Then, at t = 4s, a step change in the speed reference makes the rotor accelerate smoothly to a new operating point of 175 rad/s, demonstrating how the system would behave under dynamic conditions. However, at t=20s, a three-phase fault is introduced, causing a sharp spike in rotor speed followed by damped oscillations. These oscillations gradually diminish as the control system stabilizes the rotor, demonstrating the effectiveness of the DFIG control strategy in mitigating disturbances and maintaining operational stability.

The 6.13 figure illustrates the torque response of the system, where the interaction between electromagnetic torque and aerodynamic torque is presented. At the beginning, electromagnetic torque gives small oscillations due to coupling dynamics that rapidly dampen, and the system reaches a steady state. There is a significant rise in torque at t=4s, which is the instant of the step change in rotor speed. At t=20s, when the fault is introduced, electromagnetic torque shows sharp transients, which means that the generator is immediately affected by the fault. Despite this disturbance, the torque follows aerodynamic torque. This ensures that during recovery, the system efficiently converts energy. These results confirm the strength of the control mechanisms in maintaining system performance under normal and faulty conditions.

6.2.1 *Electrical Parameters*

1.Initial Operating Conditions**:** In the initial phase of the simulation, the generator operates at a rotational speed of 157 rad/s, synchronized with the grid frequency. In this state, a major part of the active power generated by the induction machine is delivered to the grid through the stator winding. Since, at synchronous speed, slip is zero, there is practically no power transfer through the rotor except for a small loss due to resistance. During this stage, the system does not engage in reactive power generation, keeping the main focus on active power transfer. Below graphs demonstrate how the system worked.

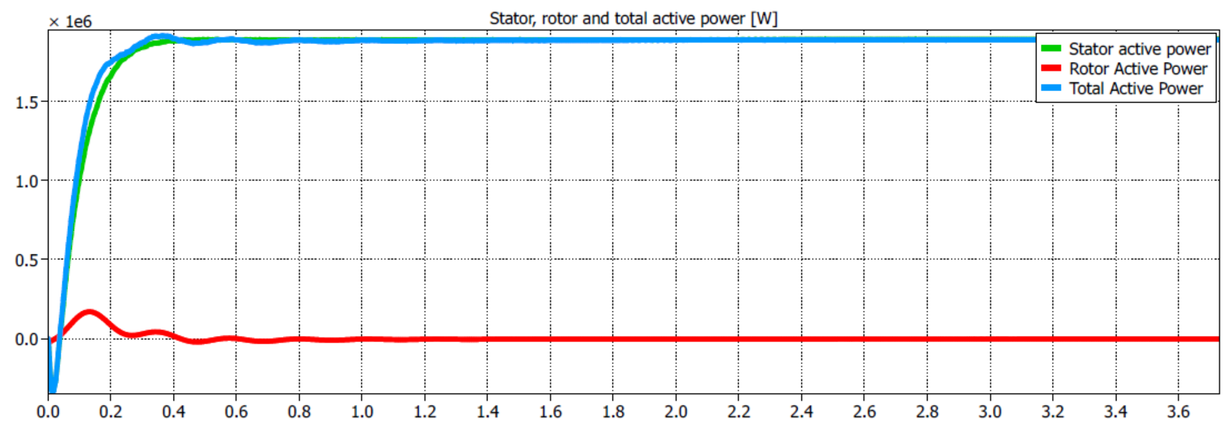

Figure 6.14 Stator, rotor and total active power at synchronous speed initial conditions

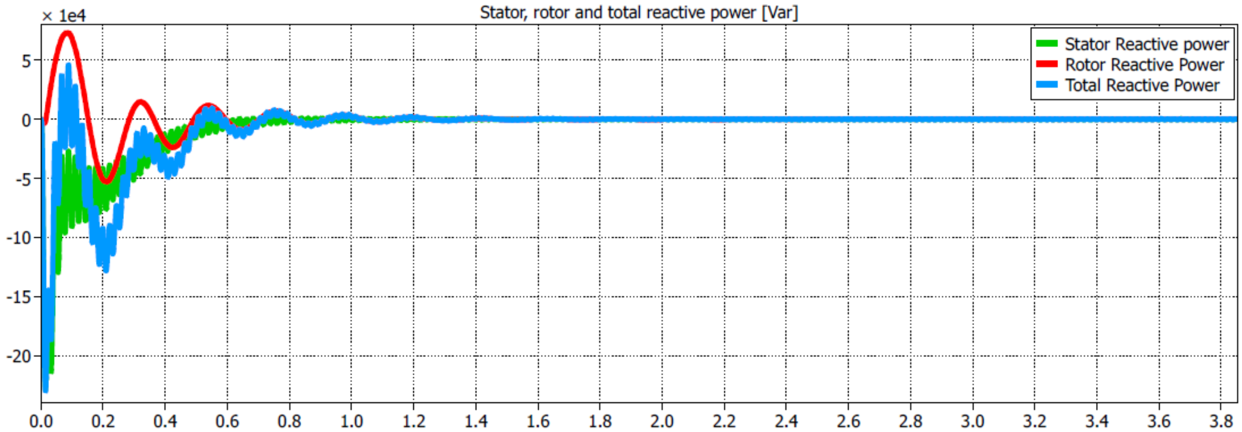

Figure 6.15 Stator, rotor and total reactive power at synchronous speed initial operating conditions

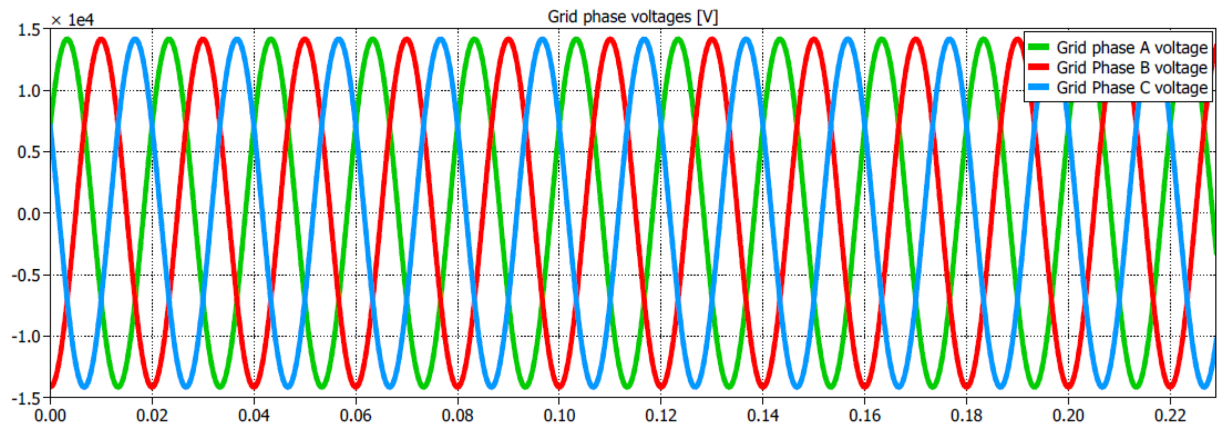

Figure 6.16 Grid phase voltages at synchronous speed initial operating conditions

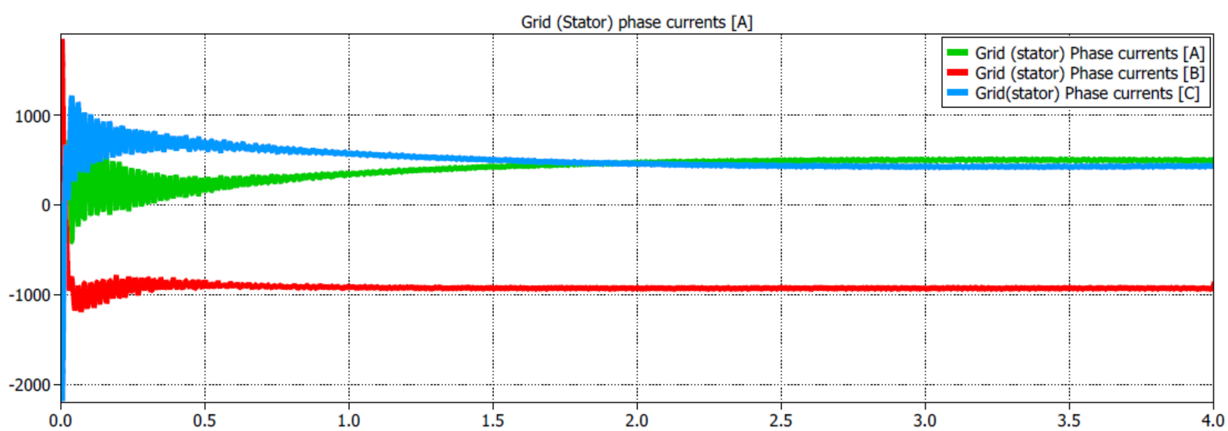

Figure 6.17 Grid(stator) phase currents at synchronous speed initial conditions

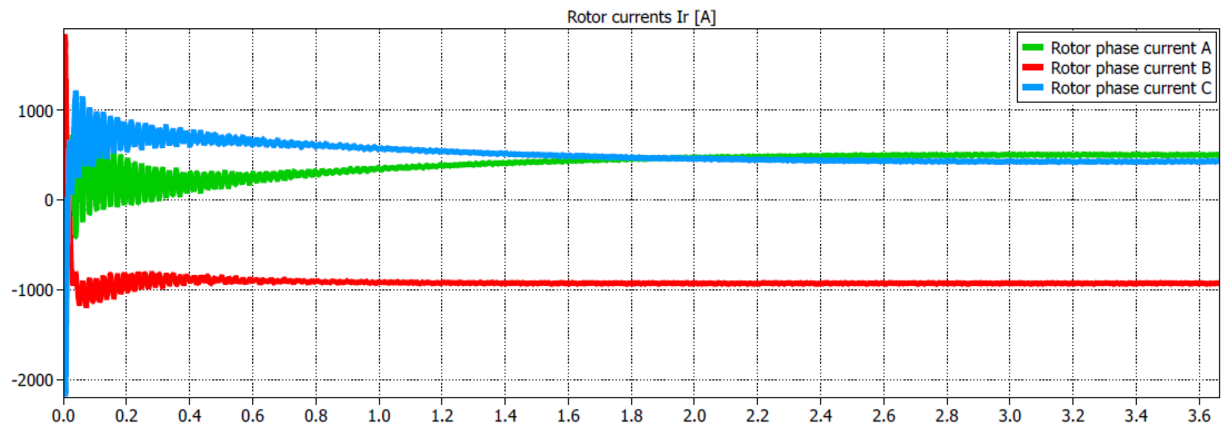

Figure 6.18 Rotor phase currents at synchronous speed initial operating conditions

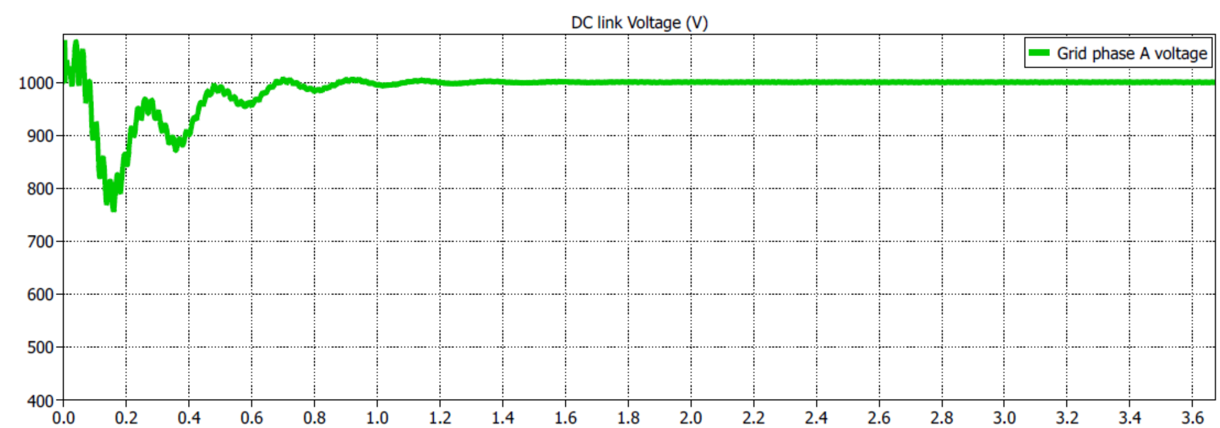

Figure 6.19 DC Link voltage at synchronous speed initial operating conditions

Speed Transition Phase: The rotational speed of the turbine is increased to 175 rad/s at 3 seconds into the simulation. This is achieved by applying a step change in the reference input of the speed controller. This acceleration aims to simulate conditions for maximum power generation corresponding to a wind speed of 12 m/s. Note that in practical implementation, an external MPPT loop is normally used to optimize the power extraction. However, it is not included in this model. Instead, the step change in the speed reference is artificially imposed to create an extreme test case. This will impose a severe test to the system and will be able to demonstrate its stability and robustness due to rapid changes in operating conditions.

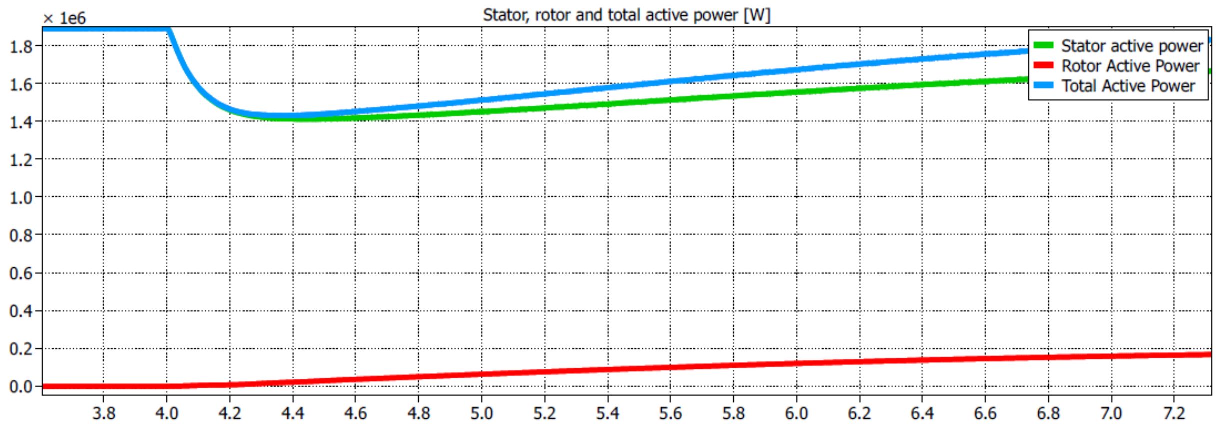

Figure 6.20 Active power of stator and rotor during speed transition condition

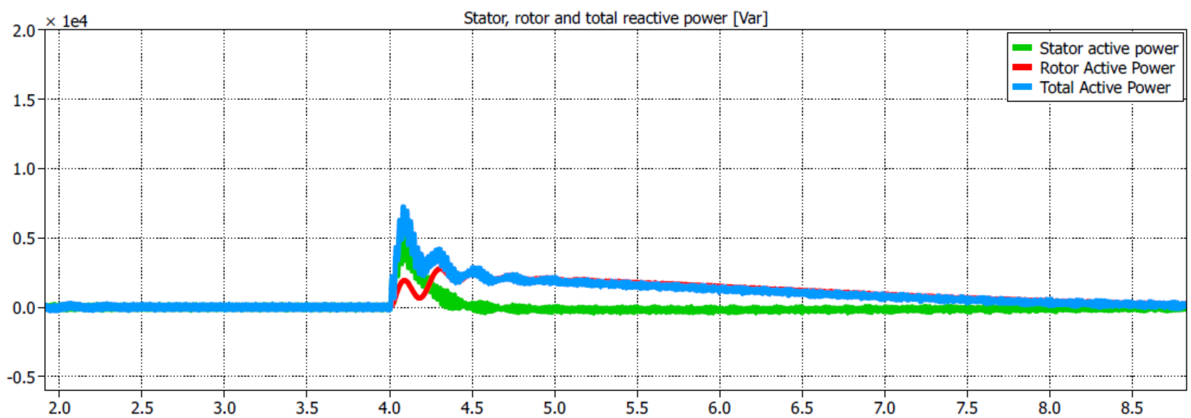

Figure 6.21 Reactive power of stator and rotor during speed transition condition

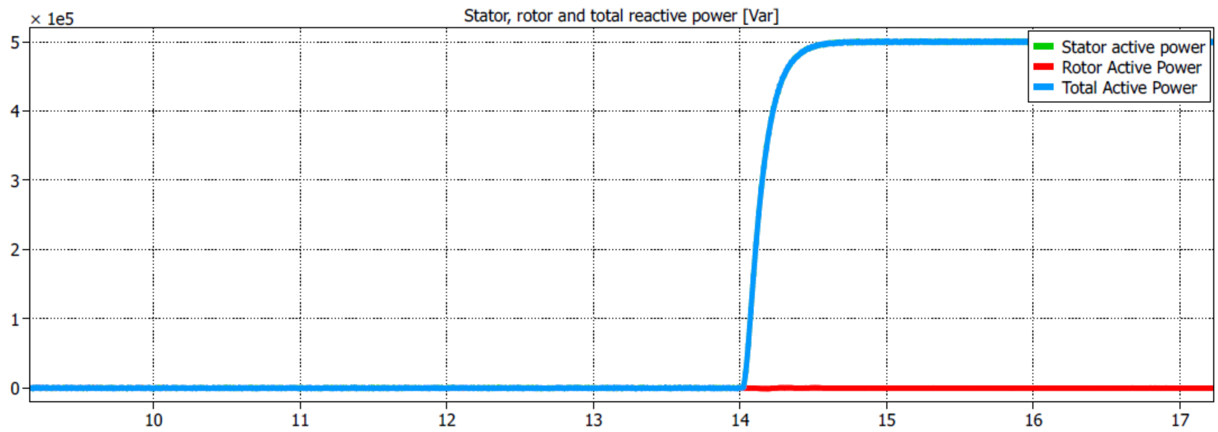

Figure 6.22 Reactive power injection

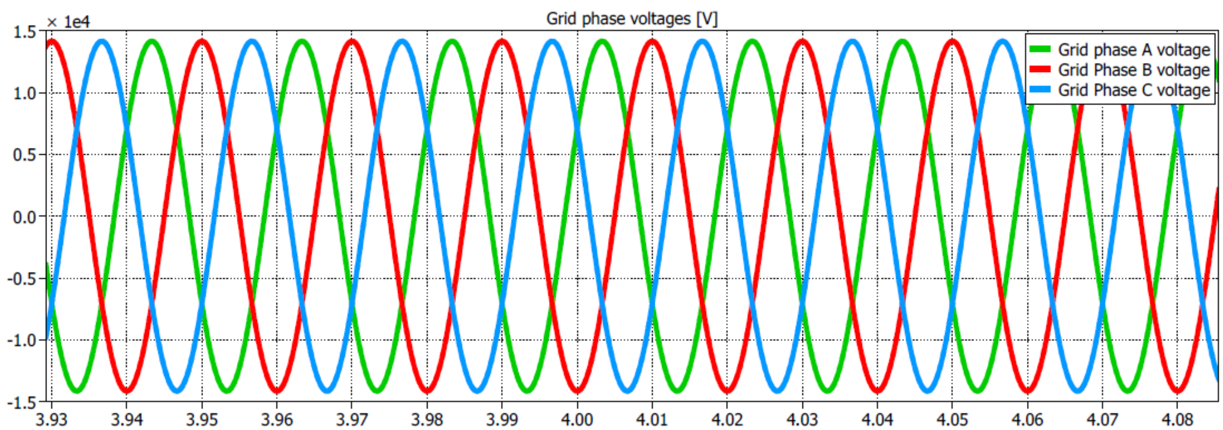

Figure 6.23 Grid(stator) phase voltages under speed transition conditions

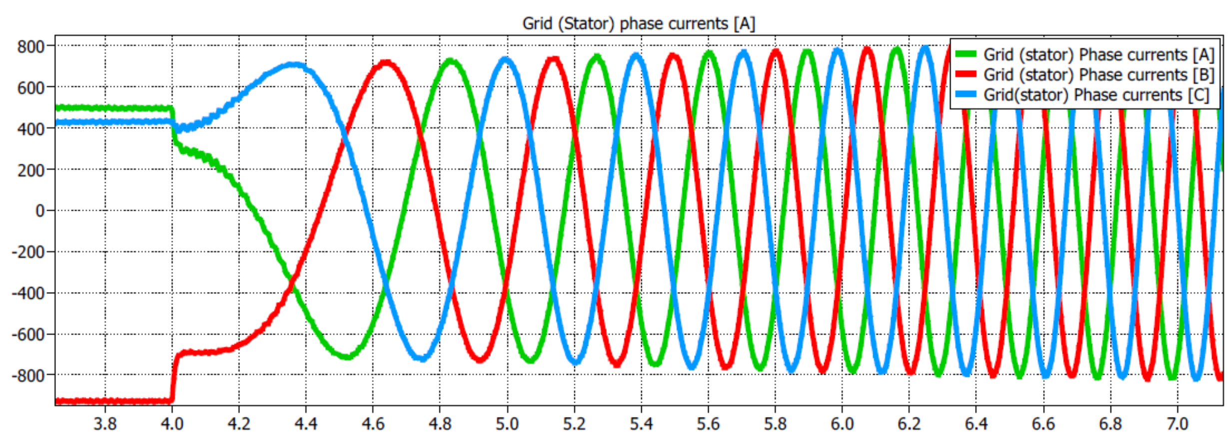

Figure 6.24 Grid(stator) phase currents under speed transition conditions

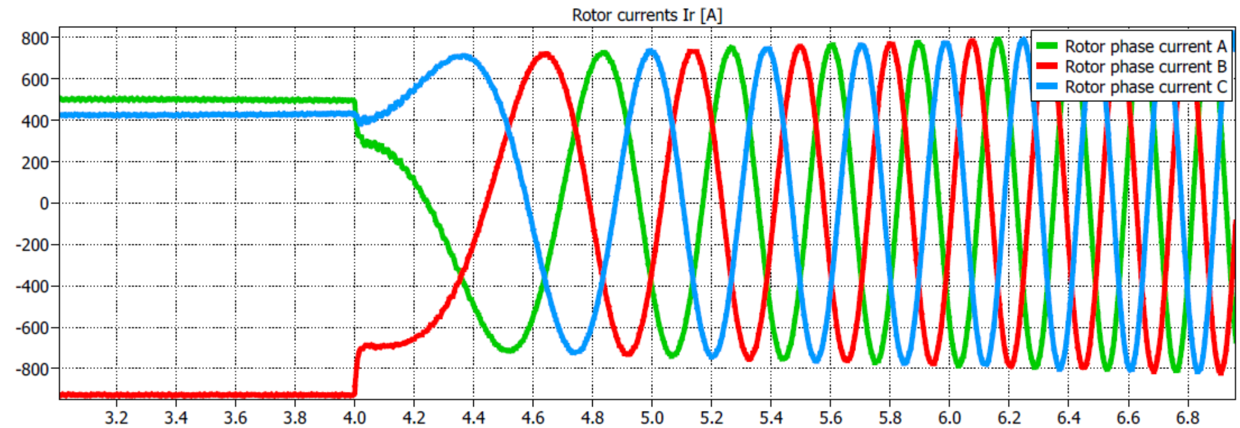

Figure 6.25 Rotor phase currents under speed transition conditions

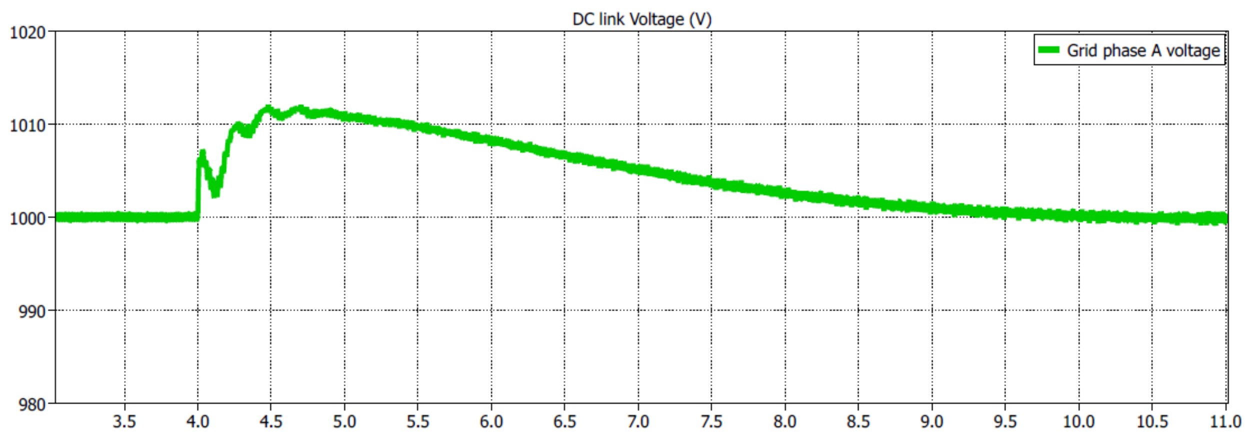

Figure 6.26 DC link voltage under speed transition conditions

Fault Condition and Recovery: A three-phase short circuit fault is applied to the 10 kV medium voltage grid at 20 seconds. A controllable voltage source is used to simulate a fault in three different ways, based on the residual voltage profile. This stage of the simulation is quite critical and important for system evaluation in terms of recovery from the disturbance in the grid and the stability once the fault is cleared. The simulation time is set to 25 seconds, which is enough to observe the response of the system, especially the mechanical part, such as rotor speed and torque. Although the 25-second timeframe is relatively long compared to the 10 kHz switching frequency of the back-to-back converters, it allows for a comprehensive evaluation of the overall system behavior.

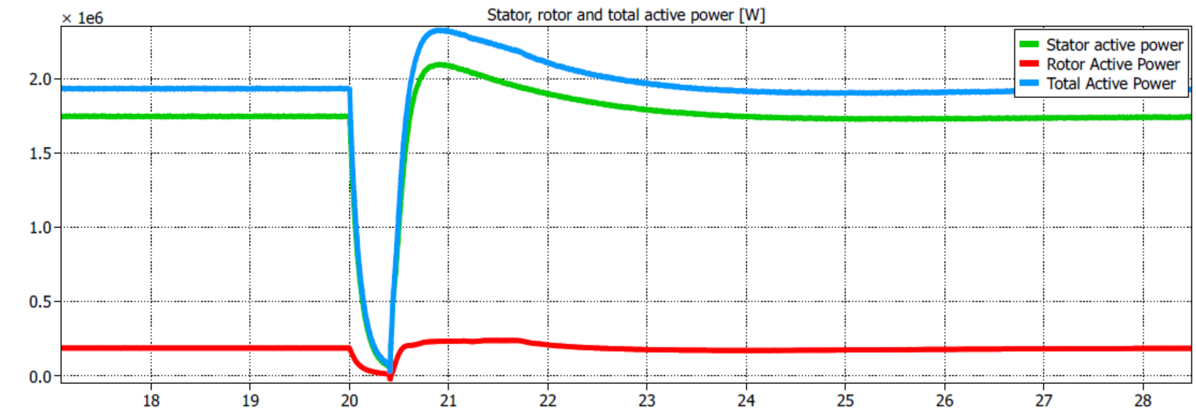

Figure 6.27 Stator, Rotor and Total Active power graphs during fault conditions

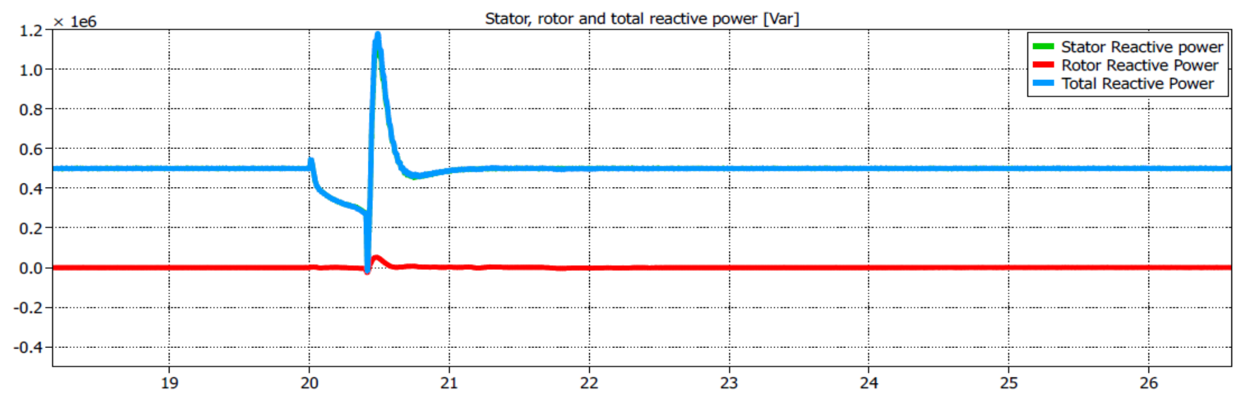

Figure 6.28 Stator, Rotor and Total Reactive power graphs during fault conditions

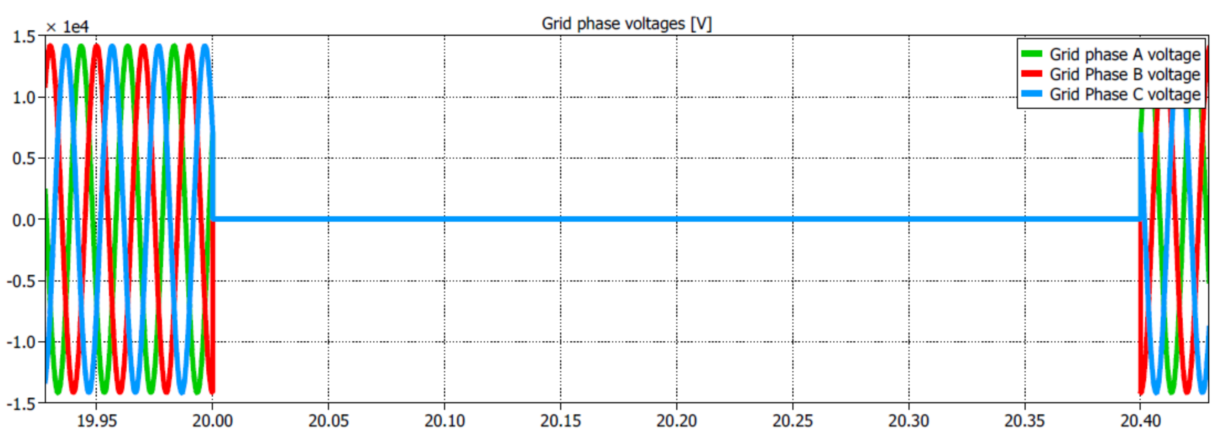

Figure 6.29 Grid (stator) voltage graphs during fault conditions

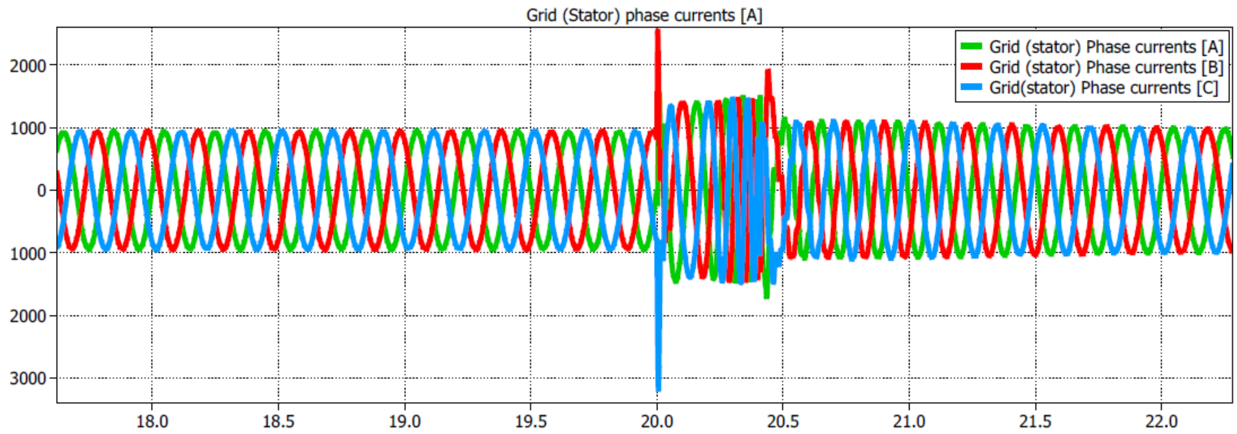

Figure 6.30 Grid (stator) phase current graphs during fault conditions

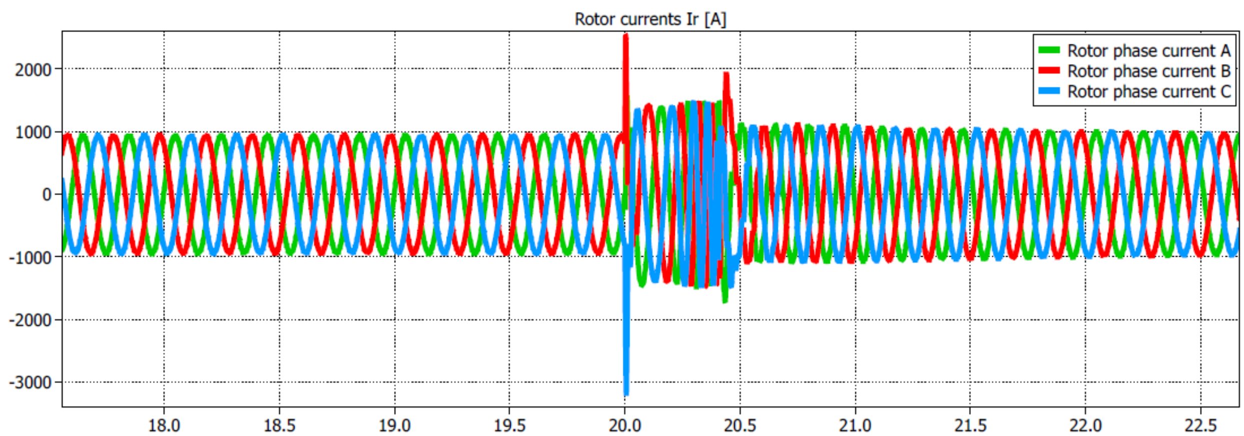

Figure 6.31 Rotor phase current graphs during fault conditions

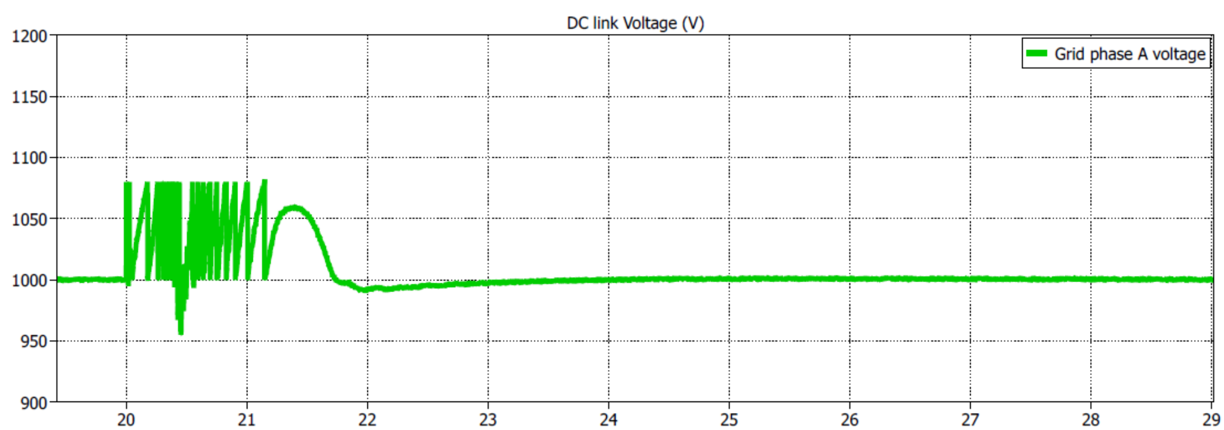

Figure 6.32 DC link voltage graph during fault conditions

Figure 6.14 shows the initial phase of the simulation. At this stage, most of the active power comes from the stator, as it is directly connected to the grid. The rotor does not contribute active power at synchronous speed. When the rotor speed increases at t=4 seconds (Figure 6.20), it begins to supply additional active power to the grid through the back-to-back converters, increasing the total active power.At t=20 seconds, a three-phase fault is introduced (Figure 6.27), causing a drop in total active power due to the resulting voltage sag. This triggers transient oscillations, but the system gradually stabilizes. After the fault is cleared, the total active power returns to its pre-fault level, demonstrating the robustness of the control system in handling disturbances.

Figures 6.15, 6.21, and 6.29 show the reactive power behavior of the stator, rotor, and total system. Initially, the stator provides most of the reactive power, while the rotor's contribution is minimal. At t=4 seconds, the rotor's reactive power increases to accommodate the higher rotor speed, and the total reactive power stabilizes soon after (Figure 6.21).

To reduce the size and cost of the Grid Side Converter (GSC), the reactive power flow is usually kept at zero by setting the reference d-axis current ($ide*$) to zero. A PI controller adjusts the voltage (vde∗)

to maintain this balance. At t=14 seconds (Figure 6.22), reactive power is injected into the stator, but the rotor's reactive power remains zero, as shown by the red line. This regulation minimizes the rotor current, reducing the GSC's size and cost. The total reactive power (blue line) closely follows the stator's reactive power (green line), confirming that the rotor's contribution is zero.

At t=20 seconds (Figure 6.29), the three-phase fault causes a spike in rotor reactive power, highlighting the system’s immediate response to maintain voltage stability. After the fault is cleared, the reactive power returns to steady-state levels, demonstrating the effectiveness of the system's reactive power compensation strategy.

The figures (6.16,6.17,6.18,6.19), (6.23,6.24,6.25,6.26) and (6.29,6.30,6.31,6.32) shows the electrical transients of voltage and current on the primary side of the transformer (10 kV side),rotor current and the DC-link voltage of the back-to-back converter and at initial transient conditions, speed transitional conditions and fault conditions. AC voltage of the stator and stator current are 180 degrees out of phase. It demonstrates generation mode. The AC current shows a great peak right after the occurrence of the fault and then settles below a threshold due to saturation of the current controller. Due to the terminal voltage drop of the transformer, the grid-side inverter temporarily loses the possibility of transferring power, and therefore the DC-link voltage remains almost uncontrolled during the initial period after the fault (Figure 6.32). During this period, the DC-link capacitor is charged or discharged by the machine-side inverter alone since the power transfer to the grid is hindered.

At the instant of the fault, the q-axis voltage (vrq) and current (irq) of the rotor remain at their respective pre-fault values and start charging the capacitor with almost the same amount of active power. This causes the DC-link voltage to increase very quickly, but it is clamped at a safe level-in this case, not more than 108% of the nominal voltage, or 1080 V-by the firing of the chopper circuit. The speed controller then tries to bring the rotor rotational speed back to 175 rad/s by adjusting the reference q-axis current. However, the current controller applies the q-axis voltage (vRq) of opposite polarity due to the reduced back EMF.

This leads to a short period of negative active power, which discharges the capacitor until the DC-link voltage catches up. During the recovery of the grid voltage, the back EMF rises, and the polarity of q-axis voltage goes back to the pre-fault condition, enabling positive active power to recharge the capacitor. In this phase, the limited power transfer capability of the grid-side inverter makes the net power flowing into the capacitor more than the demand, causing oscillations in the DC-link voltage between the clamped level and the nominal value. The oscillations continue until the grid voltage is fully recovered and the grid-side inverter resumes normal power transfer.

The simulation results confirm the DFIG's satisfactory performance across sub-synchronous, synchronous, and super-synchronous rotor speed ranges under both normal and faulted operating conditions. These findings highlight the system's robust control capabilities, efficient energy conversion, and resilience to grid disturbances. A detailed summary and recommendations for further optimization are provided in the conclusion.

Chapter 7. CONCLUSION

The modeling and simulation of a Doubly Fed Induction Generator (DFIG) for wind energy applications using PWM-based back-to-back converters has been presented in this thesis. With the help of PLECS transient effects have been analyzed. The simulation results showed that a DFIG can operate efficiently at variable wind conditions, smoothly transitioning between sub-synchronous, synchronous, and super-synchronous speeds. The use of two-level back-to-back converters allows for seamless control of active and reactive power flow, ensuring stability and grid compatibility even during disturbances such as three-phase faults. The DFIG showed good fault ride through capability, efficient power conversion, and reliable grid integration through detailed simulations under normal and fault conditions.

These findings have further established the necessity for DFIG systems in wind energy applications of modern times, which demands a highly flexible, efficient, and stable renewable energy source. This work contributes to the larger goal of enhancing the capabilities of wind energy conversion systems towards sustainable and resilient energy infrastructures.

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