

Heaven's Light is Our Guide



**FAULT RIDE THROUGH CAPABILITY
IMPROVEMENT OF A DFIG BASED WIND FARM
USING ACTIVE POWER CONTROLLED BRIDGE
TYPE FAULT CURRENT LIMITER AND BRIDGE-
TYPE FLUX COUPLING NON-SUPERCONDUCTING
FAULT CURRENT LIMITER**

A Thesis submitted in partial
fulfilment for the requirements of the
degree of

Bachelor of Science
in
Electrical and Electronic Engineering

By

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DECLARATION

This is to certify that the thesis work entitled “**Fault Ride Through Capability Improvement of a DFIG Based Wind Farm Using Bridge-Type Flux Coupling Non-Superconducting Fault Current Limiter**” has been carried out by Md. Najmul Huda bearing Roll no. 141054 and Jakir Hasan bearing Roll no. 141061 under my guidance and supervision and be accepted in partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical and Electronic Engineering. This research results presented in the thesis have not been included in any other paper submitted for the award of any degree to any other university or institute.

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ABSTRACT

Doubly fed Induction generators (DFIGs) have drawn a prominent interest in the field of wind power generation but they are vulnerable to grid faults. In order to intensify the fault ride through (FRT) capability, the DFIG should be connected with the grid throughout the time for maintaining the grid codes. Bridge type fault current limiters (BFCLs) are one of the newest additions to solve the issues with FRT capability. There are several existing schemes to control a BFCL. However, no attempt had been taken to use the active power of the DFIG for controlling the BFCL. In this paper, a new control scheme using the active power of the system is proposed. Moreover, a bridge type modified flux-coupling non-superconducting fault current limiter (BFC-NSFCL) is proposed for compensating fault current and voltage sag. The BFC-NSFCL is a combination of bidirectional bridge switch and a flux coupling reactor which utilizes magnetic flux cancellation effect so that the fault current limiter (FCL) can behave as a short circuit under normal operating conditions. Last of all, a non-linear controller is used for controlling the gate pulse in the IGBT of the bridge. Theoretical and graphical analysis for the BFC-NSFCL has been developed and proved by MATLAB/SIMULINK software. To illustrate its efficacy, its different performances have been compared and analyzed with performances of conventional BFCL and series dynamic braking resistor (SDBR).

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LIST OF ABBREVIATIONS

DFIG	Doubly Fed Induction Generator
WT	Wind Turbine
GSC	Grid Side Converter
RSC	Rotor Side Converter
IG	Induction Generator
BADC	Bangladesh Agriculture Development Corporation
DTC	Direct torque control
FCL	Fault Current Limiter
SFCL	Superconducting Fault Current Limiter
NSFCL	Non-Superconducting Fault Current Limiter
IEA	International Energy Outlook
3LG	Three-line-to-ground
2LG	Two-Line-To-Ground
1LG	Single-Line-To-Ground
DVR	Dynamic Voltage Restorer
STATCOM	Static Synchronous Compensator
SDBR	Series Dynamic Breaking Resistor
SSC	Static Series Compensator
SVC	Series Voltage Compensator
WTGS	Wind Turbine Generation System
FRT	Fault Ride Through
PWM	Pulse Width Modulation
GOB	Government of Bangladesh
LVRT	Low Voltage Ride Through
HVRT	High Voltage Ride Through
BFCL	Bridge Type Fault Current Limiter
PRFCL	Parallel Resonance Fault Current Limiter

PCC	Point of Common Coupling
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
BFC-NSFCL	Bridge Type Flux Coupling Non-Superconducting Fault Current Limiter
SMES	Superconducting Magnetic Energy Storage
WRIG	Wound Rotor Induction Generator
SCIG	Squirrel Cage Induction Generator
PLL	Phase-Locked Loop
NC-MBFCL	Nonlinear Controller Modified Bridge FCL
IPP	Independent Power Producer
PMSG	Permanent Magnet Synchronous Generator
IGBT	Insulated Gate Bipolar Transistor
MOV	Metal Oxide Varistor
BPDB	Bangladesh Power Development Board

CHAPTER 1

INTRODUCTION

1.1 Introduction

As the technological development is evolving so fast, today, the number of technology enthusiasts is more than it was yesterday. And since technology is nothing without electrical energy, the consumers of this energy are rising on an exponential rate. Till date, we humans were mostly dependent on the fossil fuel as our major source of energy. But the fossil fuels are limited and there is no doubt that one day there will be days in the future when no fossil fuel will be left for us to consume.

Wind energy is considered to be the most promising solution to the world's energy crisis since it is easily available, harnessing of it causes no carbon emission and most importantly, it is renewable. There had been several studies that shows fossil fuel will no longer be the major source of energy as its reserve is declining every day. A study showed that, total oil reserve will be depleted by the year of 2066. The gas and coal reserve will have the same consequence by the year of 2068 and 2126 respectively [1]. In recent years, wind energy is considered to be the best alternative to fossil energy. There is an estimation that, by the year of 2020, approximately 10 % of global energy will be fulfilled from wind energy [2].

The most common mean to capture the wind energy is to drive a wind turbine with the flow of wind keeping a generator on the same shaft. The most popular generator for this job is the Doubly Fed Induction Generator (DFIG) for its flexibility in operation and some other important features like higher output power, improved power quality and higher efficiency. In addition, it provides lower mechanical tension on turbine, fluctuating speed operation, disassociated control of active and reactive power [3].

But there is a problem associated with the DFIGs. The grid is directly interfaced with the stator winding of a DFIG. So, if there is any problem in the grid i.e. faults, the DFIG will get affected by it directly. The DFIG has a back to back converter configuration to provide it the variable speed operation. The stator is linked with the grid by the grid side converter (GSC). The rotor side converter (RSC) is connected with the GSC via a dc link capacitor.

Several types of faults can occur in a transmission line due to numerous reasons. During the faults, the current in the faulty line increases by a few times more than the normal value. The electrical equipment connected to the faulty line can suffer from severe damages if high current passes through them. Since the DFIGs are inextricably connected to the grid, it may get damaged by the high fault current unless some protective measures are taken. This necessitates the separation of the DFIG during the fault, which is certainly not the best solution. The

shutdown of a DFIG will trigger some other unaccountable events on the power system [4]. Also as per the grid codes, the DFIG needs to be connected to the grid during faults [5]. Hence improving the FRT capability is the best possible solution to this problem.

1.2 Literature Review

In the event of fault, the DFIG terminal voltages decrease expressively from the rated voltage and the RSC is highly effected due to injects of high fault current. As consequence, the performance of the DFIG under these conditions can considerably affect system stability. In literatures, there are many solutions have been performed and well documented in order to enhance the transient stability of the DFIG based wind generator (WG). Among the offered solutions, some research group's proposed internal controllers. Non-linear control strategy stabilizes the internal dynamics through rotor voltage control, and improves the dynamic behavior of DFIG after clearing fault [6].

In 2007, A.H. Kasem, E.F. El-Saadany and their team proposed a comprehensive time domain model for the DFIG with the decoupled dq controller [7]. The scheme protects the DFIG components, fulfills the grid code requirements and optimizes the hardware added to the generator. This paper presents a new FRT technique for wind-power DFIG. First, the optimum value for crowbar resistance is selected and the time setting for the crowbar removal is also investigated. Both rotor- and grid-side converters are employed to supply reactive current to compensate the generator demand of reactive power and feed the reactive power required by the grid code to the system. And then, the necessary TCM is designed to intensify the reactive current in feed during the fault and guarantee healthy operation of the proposed FRT technique. However, this model is sensitive to the generator parameters and other phenomena such as disturbances and unmodeled dynamics.

To protect the RSC of the DFIG from the excessive current, a series short circuit resistor is connected in the RSC which is called crowbar protection. This crowbar solution-based wind generator needs to disconnect from the grid in the event of fault to protect the RSC of the DFIG [8]. A conventional resistive crowbar (i.e., R-crowbar) circuit has been reported as the common solution to protect RSC switching devices and dc-link capacitor against the effect of transient-state by completely disconnecting the power converter from the rotor windings [9]. However, the crowbar method adversely affects the power network no longer applicable to the new grid codes with the increasing penetration of the DFIG based WT. For this reason, to accomplish the requirement of the new grid codes and to ensure continue operation on the grid side, it is necessary to find a suitable solution to improve the transient stability of the DFIG based wind power systems as well as low voltage ride through (LVRT) capability during the fault.

In the year of 2013, M. E. Elshiekh, D. A. Mansour and A. M. Azmy proposed a method to improving fault ride-through capability of DFIG-based wind turbine using superconducting

fault current limiter [10]. SFCL is considered as a self-healing method since it does not need any control action to be changed from superconducting to non-superconducting states. So, during normal condition, dc is passed through the SFCL and the system runs without any interruption. But during fault conditions, the nature of SFCL absorbs the fault current and stabilizes the system. Their model is simple and effective. However, this model is not economical since superconductors are too much costly.

With the solutions of the problems mentioned above, in 2014, Mohamed Benbouzid and Brice Beltran proposed a second-order sliding mode control for DFIG-based wind turbines fault ride-through capability enhancement [11]. They proposed a second-order sliding mode as an improved solution that handle the classical sliding mode chattering problem. The goal was to control rotor voltages and currents, to reduce the rotor over-voltages and/or over-currents, and therefore avoid the crowbar use/activation in order to keep full DFIG control at all times to meet the FRT requirements. The main and attractive features of HOSMs are robustness against grid faults and no extra mechanical stress on the drive train. The results they achieved showed promising successful ride-through performances over well-known PI-based control and even over classical first-order sliding mode control. But, it has one major drawbacks. They couldn't propose a technique to deal with the output power fluctuation.

In the same year of 2014, Issarachai Ngamroo and Tanapon Karaipoom proposed a cooperative control of a resistive type SFCL and a superconducting magnetic energy storage (SMES) for enhancing fault ride through (FRT) capability and smoothing power fluctuation of the DFIG based wind farm [12]. The SMES is used to provide voltage to the system during fault to recover the voltage and the SFCL is used to improve the fault ride through capability providing a shunt path to the fault current. But, this method has certain drawbacks. It was found that, the higher the resistance of the BFCL, the better the results. But, the high resistance results in the high energy loss during the period of fault current limitation. Additionally, the resistance value of the SFCL in these works is selected based on trial-and-error which cannot guarantee the optimal value.

In the following year, in 2015, Gilmanur Rashid and Mohd. Hasan Ali proposed a method to enhance the transient stability of doubly fed induction machine-based wind generator using bridge-type fault current limiter [4]. Their model consisted a bridge that has an IGBT that senses the fault and gets disconnected during the fault. The high current then passes through the shunt resistor and thus the extra energy is absorbed. The absorption of energy causes the fault current to cease and the system voltage rises up. However, this model can be further developed using parallel resonance fault current limiter.

In the same year, L. Huchel, Mohamed Shawky El Moursi proposed that, FRT capability can be improved by a parallel capacitor control strategy [13]. They developed a technically simple and cost-effective scheme considering transmission line auto-reclosing which may cause

multiple fault inceptions. By comparing the parallel capacitor scheme with solutions utilizing rotor circuit crowbar or dc chopper resistor, it can be stated that for the proposed scheme, the blocking of the inverters in back-to-back topology can be avoided. The impact of transmission line auto-reclosing is also considered in the design to tackle the multiple fault inceptions in case of permanent fault. However, this kind of control could be easily saturated when dealing with substantial sag.

In the following year, in 2016, Gilmanur Rashid and Mohd. Hasan Ali developed their previous model proposing that the FRT capability can be further improved using parallel resonance fault current limiter [14]. Their system consists of a bridge with an IGBT that senses the fault and gets disconnected during the fault. The high current then passes through the resonant circuit and gets minimized. The main job to design the PRFCL is to determine appropriate values of the shunt path capacitor C_{sh} and inductor L_{sh} . They were found through trial and error process and the best combinations were used in the shunt path. However, their model can be further improved by using any optimization technique such as neural network or fuzzy logic or a combination of both.

Understanding the limitations, in 2017, they came up with the idea of implementing fuzzy logic in their PRFCL and got some significantly better results [15]. They took the PCC voltage as the controlling function and used fuzzy logic to control the pulse to the gate of the IGBT of the bridge they were using. They controlled the pulse width with some specific membership functions. The result outperformed the previous models. However, the fuzzy logic they used requires updated membership functions. So, the model needs constant maintenance. Which increases the total cost.

Fault current limiters (FCLs) are developed to overcome the aforementioned problems. An ideal FCL should have the following characteristics [16].

- Zero impedance in the normal operation.
- No power loss in the normal operation.
- Large impedance in the fault conditions.
- Quick appearance of impedance when a fault occurs.
- Fast recovery after fault removal.

The implementation of FCLs in electric power systems is not restricted to suppressing the amplitudes of short-circuit currents. They are also utilized to variety of performances such as power quality improvement, power system transient stability enhancement, reliability improvement, and increasing transfer capacity of system electrical energy. Therefore, an ideal FCL should have another important characteristic in addition to the listed characteristics.

In this work, two different fault current limiting schemes are proposed.

- First, a new scheme for controlling the BFCL operation using the active power reference is proposed. So far in the literature there is no work that employ active power of the DFIG as the control input.
- In addition to that, to reduce the power loss, a bridge type non-superconducting flux coupling fault current limiter is proposed to augment the fault ride through of a DFIG based wind farm.

1.3 Motivations

The combustion of conventional fossil fuel across the globe has caused increased level of environmental pollution [17]. Several international conventions and forums have been set up to address and resolve the issue of climate change. These forums have motivated countries to form national energy policies dedicated to pollution control, energy conservation, and energy efficiency, development of alternative and clean sources of energy [1].

Renewable energy like solar, wind, and tidal currents of oceans is sustainable, inexhaustible and environmentally friendly clean energy. Due to all these factors, wind power generation has attracted great interest in recent years. Undoubtedly, wind power is today's most rapidly growing renewable energy source. According to Global Wind Energy Council and Green Peace International estimations it is possible to mitigate the 20% of electricity demand with the wind power.

But one of the major challenges for DFIG is to stay connected to the grid during fault. Since the faults in a power system are inevitable, it is not worth the effort to seek for the ways to prevent them. Instead, power system engineers work on finding the ways to ride through the fault keeping the major parts of the system unaffected. This is the motivation where the fault current limiters emerged from.

1.4 Objectives

The main objective of this thesis is to improve the transient stability of the DFIG by an active power-controlled bridge type fault current limiter and a bridge type flux coupling non-superconducting fault current limiter. The objectives can be stated as follows:

- To maintain the grid code strictly and increase the system stability by suppressing the fault current of a DFIG based wind farm.
- To implement an active power-controlled bridge type fault current limiter to bypass and limit the transient fault current.
- To implement a bridge type flux coupling non-superconducting fault current limiter to augment the fault ride through capability of the wind farm.
- To record the responses of the system both in normal and fault condition with and without our proposed controllers.

- To compare the responses of our proposed controller with that of other existing controllers and provide apposite arguments.

1.5 Outline of the Book

This book is completed within 5 chapters. An overview of these chapters are given below.

Chapter 1

This chapter deals with introduction, literature review, motivation, objectives and outlines of this book.

Chapter 2

A short description on wind energy is provided in this chapter. In addition to that, the prospects of wind energy in Bangladesh is also discussed. Further, different types of wind generators are discussed. Further, the basics of the Doubly Fed Induction Generator are presented including functioning, mathematical model, working principle and application

Chapter 3

In this chapter, an overview of bridge type fault current limiter and its control scheme using active power is given. Later, the bridge type flux coupling non-superconducting fault current limiter is introduced and its construction, working principle and design considerations are discussed.

Chapter 4

The simulation results and discussions are provided in chapter 4.

Chapter 5

Finally, the findings of the thesis are wrapped up in chapter 5. The prospects of this work are also stated.

CHAPTER 2

WIND ENERGY AND ITS CONVERSION

2.1 Introduction

Electrical power is the most widely used source of energy for our homes, work places and industries. Population and industrial growth have led to significant increases in power consumption over the past three decades. To meet world's increasing energy demand and to save the environment, there is no alternative of renewable energy sources. Wind turbines contribute a large part to meet the world's energy crisis by providing clean energy as it is a part and parcel of the wind energy generation system. The speed of wind continuously changes with time due to change of temperature of the air. That is why off-shore and on-shore wind turbines are introduced. These wind turbines extract power from wind and provide sufficient conversion of wind energy into electrical energy.

2.2 Renewable Energy

Renewable energy, often referred to as clean energy, comes from natural sources or processes that are constantly replenished. For example, sunlight or wind keep shining and blowing, even if their availability depends on time and weather.

While renewable energy is often thought of as a new technology, harnessing nature's power has long been used for heating, transportation, lighting, and more. Wind has powered boats to sail the seas and windmills to grind grain. The sun has provided warmth during the day and helped kindle fires to last into the evening. But over the past 500 years or so, humans increasingly turned to cheaper, dirtier energy sources such as coal and fracked gas.

As renewable use continues to grow, a key goal will be to modernize world's electricity grid, making it smarter, more secure, and better integrated across regions.

2.2.1 Types of Renewable Energy

There are many forms of renewable energy. Most of these renewable energies depend in one way or another on sunlight. Wind and hydroelectric power are the direct result of differential heating of the Earth's surface which leads to air moving about (wind) and precipitation forming as the air is lifted. Solar energy is the direct conversion of sunlight using panels or collectors. Biomass energy is stored sunlight contained in plants. Other renewable energies that do not depend on sunlight are geothermal energy, which is a result of radioactive decay in the crust

combined with the original heat of accreting the Earth, and tidal energy, which is a conversion of gravitational energy.

A list of existing renewable energy sources are given below:

- Solar energy
- Wind energy
- Hydroelectric energy
- Bio-mass energy
- Hydrogen and fuel cells
- Geothermal energy
- Tidal energy

2.2.2 Wind Energy

The wind is a clean, free, and readily available renewable energy source. Each day, around the world, wind turbines are capturing the wind's power and converting it to electricity. This source of power generation plays an increasingly important role in the way we power our world.

Wind is a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. This wind flow, or motion energy, when "harvested" by modern wind turbines, can be used to generate electricity.

2.2.3 Prospect of Wind Energy

The wind is a clean, free, and readily available renewable energy source. Each day, around the world, wind turbines are capturing the wind's power and converting it to electricity. This source of power generation plays an increasingly important role in the way we power our world.

Wind energy looks set to become a major generator of electricity throughout the world. Particularly in Europe, the offshore exploitation of wind energy is likely to become one of the most important means of reducing carbon dioxide emissions from the electricity sector. But achieving the levels of generation seen in the scenarios will require considerable investment in electricity grids, interconnection and in other infrastructure.

However, it appears that there is strong motivation from many governments and industries to facilitate this expansion.

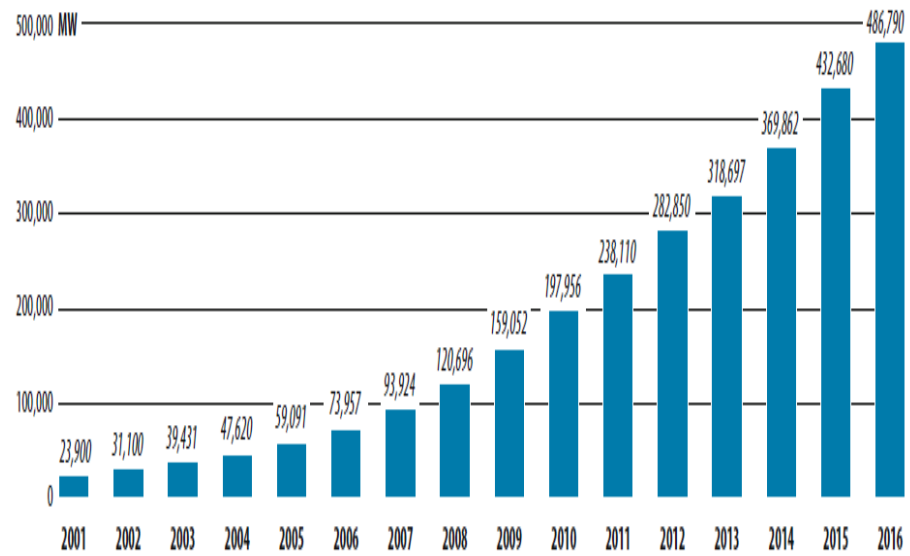


Fig. 2.1 Global cumulative installed wind capacity (2001-2016) [18].

It has been found that, the consumption of wind energy is increasing very fast and so total cumulative installed wind capacity is rising rapidly. This scenario is shown in Fig. 2.1.

2.2.4 Prospect of Wind Energy in Bangladesh

Most of the lands in Bangladesh are plain. Since wind velocity is directly proportional to height, Bangladesh is not suitable for harnessing of wind energy in a large scale. However, the lengthy period wind flux, particularly in the islands and southern maritime facial of Bangladesh, announce that the average wind speed remains between 3 and 4.5 m/s in the months of March to September and 1.7 to 2.3 m/s for the residual period of the year [19]. So, in islands and coastal areas the appeal of wind mills for pumping and electrification is very high.

Bangladesh Power Development Board (BPDB) has completed a 1000 kW capacity wind battery hybrid power project in Kutubdia islands [20]. Under this project, a total of 50 units of 20 kW capacity stand-alone type wind turbines are being installed. The total power generated by all the wind turbines is stored in a battery bank. Wind Battery Hybrid Power Plant (WBHPP) was officially started on March 30th, 2008. The other project of BPDB has completed a 0.90 MW capacity grid connected to wind energy at Muhuri Dam area in Feni district in 2004 [21]. The BPDB has allotted that wind energy can contribute up to 10% of the energy generated.

Some other steps have been taken to install 15 MW wind power plant across the coastal regions of Bangladesh. Installation of wind monitoring stations at Inani beach of Cox'sbazar, Parky

beach of Anwara, Sitakundu of Chittagong and at Chandpur are underway. The feasibility of wind condition for generation of electricity at different places in Bangladesh and illuminates that maximum annual average wind speed is 2.42 m/s in Cox's Bazaar and minimum 2.08m/s in Hatia Island.

Besides all these existing projects, a few projects are undergoing planning too. BPDB has planned to implement 50-200 MW wind power project at Parky Beach area, Anwara in Chittagong on independent power producer (IPP) basis. Power Division and BPDB have primarily identified 22 potential sites for wind resource mapping in Bangladesh. BPDB has also plan to expand On-shore wind power plants along the coastline of coastal regions of Bangladesh.

2.3 Wind Turbine

Wind turbines, like aircraft propeller blades, turn in the moving air and power an electric generator that supplies an electric current. Simply stated, a wind turbine is the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.

2.3.1 Components of Wind Turbine

The basic components of wind turbine are as follows:

- Foundation
- Tower
 - Tubular tower
 - Lattice tower
 - Guy tower
 - Tilt up tower
 - Free standing tower
- Rotor
- Blades
 - Single bladed turbines
 - Tow bladed turbines
 - Three bladed turbines
 - Multi bladed turbines

- Hub
 - Hinge-less hub
 - Teetering hub

- Nacelle
 - Drive shaft
 - Gear box
 - Break
 - Generator
 - Wind vane
 - Yaw mechanism
 - Anemometer
 - Cooling unit
 - Control panel
 - Power converter
 - Step up transformer

2.3.2 Types of Wind Turbine

Modern wind turbines fall into two basic groups i.e. the horizontal-axis variety and the vertical-axis design.

2.3.2.1 Horizontal Axis Turbine

Like the traditional farm windmills used for pumping water, the horizontal axis wind turbine are the most used turbines in wind farm technology. All of the components (blades, shaft, generator) of this turbine are on top of a tall tower and the blades face into the wind. A typical horizontal axis turbine is shown in Fig. 2.2(a). The shaft is horizontal to the ground. The wind hits the blades of the turbine that are connected to a shaft causing rotation. The shaft has a gear on the end which turns a generator. The generator produces electricity and sends the electricity into the power grid. The wind turbine also has some key elements that adds to efficiency. Inside

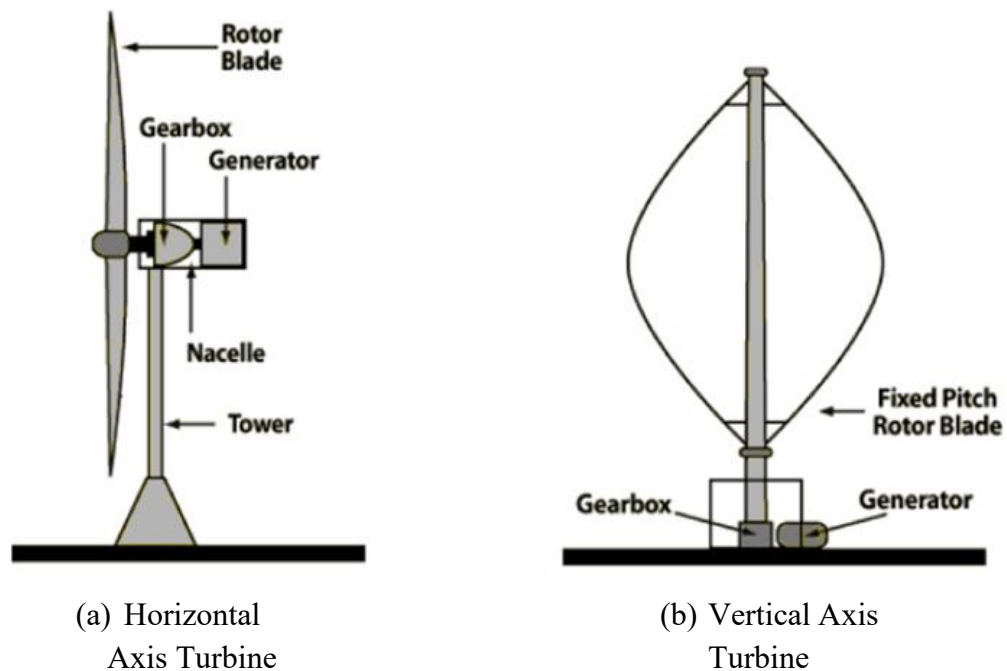


Fig. 2.2 Different Types of Wind Turbines

the Nacelle (or head) is an anemometer, wind vane, and controller that read the speed and direction of the wind. As the wind changes direction, a motor (yaw motor) turns the nacelle so the blades are always facing the wind. The power source also comes with a safety feature. In case of extreme wind, the turbine has a brake that can slow the shaft speed. This is to inhibit any damage to the turbine in extreme conditions.

2.3.2.2 Vertical Axis Turbine

The vertical axis wind turbines are shaped like the eggbeater-style Darrieus model, named after its French inventor. In these turbines, the shaft the blades are connected to is vertical to the ground as seen from Fig. 2.2 (b). All of the main components are close to the ground. Also, the wind turbine itself is near the ground, unlike horizontal where everything is on a tower. There are two types of vertical axis wind turbines; lift based and drag based. Lift based designs are generally much more efficient than drag, or ‘paddle’ designs.

2.3.3 Fixed Speed and Variable Speed Wind Turbines

Wind turbine is classified into two types. They are fixed speed turbines and variable speed turbines.

2.3.3.1 Fixed Speed Wind Turbine

In fixed speed turbines the maximum efficiency is obtained at a particular speed only. That is, regardless of the wind speed, the rotor speed of the wind turbine is fixed and it is determined

by the gear ratio, frequency of the supply grid and design of the generator. The device consists of an induction generator connected directly to the grid as shown in Fig. 2.3. An installation of soft starter unit along with capacitor bank is necessary for reducing reactive power consumption. Fixed speed turbines are being simple, reliable, cheap, robust and well proven. And the cost of electrical parts are also low the disadvantages are, limited power quality control an uncontrollable reactive power consumption ,and mechanical stresses due to fixed speed operation, all fluctuations in the wind speed are transmitted as fluctuations in mechanical torque and then it causes fluctuations in the electrical power on the grid.

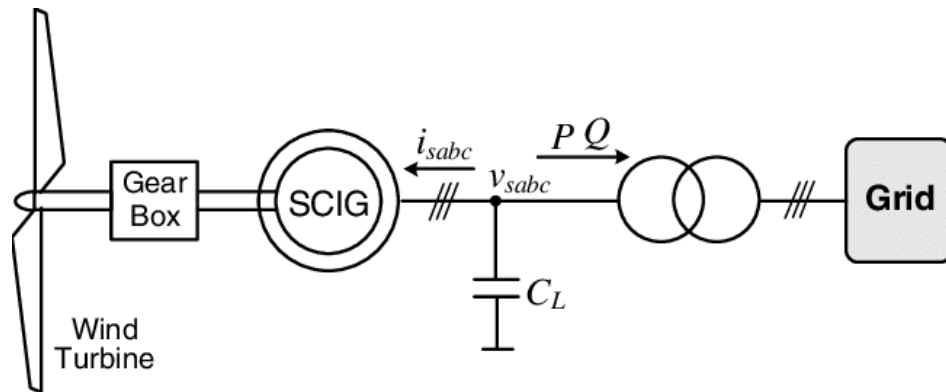


Fig. 2.3 Fixed Speed Wind Turbine

2.3.3.2 Variable Speed Wind Turbine

In variable speed wind turbines, the maximum efficiency is obtained over a wide range of wind speeds. The electrical System design of the variable speed wind turbines are more complicated as compared with fixed speed wind turbine. It is equipped with an induction or synchronous generator which connected to the grid through a power converter. The power converter is used to control the generator speed. The schematic diagram of a variable speed is shown in Fig. 2.4.

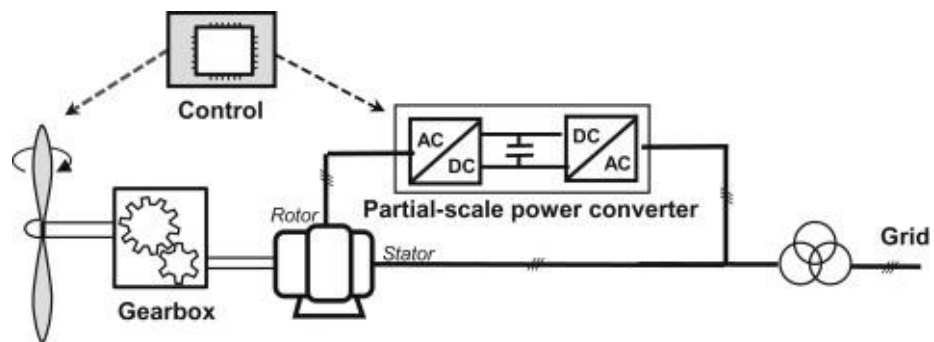


Fig. 2.4 Variable Speed Wind Turbine

2.3.4 Modeling of a Wind Turbine

The power extracted from the wind imposed on the turbine is known as the mechanical power. It can be expressed as follows [11], [22],

$$P_{\omega} = \frac{1}{2} \pi \rho R^2 V_{\omega}^3 C_p(\lambda, \beta) \quad (2.1)$$

Where P_{ω} is the power imposed on the turbine, ρ is the density of air, R is the radius of rotor blade, V_{ω} is the velocity of wind, C_p is the coefficient of power, λ is the ratio of the tip speed and β is the blade pitch angle.

Here C_p is a function of λ and β . C_p can be further expressed as,

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6 \lambda \quad (2.2)$$

$$\lambda = \frac{\omega_r R}{V_{\omega}} \quad (2.3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (2.4)$$

Here ω_r is the angular mechanical speed and C_1, C_2, C_3, C_4, C_5 and C_6 are different constants that defines the turbine characteristics.

2.4 Wind Turbine Generators

The function of wind generators is to convert of mechanical energy of the turbine to electrical energy. Any types of three-phase generator can connect to with a wind turbine. There are several types of generators for this task. The generators of wind farm technology are mainly of two types:

- Asynchronous Generators
- Synchronous Generators

Squirrel cage induction generator (SCIG) and wound rotor induction generator (WRIG) come under asynchronous generators. Wound rotor generator (WRSG) and permanent magnet generator (PMSG) are under synchronous generator. Detailed explanations are given below.

2.4.1 Asynchronous Generators

An induction generator or asynchronous generator is a type of alternating current (AC) electrical generator that uses the principles of induction motors to produce electric power. Induction generators operate by mechanically turning their rotors faster than synchronous speed. They can fall into two categories.

2.4.1.1 Squirrel Cage Induction Generator (SCIG)

The fixed speed concept is used in this type of wind turbine. In this configuration the Squirrel Cage Induction Motor is directly connected to the wind through a transformer is shown in Fig. 2.5. A capacitor bank is here for reactive power compensation and soft starter is used for smooth grid connection. The main disadvantage of SCIGs is that they do not support any speed control.

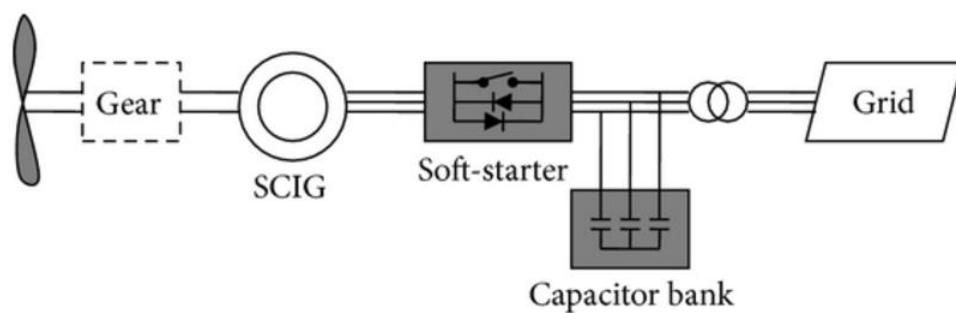


Fig. 2.5 SCIG based wind turbine

2.4.1.2 Wound Rotor Induction Generator (WRIG)

The variable speed concept is used in this type. Wound Rotor Induction Generator is directly connected to the grid as shown in Fig. 2.6. The variable rotor resistance is for controlling slip and power output of the generator. The soft starter used here for reduce inrush current and reactive power compensator is used to eliminate the reactive power demand. The speed range is limited, poor control of active and reactive power, the slip power is dissipated in the variable resistance as losses are the disadvantages of this configuration.

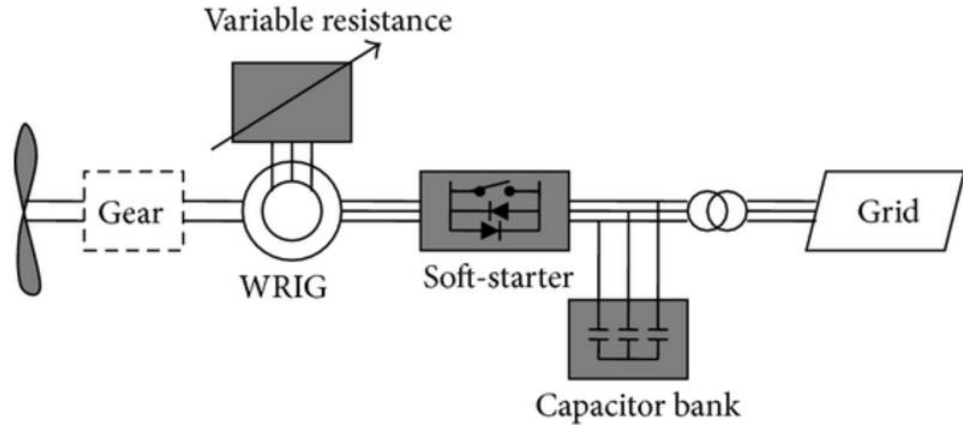


Fig. 2.6 WRIG based wind turbine

2.4.2 Synchronous Generators

The synchronous generator or alternator is an electrical machine which converts the mechanical power from a prime mover into an AC electrical power at a particular voltage and frequency. The synchronous motor always runs at the constant speed called synchronous speed. They are of two types.

2.4.2.1 Wound Rotor Synchronous Generator (WRSG)

Turbine with wound rotor connected to the grid is shown in Fig. 2.7. The main advantage of this configuration is it neither require soft starter nor a reactive power comparator. The partial scale frequency converter used in the system will perform reactive power compensation as well as smooth grid connection. The wide range of dynamic speed control depends on the size of frequency converter. The main disadvantage is that in the case of grid fault it requires additional protection and use slip rings, this makes electrical connection to the rotor.

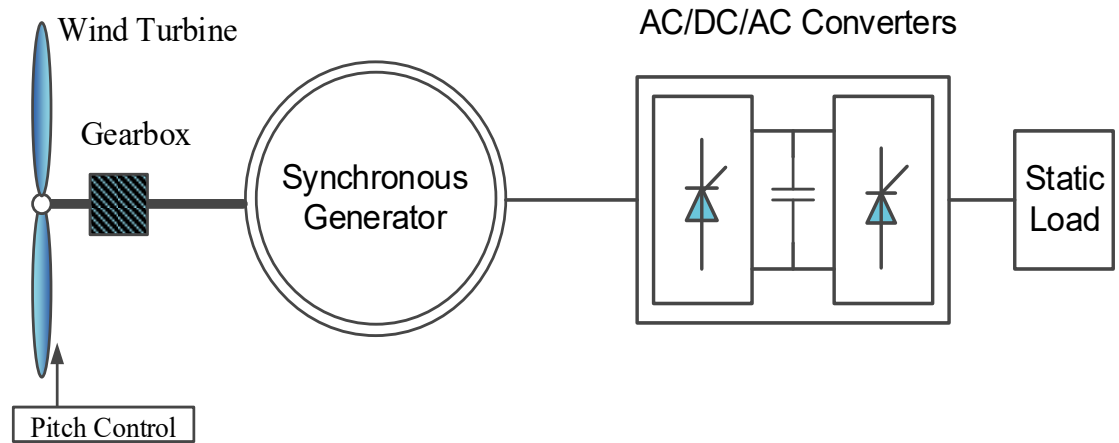


Fig. 2.7 Wound rotor synchronous generator

2.4.2.2 Permanent Magnet Synchronous Generator (PMSG)

A permanent magnet synchronous generator is a generator where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous refers here to the fact that the rotor and magnetic field rotate with the same speed, because the magnetic field is generated through a shaft mounted permanent magnet mechanism and current is induced into the stationary armature.

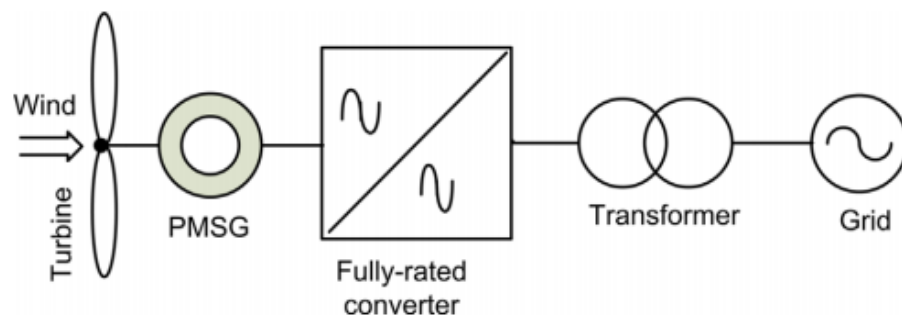


Fig. 2.8 Permanent Magnet Synchronous Generator

Synchronous generators are the majority source of commercial electrical energy. They are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for the grid. Some designs of Wind turbines also use this generator type.

2.5 Doubly Fed Induction Generator (DFIG)

A Doubly Fed Induction generator as its name suggests is a 3-phase induction generator where both the rotor and stator windings are fed with 3 phase AC signal. It consists of multi-phase windings placed on both the rotor and stator bodies. It also consists of a multiphase slip ring assembly to transfer power to the rotor. It is typically used to generate electricity in wind turbine generators.

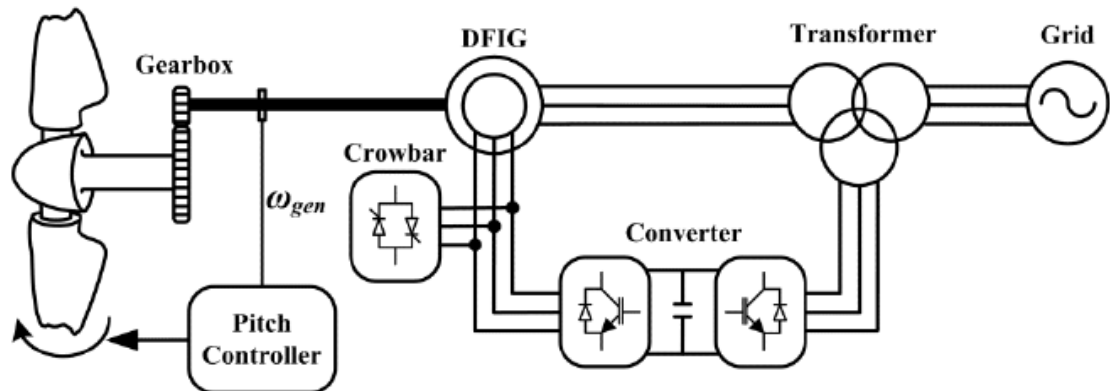


Fig. 2.9 DFIG based wind farm

The DFIG is basically an induction generator whose stator side is attached to the grid directly. Though the stator winding is also attached to the grid, the rotor winding is interfaced with the grid via Rotor Side Converter (RSC) and the Grid Side Converter (GSC) that are connected through a dc-link capacitor. The configuration of a DFIG in wind turbine system is shown in Fig. 2.8.

2.5.1 Advantages of DFIG

- The amplitude and frequency of the voltages remain constant while operating at variable speed.
- The amount of power generated as a function of the available wind power is optimized.
- Sudden variations in the rotor torque and generator output power is virtually eliminated.
- Electrical power generation happens even at low wind speeds.
- It will be able to control the power factor.
- The speed is variable within a sufficient range with the limit converter costs.
- The stator active and reactive power can be controlled independently by controlling the rotor currents with the converter.
- Furthermore, the grid side converter can control its reactive power to the grid independently of the generator operation.

2.5.2 Disadvantages of DFIG

- A multistage switch gear box is still necessary in the drive train, because the speed range of a DFIG without gearbox is far away from a common turbine speed of 10-15 rpm.
- The major drawback of DFIG based wind turbine is their operation during abnormal conditions like grid faults and voltage sags, short circuit fault (phase-to-phase, phase-to-ground, three line-to-ground) and open circuit fault. So that many control strategies are required for solving these problems.

2.5.3 Working Principle of DFIG

DFIG works in a generating principle that is widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly (in brushless doubly-fed electric machines), but there are problems with efficiency, cost and size. A better alternative is a brushless wound-rotor doubly-fed electric machine.

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus, in the typical $\pm 30\%$ operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter. The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages and high currents resulting from these voltages from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

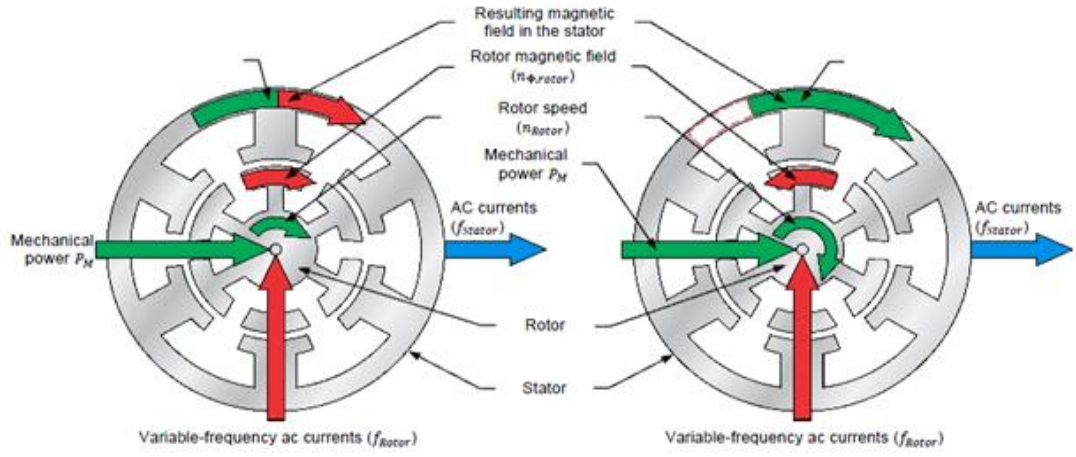
The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the

start of the grid disturbance when the remaining voltage stays above 15% of the nominal voltage. Thus, it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault. For zero voltage ride through it is common to wait until the dip ends because with zero voltage it is not possible to know the phase angle where the reactive current should be injected.

As a summary, a doubly-fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances (low voltage ride through, LVRT). Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason.

2.5.3 Variable Speed Operation of DFIG

In a conventional three-phase synchronous generator, when an external source of mechanical power (i.e., a prime mover) makes the rotor of the generator rotate, the static magnetic field created by the dc current fed into the generator rotor winding rotates at the same speed η_{rotor} as the rotor. As a result, a continually changing magnetic flux passes through the stator windings as the rotor magnetic field rotates, inducing an alternating voltage across the stator windings. Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings. The magnetic field created in the rotor is not static (as it is created using three-phase ac current instead of dc current), but rather rotates at a speed $\eta_{\phi, \text{rotor}}$ proportional to the frequency of the ac currents fed into the generator rotor windings. This means that the rotating magnetic field passing through the generator stator windings not only rotates due to the rotation of the generator rotor, but also due to the rotational effect produced by the ac currents fed into the generator rotor windings. Both the rotation speed η_{rotor} of the rotor and the frequency f_{rotor} of the ac currents fed into the rotor windings determine the speed $\eta_{\phi, \text{stator}}$ of the rotating magnetic field passing through the stator windings, and thus, the frequency f_{stator} of the alternating voltage induced across the stator windings.



(a) Stator and rotor magnetic field in the same direction

(b) Stator and rotor magnetic field in the opposite direction

Fig. 2.10 Constant frequency operation for variable wind speed.

So, when the magnetic field at the rotor rotates in the same direction as the generator rotor as shown in Fig. 2.9 (a), the rotor speed n_{rotor} and the speed $n_{\phi,rotor}$ of the rotor magnetic field (proportional to f_{rotor} add up. The frequency f_{stator} of the voltages induced across the stator windings of the generator ac can thus be calculated using the following equation.

$$f_{stator} = \frac{n_{rotor} \times N_{poles}}{120} + f_{rotor} \quad (2.5)$$

Conversely, when the magnetic field at the rotor rotates in the direction opposite to that of the generator rotor as shown in Fig. 2.9 (b), the rotor speed n_{rotor} and the speed $n_{\phi,rotor}$ of the rotor magnetic field subtract from each other.

$$f_{stator} = \frac{n_{rotor} \times N_{poles}}{120} - f_{rotor} \quad (2.6)$$

The f_{stator} of both these equations must be equal to $f_{network}$ which is the frequency of the ac power network to which the doubly-fed induction generator is connected, expressed in hertz (Hz). However, The f_{rotor} depends on the wind speed. As wind speed changes continuously, so adjustable ac current has to fed to the rotor winding of DFIG. Equation (2.5) can be further written as,

$$f_{rotor} = f_{network} - \frac{\eta_{rotor} \times N_{poles}}{120} \quad (2.7)$$

If the generator rotor rotates at the nominal (singly-fed) synchronous speed η_s , the frequency f_{rotor} of the ac currents that need to be fed into the generator rotor windings will be equal to 0 Hz (i.e., dc current). The machine would thus operate as a conventional (singly-fed) three-phase synchronous machine.

When the generator rotor speed f_{rotor} decreases below the nominal synchronous speed ηs , the frequency f_{rotor} of the ac currents that need to be fed into the generator windings increases accordingly and is of positive polarity. The positive polarity of the frequency f_{rotor} indicates that the phase sequence of the three-phase ac currents fed into the rotor windings must make the rotor magnetic field rotate in the same direction as the generator rotor.

2.5.4 Configuration of Back-to-back Converter

To provide the variable speed operation of DFIG, a back-to-back converter configuration is used. In this scheme, two different converters are connected via a dc link capacitor, hence the name. A brief discussion about each of these converter is provided below.

2.5.4.1 Rotor Side Converter (RSC)

This full bridge consists of a two level, six pulse insulated gate bipolar transistor (IGBT) and works as a power electronic converter that interfaces the rotor side with the dc link. The RSC takes the terminal voltage V_t , the terminal active power P_t and the reactive power Q_t as inputs and controls the output active and reactive power.

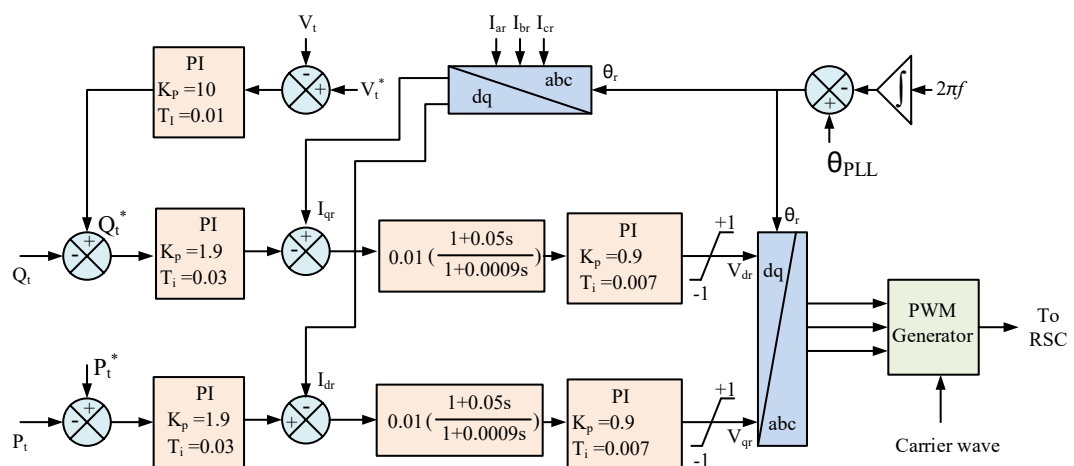


Fig. 2.11 RSC controller

Proportional and integral (PI) controller is used to produce the required three phase reference signal for pulse width modulation (PWM) signal generator block that generates pulse for IGBT switches of the RSC. In order to convert three phase quantities into equivalent d-q components and vice versa, the slip angle is produced by comparing the rotor position and terminal voltage angle with the help of phase-locked loop (PLL). Quantities with “*” refer to reference value as shown in Fig. 2.10.

The GSC also contains a two-level, six-pulse, IGBT based full bridge power electronic ac/dc converter with the dc side connected to the dc link and the ac side interfaced to the grid. This converter essentially helps to maintain a constant power factor at the connection point. A frequency of 1650 Hz is chosen as it is an odd multiple of the third harmonic and can minimize up to thirteenth harmonics. The GSC controller scheme is given in Fig. 2.11.

Fig. 2.12 GSC controller

2.5.5 Modeling of DFIG

A grid connected DFIG exhibits two types of dynamics i.e. during normal condition and during fault. The dynamics are discussed with necessary equations in the following subsections.

2.5.5.1 DFIG Under Normal Condition

For modeling of DFIG, Park's model [23]–[25] is very useful and widely used. The model has a stator-oriented frame of reference. The reference frame is specially generated for DFIG and is very useful for analyzing the response of DFIG under normal and fault condition. The stator and rotor voltages in abc frame can be stated using motor convention by the following expressions.

$$\vec{u}_s = R_s \vec{i}_s + \frac{d}{dt} \vec{\lambda}_s \quad (2.8)$$

$$\vec{u}_r = R_r \vec{i}_r + \frac{d}{dt} \vec{\lambda}_r - j\omega_m \vec{\lambda}_r \quad (2.9)$$

The fluxes induced in the stator and rotor can be expressed as,

$$\vec{\lambda}_r = L_r \vec{i}_r + L_m \vec{i}_s \quad (2.10)$$

$$\vec{\lambda}_s = L_s \vec{i}_s + L_m \vec{i}_r \quad (2.11)$$

Where $\vec{u}_s$ and $\vec{u}_r$ are the space vector of the stator and rotor voltage respectively, $\vec{i}_s$ and $\vec{i}_r$ are the space vector of the stator and rotor current respectively, R_s is the stator resistance, R_r is the rotor resistance, L_m is the magnetizing inductance, $\vec{\lambda}_s$ and $\vec{\lambda}_r$ is the space vector of the stator and rotor flux respectively and ω_m is the slip angular frequency.

L_s and L_r can be further expressed by the following expressions.

$$L_s = L_{ls} + L_m \quad (2.12)$$

$$L_r = L_{lr} + L_m \quad (2.13)$$

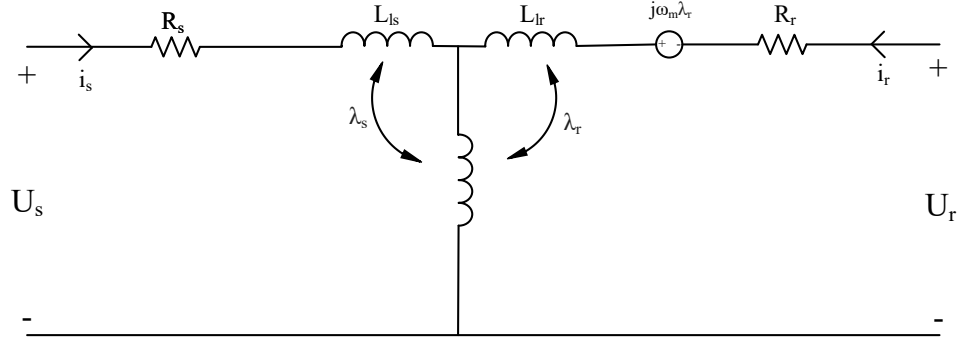


Fig. 2.13 Equivalent circuit of a DFIG

Fig. 2.12 clearly illustrates the construction of the equations (2.12) to (2.13). Manipulating (2.10) and (2.11), we obtain,

$$\vec{\lambda}_r = \frac{L_m}{L_s} \vec{\lambda}_s - \sigma L_r \vec{i}_r \quad (2.14)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (2.15)$$

Substituting the value of $\vec{\lambda}_r$ into (2.11) and with some further adjustments, we obtain,

$$\vec{u}_r = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_m \right) \vec{\lambda}_s + (R_r + \sigma L_r) \left(\frac{d}{dt} - j\omega_m \right) \vec{i}_r \quad (2.16)$$

We can obtain the open circuit voltage of the rotor $\vec{u}_{r0}$ by putting the value of $\vec{i}_r = 0$ in (2.16).

$$\vec{u}_{r0} = \frac{L_m}{L_s} \left(\frac{d}{dt} - j\omega_m \right) \vec{\lambda}_s \quad (2.17)$$

Now, since the transient reactance and the rotor resistance are both negligible, the right-hand side of (2.16) is smaller compared to $\vec{u}_{r0}$ during normal operation. So, we can write $\vec{u}_{r0}$ as,

$$\vec{u}_{r0} = j\omega_r \frac{L_m}{L_s} \vec{\lambda}_s = \frac{L_m}{L_s} \frac{\omega_r}{\omega_s} U_s e^{j\omega_s t} \quad (2.18)$$

Where ω_r and ω_s are the synchronous and slip angular frequency respectively. The magnitude of $\vec{u}_{r0}$ can be found as,

$$U_{r0} = \frac{L_m}{L_s} \frac{\omega_r}{\omega_s} U_s = \frac{L_m}{L_s} s U_s \quad (2.19)$$

Where s is the slip which can be expressed as,

$$s = \frac{\omega_s - \omega_m}{\omega_s} \quad (2.20)$$

$$\omega_r = \omega_s - \omega_m \quad (2.21)$$

From (2.19) it can be seen that, during normal condition, the rotor voltage is a function of the amplitude of stator voltage and the slip.

2.5.5.2 DFIG Under Fault

At fault instant, the open circuit voltage experiences a drastic change. This changed voltage is expressed as,

$$\overrightarrow{u_{r0}} = -\frac{L_m}{L_s} \left(j\omega_m + \frac{1}{\tau_s} \right) \frac{U_s}{j\omega_s} e^{j\omega_s t_0} e^{-\frac{t}{\tau_s}} \quad (2.22)$$

This open circuit voltage rotates in the opposite direction at an angular frequency of ω_m . This rotating voltage can be expressed as,

$$\overrightarrow{u_{r0}} = -\frac{L_m}{L_s} \left(j\omega_m + \frac{1}{\tau_s} \right) \frac{U_s}{j\omega_s} e^{j\omega_s t_0} e^{j\omega_m t_0} e^{-\frac{t}{\tau_s}} \quad (2.23)$$

Obviously $|\overrightarrow{u_{r0}}|$ reaches its peak during fault. Since $\frac{1}{\tau_s}$ is very small [23], (2.23) can be written as,

$$U_{r0}(t_0) = \frac{L_m}{L_s} \frac{\omega_m}{\omega_s} U_s = \frac{L_m}{L_s} (1-s) U_s \quad (2.24)$$

Hence the open circuit rotor voltage is proportional to $(1-s)$ during fault. But during normal condition, it is proportional to s as seen from (2.19).

2.6 Chapter Conclusion

This chapter described the wind turbine classifications and their advantages and disadvantages. The parts of wind turbine are also mentioned as well as their working principle. Further the energy extracted from the wind and also the different control strategies are mentioned.

CHAPTER 3

IMPROVEMENT OF FRT BY PROPOSED FAULT CURRENT LIMITERS

3.1 Introduction

In recent years, Doubly fed Induction generator (DFIG) based wind turbines (WT) have become very popular due to their lower cost, simple structure, ability to control active and reactive power independently, reduced converter power rating (30% of generated power). But the main drawback of DFIG is that it is very sensitive to grid voltage disturbances. The rotor transient over current and dc- link over voltage that occur during grid faults are main two problems of DFIG. The thesis paper deals with the fault current limiter with the control strategy to improve the transient stability capability of DFIG based WTs.

3.2 Fault Ride Through (FRT)

Fault ride through (FRT) is the requirement for a generator to maintain synchronous operation when a severe disturbance occurs in electrical proximity of the generator. For wind turbine certification, it is necessary to prove that the turbine remains on the grid even during voltage dips and surges. When grid rms voltage drops from 1 pu to 0.1-0.9 pu and persists for 0.5-30 cycles, it is called Low Voltage Ride Through (LVRT). In the event of voltage drop, DFIGs are required to remain in operation and must not be disconnected from the grid. Also, DFIGs should support the grid with reactive power to help grid voltage recovery. Such requirements are known as LVRT capability.

FRT has become a household word in wind farm technology. Improving the FRT capability of DFIG based wind farms has become a matter of prime concern since the stability of the entire grid connected system depends on it [27][28]. A large number of power system operators decided upon a set of standards named grid code to define the stability standard of every grid connected generating stations [29]. The grid codes standardize several system parameters such as terminal voltage, power factor regulation, frequency operating range, LVRT capability and grid support capability [30]. For a stable and sustainable operation of every DFIG based wind farm, grid codes are strictly maintained.

3.3 Fault Current Limiter (FCL)

Since the faults in a power system are inevitable, it is not worth the effort to seek for the ways to prevent them. Instead, power system engineers work on finding the ways to ride through the fault keeping the major parts of the system unaffected. Over the years, several types of fault

current limiters had been proposed to improve the FRT capability of power systems in numerous literatures [31]-[34]. Each of the FCLs have their own advantages and disadvantages and they require specific environment to perform efficiently.

The DFIG Based wind farms are always connected to the grid. Any type of fault would hamper the sound operation of the farm and might even damage the expensive machinery [35]. Hence the farms are provided with some arrangement to enhance the FRT capability of the system. There have been several proposals in this regard. Vastly the FCLs in DFIG based wind farms are divided into two categories i.e. Non-superconducting FCLs (NSFCLs) and Superconducting FCLs (SFCLs) [36]. Both of these types have their own way of dealing with faults and hence the application of them are different.

SFCLs have been extensively used in power system due to their excellent capability of minimizing fault current. But The use of SFCLs are fairly a recent addition in DFIG based wind farms [37]. The main advantage of using SFCL is that there are no power loss during the normal operation. Also SFCLs require no control action to change its state from superconducting to non-superconducting. This is called self-healing and it provides an important advantage to increase the speed of the system. To improve the energy management of the system during and after the fault, later, a cooperative control of SFCL and superconducting magnetic energy storage system (SMES) was introduced [38]. It enhanced the FRT capability and reduced the fluctuations in output power response significantly. Some of the other uses of SFCLs in DFIG based wind farms are discussed extensively in various literatures [39][40].

However, there are certain demerits while using the SFCLs. Most of the SFCLs have complex circuit topology and the materials to construct a SFCL are costly and not easy to be assembled. Moreover, the materials are brittle, hard to shape and sometimes chemically unstable in some environment. Also, a liquid cryogenic system is required for the superconducting materials to reach the superconducting state from the quench state. Since the SFCLs in DFIG based wind farms are placed in transmission lines, it interferes with the communication line that are carried parallel to the transmission lines. Since the non-superconducting fault current limiters overcome most of these problems, they are gaining popularity day by day.

The main advantage of NSFCLs is that they provide dynamic stability of power systems with minimal cost compared to the SFCLs [41]. Although there are more power loss in NSFCL than that of SFCLs, it can be considered negligible for high voltage systems. Over the years, several NSFCLs have been proposed [42]-[44]. But they are responsible for extensive power loss in the system due to their static components.

The bridge-type fault current limiter (BFCL) is a fairly new non-superconducting FCL. The BFCL is a new technique with promising applications in power systems and fault ride through

capability enhancement of DFIG based wind farms [4]. It has a promising application in the improvement of FRT capability. A brief explanation of a BFCL and its control schemes are provided in the later part of this chapter. Later, a new control scheme to control the BFCL is proposed.

The power loss of the traditional FCLs can be reduced significantly using the flux coupling type SFCLs. But as stated earlier, they have high cost and they induce certain problems in the system. To overcome these limitations, in this paper, a bridge-type flux coupling non-superconducting fault current limiter (BFC-NSFCL) is proposed to augment the FRT capability of DFIG based wind farms. It was first introduced in 2019 and proven effective for minimizing fault current in a simple AC system [45]. The BFC-NSFCL is yet to be used in any field of renewable energy. In this study, performance of BFC-NSFCL is investigated to enhance the FRT capability of a DFIG based wind farm. Since it has no superconducting material, the cost is significantly less. Although in BFC-NSFCL, the power loss is not as less as that of the superconducting type, the loss is negligible considering a high voltage system.

3.4 Bridge Type Fault Current Limiter (BFCL)

3.4.1 Architecture of BFCL

The BFCL consists of two distinctive parts as represented in Fig. 3.1. The main part of the BFCL is a typical bridge circuit with four diodes (D_1 - D_4). The other part is a shunt path consisting of an inductor (L_{sh}) and resistor (R_{sh}) in series. Inside the bridge, there is an IGBT switch in series with an inductance (L_{dc}).

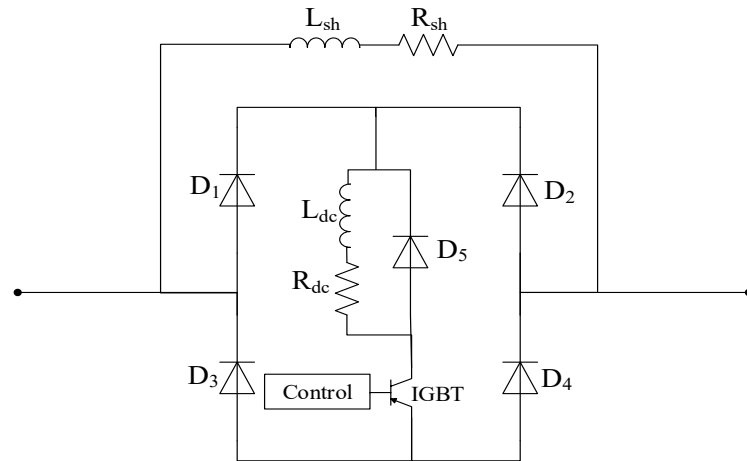


Fig. 3.1 Architecture of BFCL

R_{dc} is the intrinsic resistance of L_{dc} with very negligible magnitude. The IGBT comes with a free-wheeling diode (D_5) to protect it from the abrupt change of current during fault. The values

of R_{sh} , L_{sh} , R_{dc} and L_{dc} are selected based on the analysis carried out in [15] and the best combination is used for all the control schemes. The values that provide the best performance are shown in Table 3.1.

Table 3.1 BFCL Parameters

R_{sh}	L_{sh}	R_{dc}	L_{dc}
20 Ω	250mH	0.003 Ω	1mH

3.4.2 Operating Principle of BFCL

During normal condition, the current during positive half cycle passes through the path D_1 - L_{dc} - R_{dc} -IGBT- D_4 . During negative half cycle, the current passes through the D_3 -IGBT- R_{dc} - L_{dc} - D_2 path. The shunt path has a high impedance value that makes all the line current flow through the bridge except some leakage current of negligible magnitude. During this entire period, the IGBT is kept ON by providing HIGH pulse to its gate. In the event of fault, the IGBT is turned OFF providing LOW pulse to the gate and hence high fault current passes through the only available shunt path. The combined effect of series inductance and resistance of the shunt path ceases the current down and the system stabilizes after the circuit breakers are opened. Without the bridge circuit, the system struggles to fight the fault and might fail to protect the DFIG from getting damaged. The BFCL protects the DFIG and provides stabilization to the system within the shortest possible time.

3.4.3 BFCL Control Schemes

Over the years many control strategies have been proposed and implemented to BFCL to improve the transient stability. The most recent ones are chosen here to describe below.

3.4.3.1 BFCL Control with PCC Voltage Reference

The voltage of the point of common coupling (PCC) changes with the change in system dynamics. So, the PCC voltage can be monitored to detect any kind of abnormalities in the system. During normal condition, the voltage in PCC perturbs between 0.95 pu to 1 pu. But during any kind of line fault, the PCC voltage goes down and might become as low as zero. A controller can be used to monitor the PCC voltage variations from reaching zero to recover it to the initial level again. Monitoring the PCC voltage came out handy to improve the transient responses of the system using the BFCL [27]. The algorithm for BFCL control by using PCC voltage is shown in Fig. 3.2.

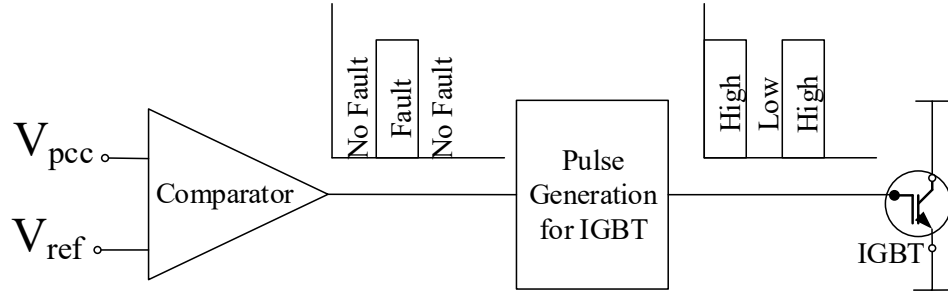


Fig. 3.2 BFCL control with PCC voltage reference

The instantaneous PCC voltage is monitored and compared with a reference level. The reference value that was taken in this case is 0.9 pu. During normal condition, when there are no faults in the system, the per unit value of the PCC voltage is always greater than 0.9. Hence, during normal condition, the output of the comparator is 1. The output is fed to a step generator to get a HIGH pulse during this period and this output is then fed to the gate of IGBT. Thus, the IGBT is kept ON during the normal condition.

In the event of a fault, the per unit value of the PCC voltage decreases beyond the reference value of 0.9. This makes the output of the comparator 0. As a result, the output of the step generator becomes LOW and the IGBT is turned OFF. The fault currents get diverted to the shunt path and gets minimized. After the opening of the circuit breakers, the system voltage begins to improve again. And when the voltage crosses the reference level, the IGBT gets turned ON.

3.4.3.2 BFCL Control with Direct and Quadrature Axes Voltage

In this control scheme, the line voltage is converted into direct axes and quadrature axes component [28], [15]. These two components are then squared and summed up. The square root of the resultant sum is called the dq component of the voltage i.e. $V_{dq,\varphi} = \sqrt{(V_{d,\varphi}^2 + V_{q,\varphi}^2)}$. $V_{dq,\varphi}$ is constantly monitored and compared with the reference threshold value, V_{th} . When the difference between the $V_{dq,\varphi}$ and V_{th} is positive, a HIGH state voltage signal is supplied to the gate of IGBT. So the IGBT is ON during normal condition and the shunt path is not in use.

During fault, the $V_{dq,\varphi}$ reduces and the difference between $V_{dq,\varphi}$ and V_{th} becomes negative. When this happens, a LOW state voltage signal is supplied to the gate of IGBT and the IGBT is turned OFF. The bridge circuit becomes open and the fault current gets diverted to the shunt path. The high resistance and inductance of the shunt path ceases the fault current down and the system stabilizes soon after. The whole process is illustrated in Fig. 3.3.

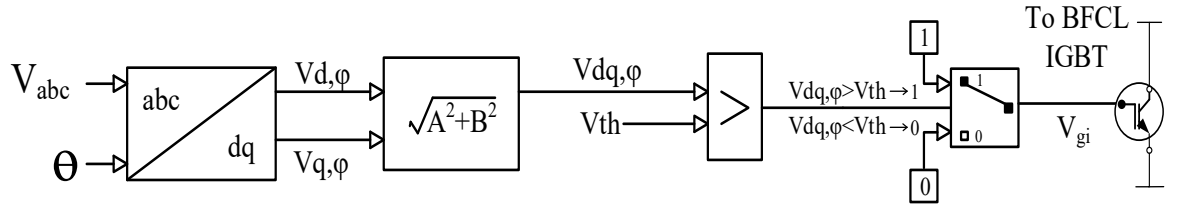


Fig. 3.3 BFCL control with direct and quadrature axes voltage

Here V_{abc} is the line voltage and θ is the instantaneous angle of an arbitrary frequency.

3.4.3.3 Proposed BFCL Control Scheme

In this paper, a new algorithm to generate the gate pulses for the control of IGBT is proposed as represented in Fig. 3.4. The active power (P_{active}) is used to generate the gate pulses for the IGBT. P_{active} is compared to a reference value, P_{ref} . When the difference between P_{active} and P_{ref} is positive, the comparator output becomes 1. This is true for the normal conditions.

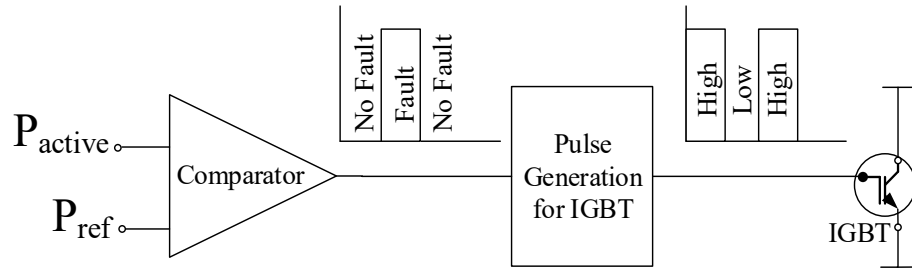


Fig. 3.4 BFCL control with active power

When there is a fault in the system, the difference becomes negative and the comparator output becomes 0. The output of the comparator is fed to a step generator to produce HIGH and LOW state voltage. This step voltage controls the IGBT switch. During normal conditions, the difference between P_{active} and P_{ref} generates a HIGH state step voltage and the IGBT stays ON. Thus, the bridge is in conduction during normal period keeping the shunt path disconnected. During faults, the output of the step generator becomes LOW and the IGBT is turned OFF. The bridge circuit becomes open from the line and the shunt path comes in the play and reduces the fault current.

3.5 Bridge type Flux Coupling Non-Superconducting Fault Current Limiter (BFC-NSFCL)

3.5.1 System Configuration

The proposed BFC-NSFCL configuration is shown in Fig. 3.5. It is installed in each of the three-phase parallel transmission line and in between of the PCC and grid lines. The proposed system has mainly two parts: one is flux coupling reactor and another one is bidirectional bridge

switch. The bidirectional bridge switch mainly consists of a diode bridge rectifier circuit, an IGBT, a Metal oxide Varistor (MOV) and a RC snubber. It is installed at the secondary coil of the flux coupling reactor which has a vital role in normal operation in making the two coils magnetically coupled whereas the primary one is introduced during fault condition. The diode bridge rectifier holds higher reliability because it is a passive component. There is one more advantage of this switch topology and that is it can be easily implemented on the high-voltage ac power system. Last of all it has insignificant power loss in weighing up to power demand of the load.

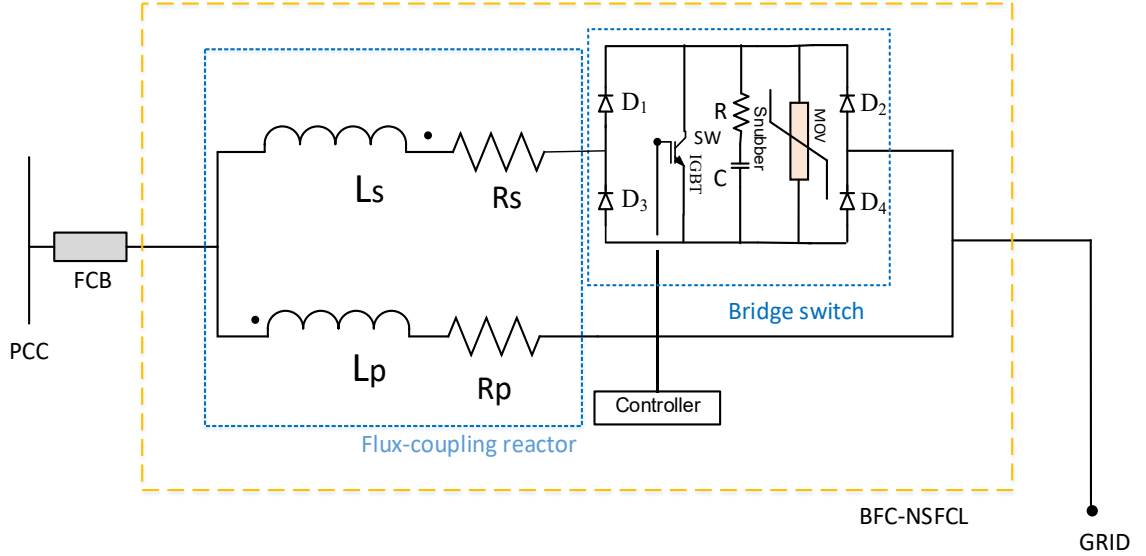


Fig. 3.5 Circuit configuration of the proposed BFC-NSFCL

The MOV and RC snubber is used for the purpose of eradicating the transient overvoltage which is caused by the changing of IGBT state. At the event of fault, the secondary current of the flux coupling reactor should be terminated as soon as possible and sometimes a transient overvoltage may occur at the terminal of bridge switch. The RC snubber is connected in parallel in the output terminals of the rectifier. It helps to avoid vandalizing the diode bridge rectifier and the IGBT and also provides protection against dv/dt phenomenon. The purpose of using MOV is to subdue the transient overvoltage which occurs for the conduction of IGBT.

3.5.2 Operating Principle

The basic working function of BFC-NSFCL can be divided into two states which are depicted in the following subsections.

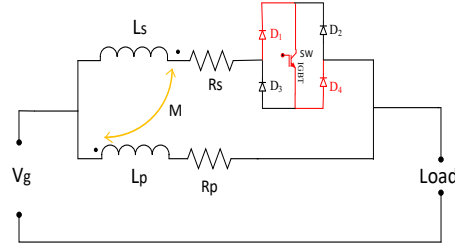


Fig. 3.6 Circuit for positive half cycle

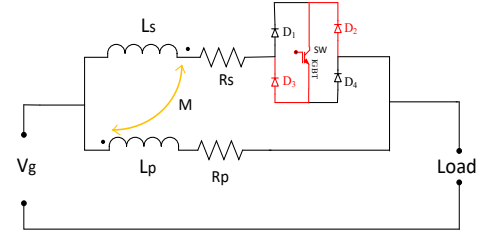


Fig. 3.7 Circuit for negative half cycle

3.5.2.1 Normal condition

The line current flows separately along the primary and secondary windings of the flux-coupling reactor. During the positive half cycle current flows through the red indicated line in Fig. 3.6 i.e. through diode D1-IGBT-D4. In the reverse half cycle current goes in the red indicated line stated in Fig. 3.7. i.e. through D3-IGBT-D2. The primary and secondary coils fluxes of the BFC-NSFCL counteract each other because its two windings are wound in a reverse and concentric alignment and are magnetically coupled in this state. That's why voltage across the flux coupling reactor is negligible.

The turn ratio of the primary side is kept low in compare to secondary side in order to secure that less line current pass across the bridge switch. The N_p/N_s i.e. $1/n$ is called turn ratio, where N_p denotes the number of turns of the primary side flux coupling reactor whereas N_s denotes the number of turns of the secondary side. The main purpose of designing this NSFCL is to obtain current sharing function so that power loss across the bridge switch can be minimized. The flux coupling reactor will stay in operation and act as a reactor if bridge switch fails for any reason. During this state, there is no impact on the circuit when the BFC-NSFCL is installed because voltage drop across it is negligible.

3.5.2.2 Fault state

Whenever a fault occurs, the control circuit and other sensing unit senses the fault. The control circuit sends signal to the IGBT and the bridge switch turns off. Then the secondary of the flux-coupling reactor becomes open circuited and the entire fault current flows through the primary side reactor.

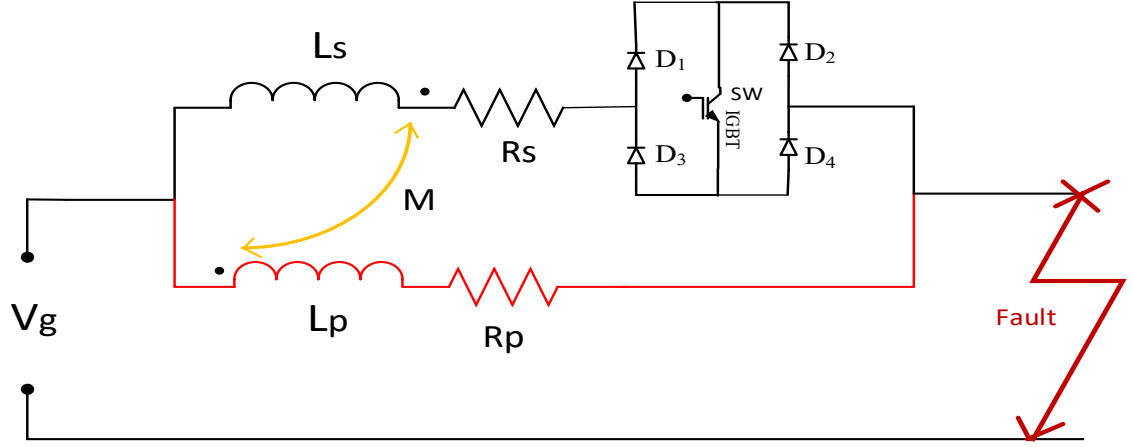


Fig. 3.8 Circuit diagram during fault state

The fault state of the BFC-NSFCL is shown in Fig. 4(h). Moreover, the value of primary inductance is set such that it can limit the fault current to the expected value. The BFC-NSFCL will recover to its previous normal state when the fault is removed and also be prepared for the next short circuit fault occurrence.

3.5.3 Gate Control of BFC-NSFCL

The line current rises significantly whenever a fault occurs in the system, but the dc reactor suppress the rate of current change di/dt . This assures the safe operation of IGBT. The per phase controller for the BFC-NSFCL is illustrated in Fig. 3.9. The instantaneous line voltage at the PCC (V_{abc}) is converted to direct and quadrature counterpart $V_{d,\phi}$ & $V_{q,\phi}$ respectively which eventually produces $V_{dq,\phi}$ by the following equation.

$$V_{dq,\phi} = \sqrt{(V_{d,\phi}^2 + V_{q,\phi}^2)} \quad (3.1)$$

This instantaneous dq voltage, $V_{dq,\phi}$ is compared with the set reference voltage V_{ref} . The deviation of voltage at the PCC, ΔV is fed to the exponential nonlinear control block in order to generate the duty ratio d for the PWM generator block. The duty ratio d can be defined as

$$d = \frac{T_{off}}{T_c} \quad (3.2)$$

where T_c is the time period of the PWM generator carrier wave, T_{off} is the time at which the NC-MBFCL bridge IGBT doesn't conduct.

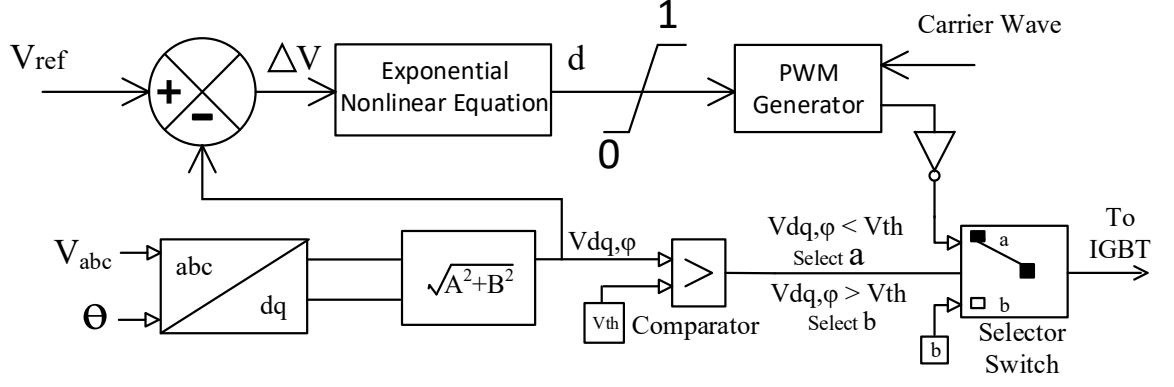


Fig. 3.9 Gate control of IGBT

This modified voltage $V_{dq,\phi}$ enables quick fault detection. A threshold voltage level $V_{th}=0.9pu$ is compared with $V_{dq,\phi}$ to detect the fault in the system. This signal is used in a switch selector that feeds a signal value of 1 to the IGBT gate at the normal operation $V_{dq,\phi} > V_{th}$ and the inverted PWM generator output signal to the IGBT gate during any fault situation ($V_{dq,\phi} < V_{th}$). Instead of applying the full impedance value of the primary path throughout the fault period, a variable value of effective primary impedance $Z_{primary}' = d * Z_{primary}$ is offered to the system for adaptive compensation by the NC-MBFCL [25], where $Z_{primary}$ is the normal path impedance. Due to the high level of nonlinearity in a power system, an exponential nonlinear based controller is used to control the MBFCL. The exponential nonlinear controller block takes ΔV as input and provides duty ratio d to emulate a variable effective primary impedance $Z_{primary}'$ during fault, governed by the nonlinear equation expressed as,

$$d = 1 - e^{-k\Delta v} \quad (3.3)$$

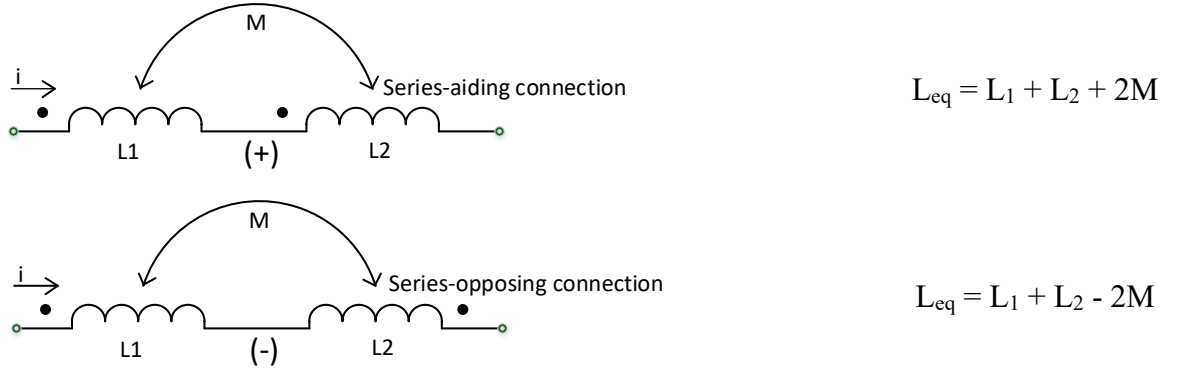
Value of duty ratio d corresponding to different values of ΔV during 3LG fault. It was found that $k=20$ gives the best fault performance for all types of faults.

3.5.4 Theoretical considerations

For understanding the counter effect of flux coupling reactor, the fundamentals of magnetically coupled is to be known first. When two loops with or without contacts between them affect each other through magnetic field generated by one of them, they are said to be magnetically coupled. When two inductors (L_1 & L_2) are in a close proximity to each other, the magnetic flux caused by current in one coil links with the other coil, thereby inducing voltage in the later.

This phenomenon is known as mutual inductance denoted by M . For determining the polarity of the mutual voltage dot convention can be used.

According to dot convention, the equivalent inductance L_{eq} will be as follows:



To perform theoretical analysis the single-phase circuit demonstrated in Fig. 3.5 is used. The voltage drop across the bridge switch is very small and it is neglected for simplicity of analysis.

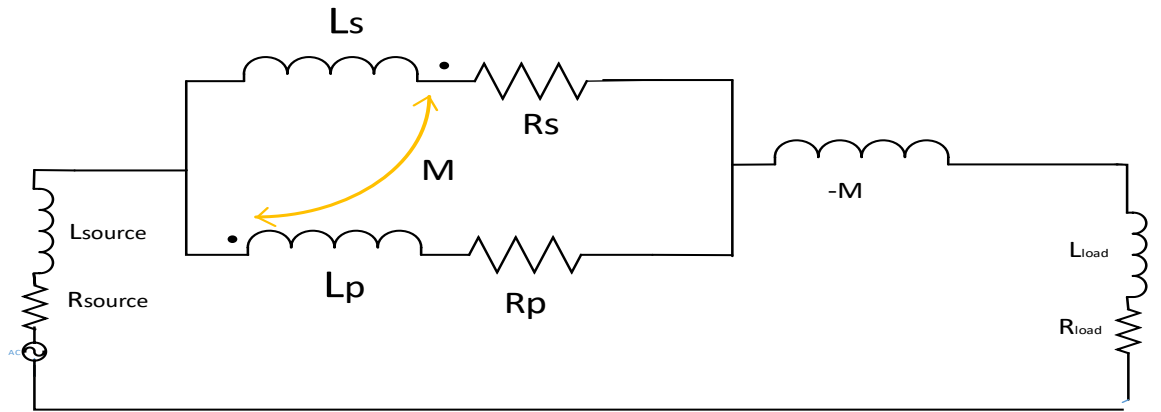


Fig. 3.10 Equivalent diagram of BFC-NSFCL during fault

During this state, the primary and secondary coils are coupled magnetically and equivalent decoupled circuit of the BFC-NSFCL is depicted in Fig. 3.10. The equivalent impedance of the fault current limiter can be written as,

$$\begin{aligned}
Z_{FCL} = R_{FCL} + j\omega L_{FCL} = & \\
& \frac{(R_p + R_s)[R_p R_s + \omega^2(M^2 - L_p L_s)]}{(R_p + R_s)^2 + \omega^2(L_p + L_s + 2M)^2} + \\
& \frac{\omega^2(L_p L_s + L_s R_p)(L_p + L_s + 2M)}{(R_p + R_s)^2 + \omega^2(L_p + L_s + 2M)^2} + \\
& j\omega \left\{ \frac{[(R_p + R_s)(L_p L_s + L_s R_p)]}{(R_p + R_s)^2 + \omega^2(L_p + L_s + 2M)^2} - \right. \\
& \left. \frac{(L_p + L_s + 2M)[R_p R_s + \omega^2(M^2 - L_p L_s)]}{(R_p + R_s)^2 + \omega^2(L_p + L_s + 2M)^2} \right\}
\end{aligned} \tag{3.4}$$

Where, R_p = Resistance of the primary coil

R_s = Resistance of the secondary coil

L_p = Inductance of the primary coil

L_s = Inductance of the secondary coil

M = Mutual inductance of primary and secondary coils of the flux coupling reactor

The value of L_p and L_s are chosen in such a way that $M = k(L_p L_s)^{1/2}$ creates a counter-effect of resultant flux in normal condition. Where k is the coupling coefficient and ideally it is 1. Using the value of L_{FCL} and R_{FCL} , the parameters of BFC-NSFCL can be calculated which are shown in Table 3.1.

Table 3.2 Parameters of BFC-NSFCL

R_s	L_s	R_p	L_p	R	M
0.21Ω	350mH	1.56 Ω	250mH	0 Ω	295.8mH

Under normal condition, the values of L_{FCL} and R_{FCL} are found as, $L_{FCL}=1.9959$ mH and $R_{FCL}=0.50158$ Ω.

3.6 Chapter Conclusion

In this chapter, different types fault current limiters including newly proposed one, their structures, operating principles and their impact on DFIG based wind farm were discussed.

CHAPTER 4

PERFORMANCE ANALYSIS

4.1 Introduction

This chapter includes the system model of the DFIG based wind farm, simulation results of different FCLs under symmetrical and unsymmetrical faults, their comparative study and discussions for choosing the best candidate in the field of FRT analysis in wind energy. There are some recognized software that can be used for power system model simulation. These include MATLAB, PSCAD etc. The simulation has been done in MATLAB/SIMULINK on 9MW DFIG based wind farm.

4.2 System Model

A short description of MATLAB /SIMULINK model for simulation of DFIG under the different types of bridge with control strategy are shown in Fig. 4.1. Symmetrical and unsymmetrical, both type of faults was implemented at point F in Fig. 4.1 to examine the responses of the system.

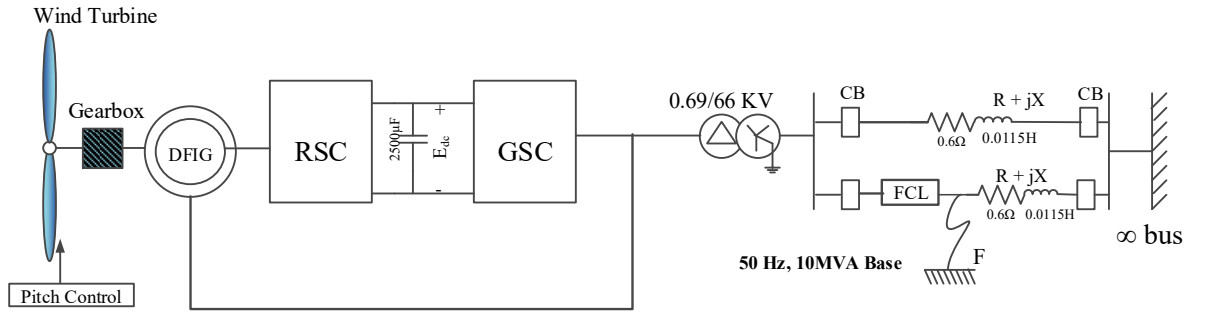


Fig. 4.1 Diagram of the system model

4.3 Simulation Results

The simulation results of DFIG for different types of fault current limiters such as Bridge Type Fault Current Limiter, Bridge Type Flux Couple Non-Superconducting Fault Current Limiter with control strategy have been given in the following pages. A fault has been Simulated at time $t=0.1$ sec for 100 milli-sec and circuit breaker opens at 0.2 sec and automatically recloses at 1.2 sec.

4.4 Simulation Results for Bridge Type Fault Current Limiter

For the purpose of transient analysis, the wind speed is kept at a constant speed of 15 m/s considering that the fault time is too small for the wind speed to have a noticeable change. The convention of CB opening, and closing is adopted from [4], [15]. To compare the system responses, three different conditions were considered.

Three different cases are considered in the simulation, they are as follows:

- 1) Case A: BFCL Control with PCC Voltage Reference [29];
- 2) Case B: BFCL Control with Direct and Quadrature Axes Voltage [15], [28];
- 3) Case C: BFCL Control with Active Power reference [Proposed]

4.4.1 Symmetrical Fault

The responses of the system for triple line to ground (3LG) fault are shown in Fig. 4.2-4.5. Fig. 4.2 illustrates the terminal voltage response of DFIG for a temporary symmetrical (3LG) fault. In the absence of any controller, the voltage goes to zero and does not improve till the breakers open. By using BFCL with V_{pcc} and dq reference as control scheme, the voltage can be improved. For V_{pcc} as reference,

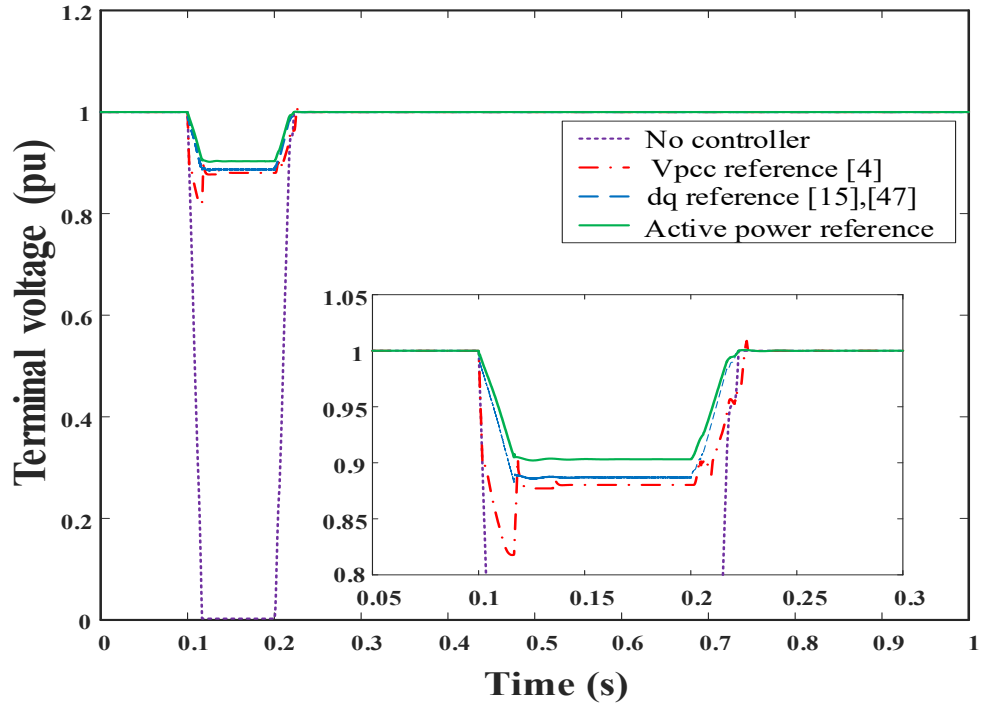


Fig. 4.2 Terminal voltage response for 3LG fault

the voltage goes very low initially and then improves to 0.87 pu. With dq reference, the maximum voltage dip is 0.89 pu. But with active power as reference, the maximum dip is 0.90 pu, which is much more improved than the other two. Moreover, for active power reference, the terminal voltage returns to the nominal value faster compared to the previous two reference methods. This clearly shows that active power reference is more sensitive and provides better voltage stabilization.

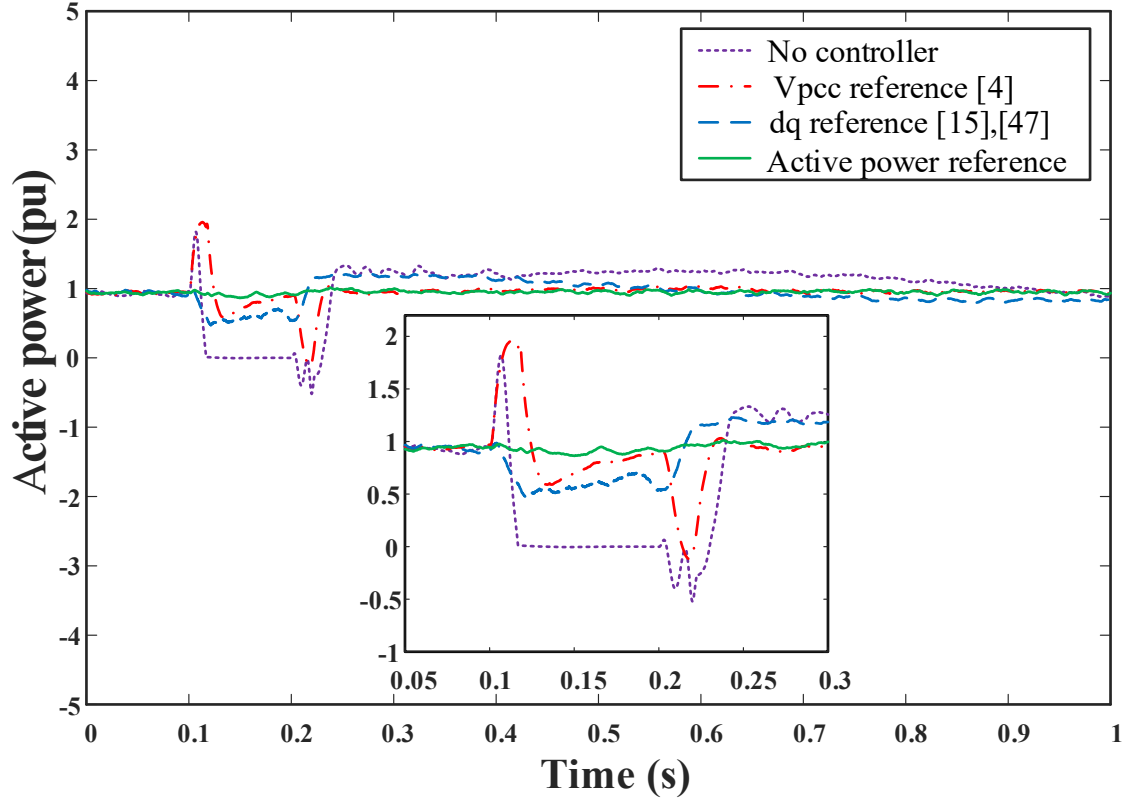


Fig. 4.3 Active power response for 3LG fault

Fig. 4.3. illustrates the response of the active power for 3LG fault. It can be clearly observed that for no controller, the response reaches zero and when the breakers are opened, the response has overshoots and does not reach steady state. For V_{pcc} and dq reference, the output power goes high suddenly and then goes low which can harm the DFIG. But with active power as reference, the output power always stays around the nominal value with least amount of fluctuations. Also, the active power reference provides improved output power stabilization.

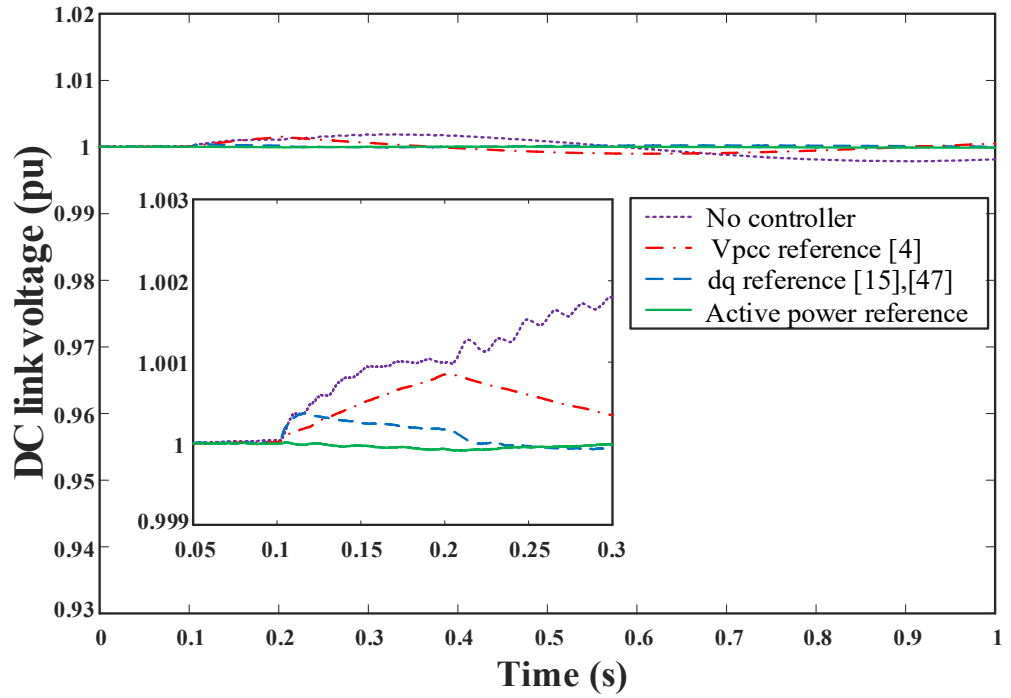


Fig. 4.4 DC link voltage for 3LG fault

The DC link voltage of the DFIG is displayed in Fig. 4.4. Here it is clearly observable that the responses with no controller and the other two control reference schemes provide output with fluctuations. Whereas, active power reference provides more constant dc link voltage.

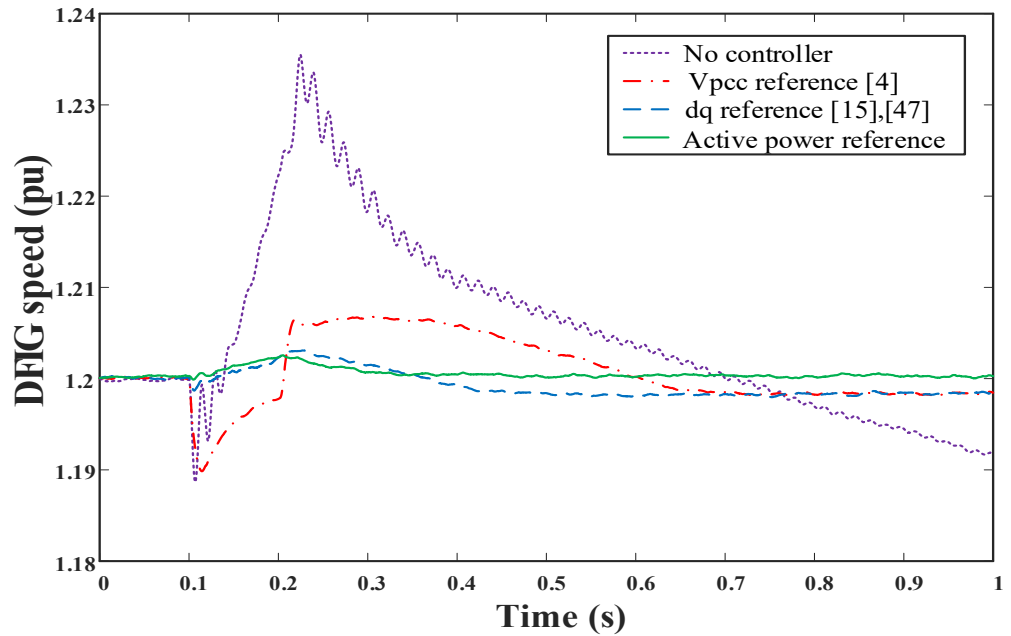


Fig. 4.5 Speed response for 3LG fault

4.4.2 Unsymmetrical Fault

The responses of the system for single line to ground (1LG) fault are displayed in Fig. 4.6-4.9. From Fig. 4.6. it can be seen that, the terminal voltage during fault goes very low. Without any controller, the voltage stays low until the breakers are opened. By using controller, the voltage dip can be reduced. However, the voltage dip for V_{pcc} reference and dq reference is much greater than that for the proposed active power reference. With V_{pcc} reference, the voltage goes down initially and then improved to around 0.92 pu. With dq reference, the voltage reduced to 0.93 pu. But, for active power as reference, the lowest voltage is 0.97 pu which is more improved than the other two.

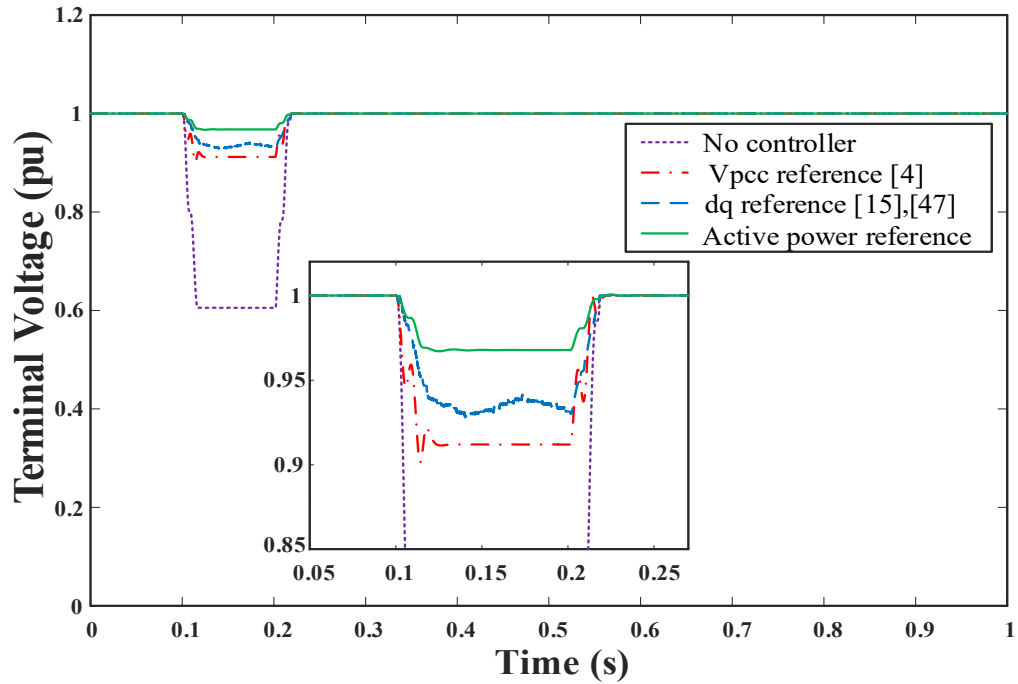


Fig. 4.6 Terminal voltage response for 1LG fault

Fig. 4.7 represents the active power response during 1LG fault. It can be seen that, when there is no controller, the active power response has unacceptable spikes. By using BFCL, the response can be improved. But, compared to other two control schemes, with the active power reference, the response is smoother, faster and efficient.

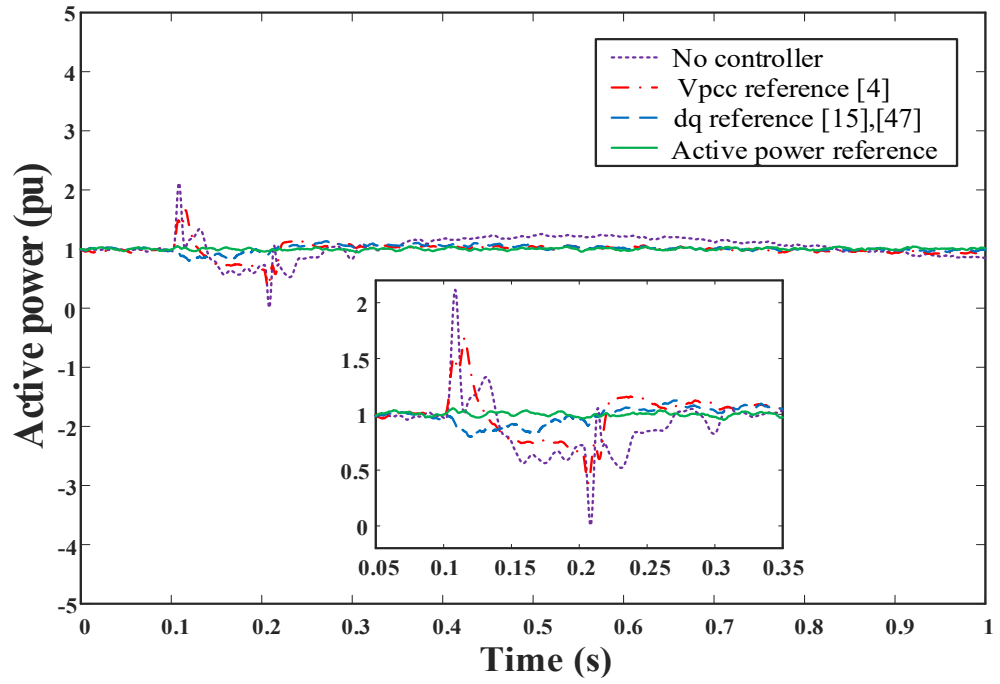


Fig. 4.7 Active power response for 1LG fault

Fig. 4.8 illustrates the DC link voltage during 1LG fault. For active power reference, the voltage is more constant than that for the no controller or the V_{pcc} reference and the dq reference.

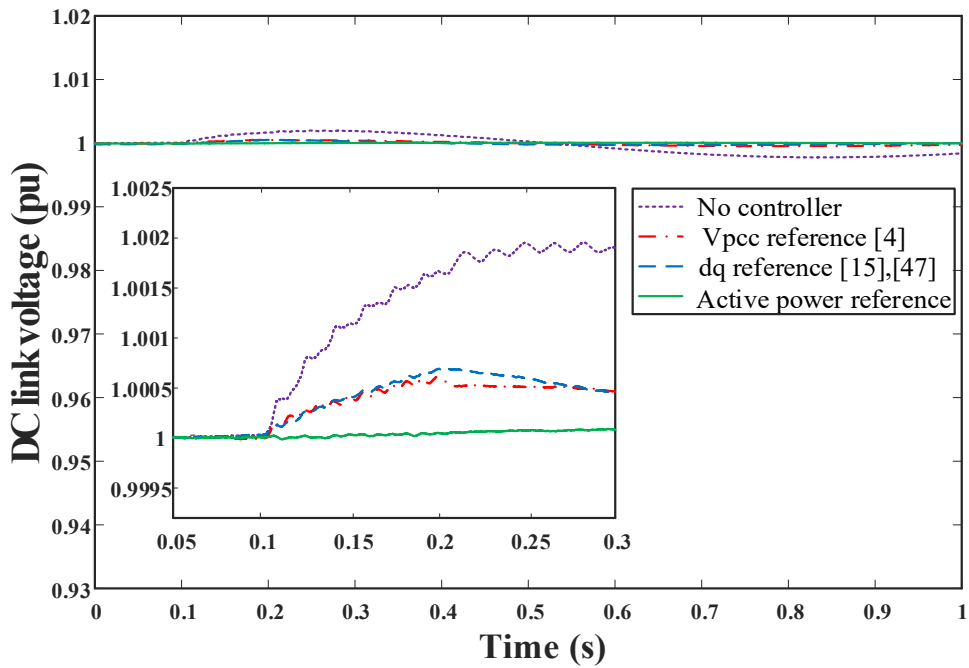


Fig. 4.8 DC link voltage for 1LG fault

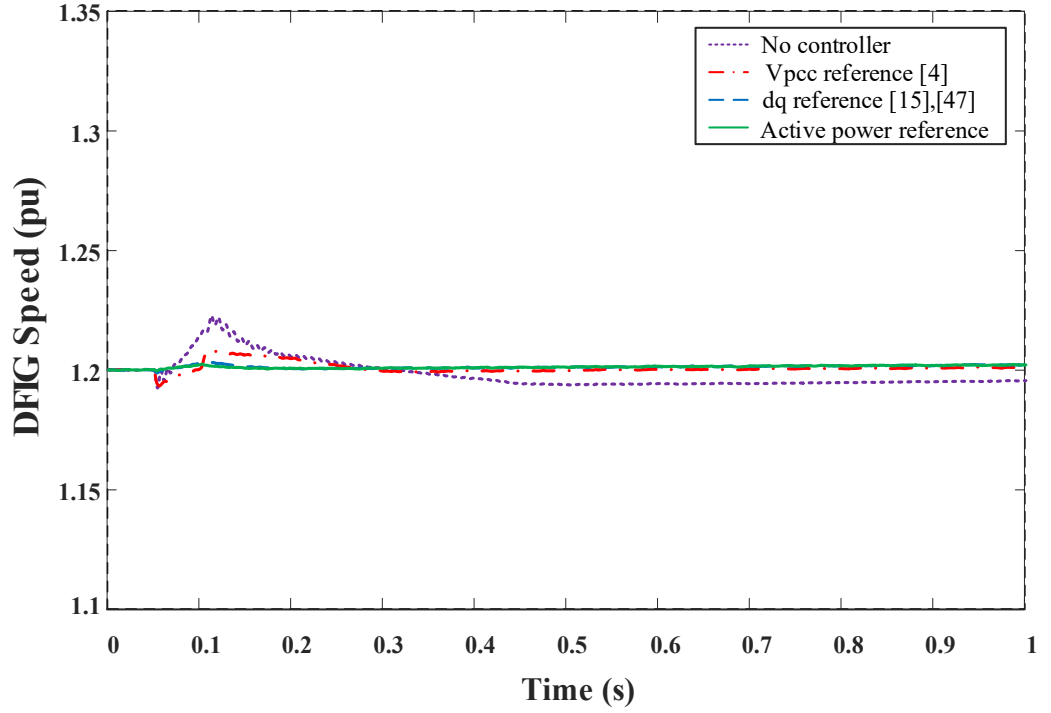


Fig. 4.9 Speed response for 1LG fault

Fig. 4.9 shows the speed response of the DFIG during a 1LG fault. From the figure it can be easily seen that, the speed response for active power reference is certainly better than the responses for no controller and other control schemes.

4.4.3 Index-based Analysis

For the numerical analysis, in this work, an index-based comparison of different schemes were carried out. Performance indices of different parameters like $vlt(pu.s)$, $pow(pu.s)$, $dclink(pu.s)$ and $spd(pu.s)$ are evaluated. The indices are represented by the following mathematical expressions.

$$vlt(pu.s) = \int_0^T |\Delta V| dt \quad (4.1)$$

$$pow(pu.s) = \int_0^T |\Delta P| dt \quad (4.2)$$

$$dclink(pu.s) = \int_0^T |\Delta V_{dc}| dt \quad (4.3)$$

$$spd(pu.s) = \int_0^T |\Delta \omega| dt \quad (4.4)$$

Here ΔV , ΔP , ΔV_{dc} and $\Delta \omega$ are the deviations of PCC voltage, active power, dc link voltage and generator speed respectively. T is the time duration within which the indices were measured. The value of T for this work was from 0 to 1 sec. Since the equations consist of deviations, the lesser the value of the indices the better wind generator's fault ride through performance. The performance indices for symmetrical (3LG) and unsymmetrical (1LG) faults are shown in the Tables 4.1 and 4.2 respectively.

Table 4.1 Performance Indices for Symmetrical (3LG) Fault

Index Parameters (%)	Indices			
	No controller	Vpcc reference	dq reference	Active power reference
vlt (pu.s)	10.1268	1.323394	1.139017	0.9966
pow (pu.s)	19.1411	7.3534	6.19968	2.2464
dclink (pu.s)	0.0335	0.0083	0.0075	0.0031
spd (pu.s)	5.5258	1.4713	0.59366	0.4174

Table 4.2 Performance Indices for Unsymmetrical (1LG) Fault

Index Parameters (%)	Indices			
	No controller	Vpcc reference	dq reference	Active power reference
vlt (pu.s)	3.974768	0.623217	0.465208	0.331418
pow (pu.s)	10.1931	4.6995	4.2538	1.1685
dclink (pu.s)	0.0236	0.0053	0.0057	0.0016
spd (pu.s)	3.06625	0.28763	0.08396	0.0412

As it can be seen from the tables III and IV, the performance of the system is the worst for no controller. For Vpcc reference, the responses improved a lot. Further, with the use of dq reference, the responses got slightly better. However, with active power reference, the performance indices are the least. Hence the active power reference provides overall superior response and ensures better stabilization of the system.

4.5 Simulation Results of Bridge Type Flux Couple Non-Superconducting Fault Current Limiter (BFC-NSFCL)

All the simulations were carried out in the MATLAB/SIMULINK environment. The wind speed is kept at a constant speed of 15 m/s considering that the fault time is too small for the wind speed to have a noticeable change. Symmetrical and unsymmetrical, both type of faults were implemented at point F in Fig. 5.1. The faults were initiated at 0.1s and applied for 0.1s. The opening of the circuit breakers was done at 0.2s and reclosing at 1.2s. Three different cases are considered in this work in order to transient enhancement analysis among the series devices. The cases are as follows:

Case A: With Series Dynamic Braking Resistor (SDBR) [44]

Case B: With Bridge Type Fault Current Limiter (BFCL) [4]

Case C: With BFC-NSFCL [Proposed]

Case D: With BFC-NSFCL with Non-Linear Controller [Proposed]

4.5.1 Symmetrical Fault Responses

When the system faces a temporary symmetrical (3LG) fault, six different responses are depicted in Fig. 4.10-4.15. The terminal voltage response of the farm near PCC is illustrated by Fig. 4.10. In case of no controller, the output voltage goes to zero during fault. The BFC-NSFCL outperforms the BFCL and the SDBR in all aspect. But in the case of the proposed FCL with a non-linear controller (BFC-NSFCL) provides the best performance. It displays the smallest amount of sag and has the lowest fluctuations. It can be said that the BFC-NSFCL with controller is the best choice for the improvement of FRT capability compared to others. It also ensures faster recovery to regain the pre-fault voltage than the BFCL and SDBR.

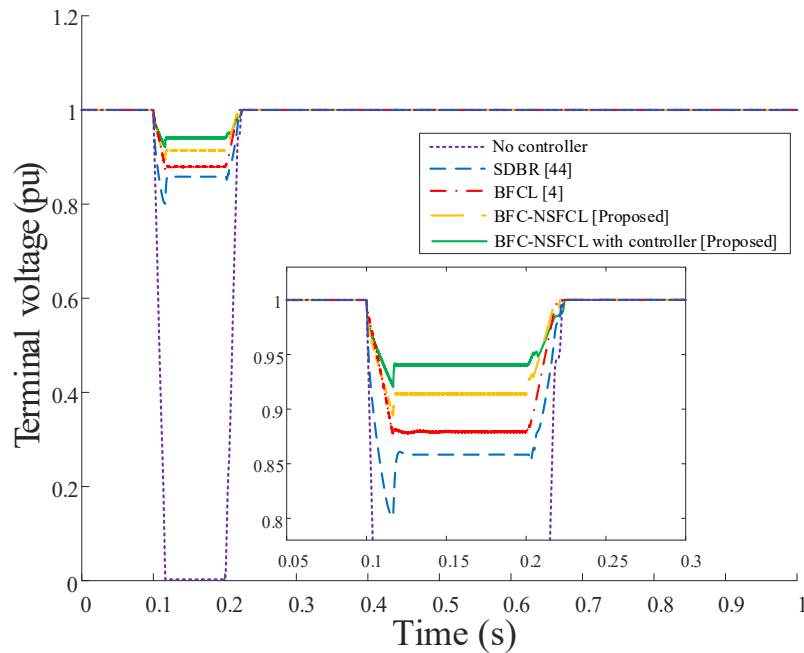


Fig. 4.10 Terminal voltage response for 3LG fault

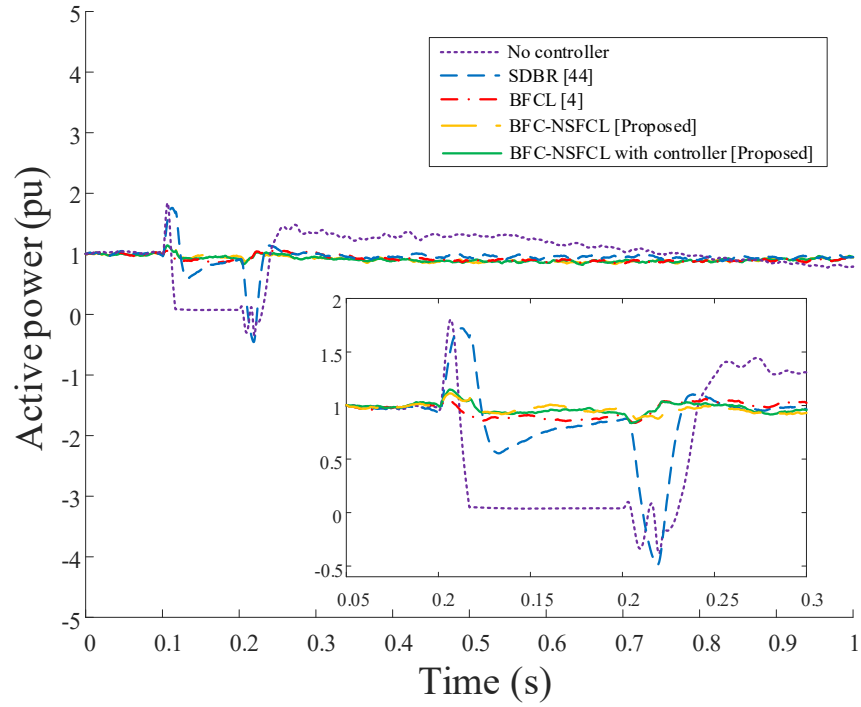


Fig. 4.11 Active power response for 3LG fault

The active power profile of the farm measured at the PCC is shown in Fig. 4.11. Without any controller, the active power becomes very low. Though SDBR, BFCL and BFC-NSFCL all can minimize certain power drop but BFC-NSFCL and BFC-NSFCL with controller show minimum amount of sag. Moreover, there is a sudden escalation of power due to the gap in power generation and demand. After considerable amount of oscillations, BFC-NSFCL and BFCL show lower power rise in compared to SDBR but the BFC-NSFCL with controller shows the lowest power rise and restore the active power to the pre-fault level with the lowest amount of oscillation.

Fig. 4.12 shows the dc link voltage of the DFIG. The traditional controlled SDBR, BFCL can keep the dc-link voltage within the reference level but have some fluctuations. The proposed BFC-NSFCL and BFC-NSFCL with controller are capable to this regard with the least fluctuations.

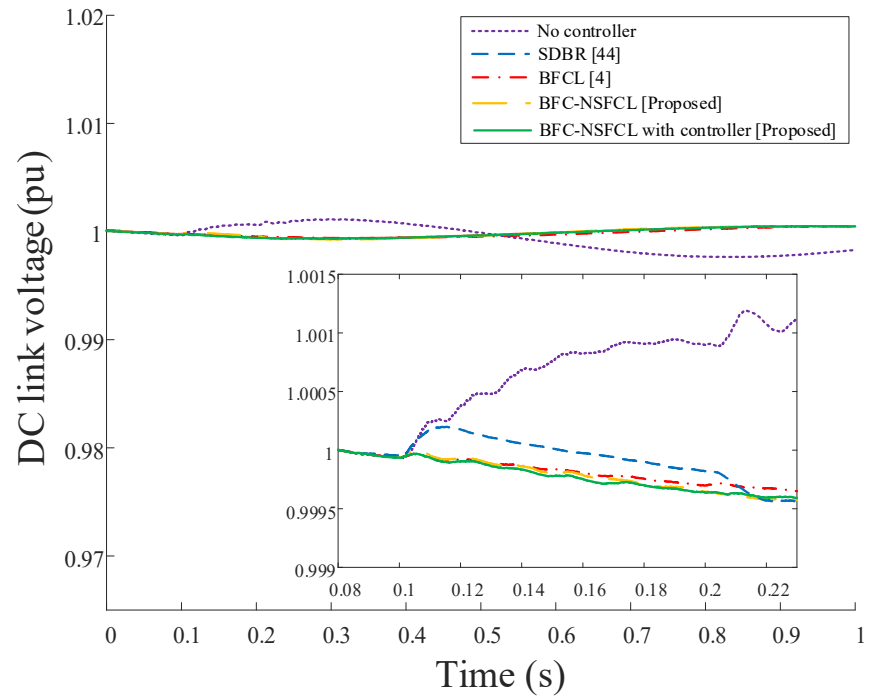


Fig. 4.12 DC link voltage for 3LG fault

The speed profile of a DFIG is presented in Fig. 4.13. There is a quick rise of rotational speed because of the mismatch between the extracted wind power and the demanded power at the instant of fault. Without any controller, there is a sudden rise at the instant of fault and a certain time is required to regain the pre-fault speed level. BFCL has the lower speed deviations in compared to SDBR. But the BFC-NSFCL in both cases with and without controller show the best performance which is quite noticeable.

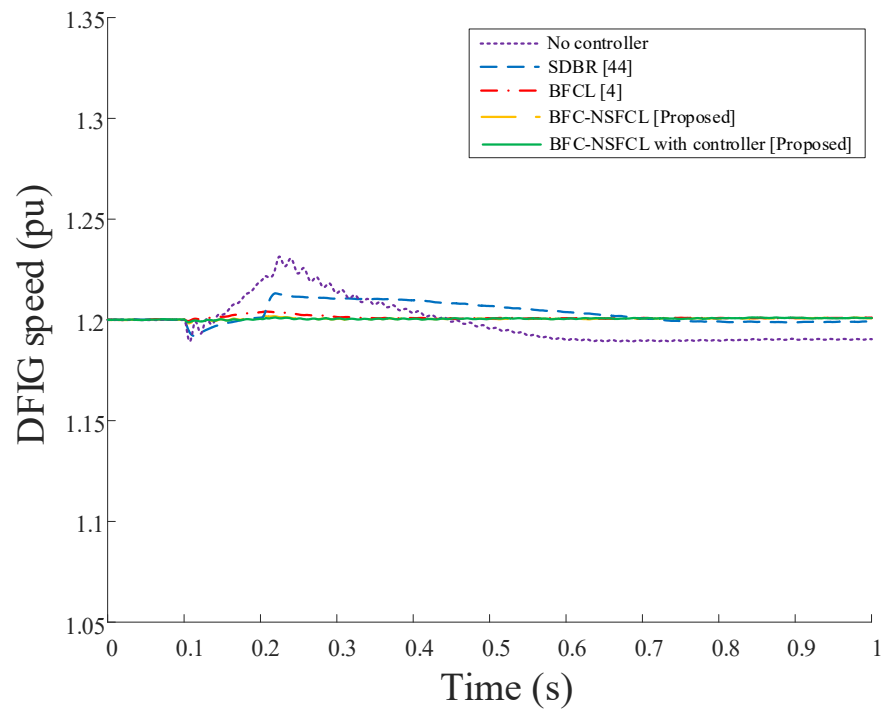


Fig. 4.13 Speed response for 3LG fault

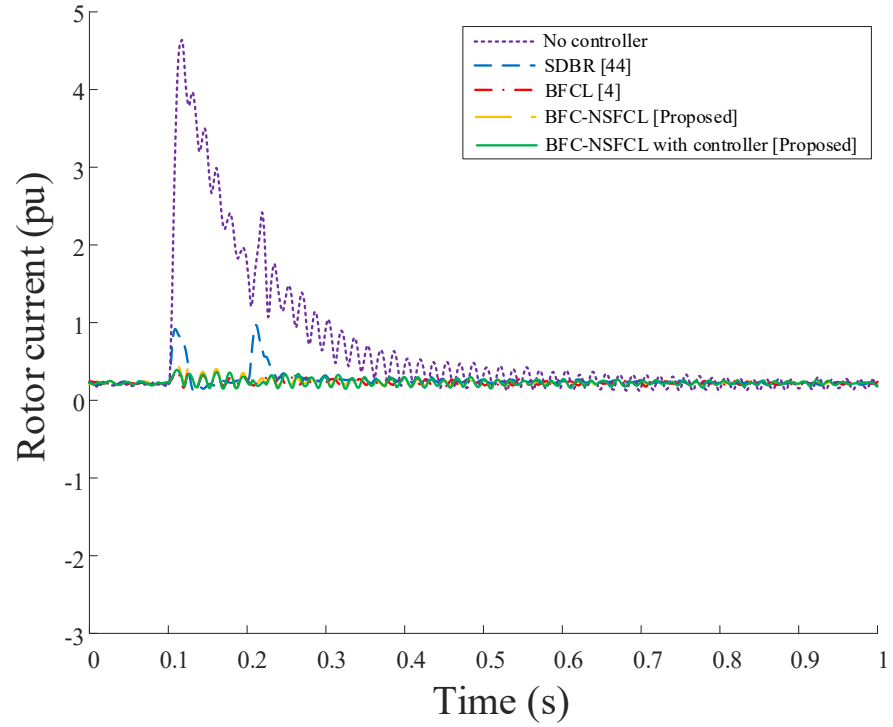


Fig. 4.14 Rotor current for 3LG fault

The rotor current of the DFIG is depicted in Fig. 4.14. Primary concern is to suppress the abrupt rise of rotor and stator current which is a fundamental requirement for the converter protection and DFIG stable operation. In the case of no controller, rotor current becomes few times higher than prefault level and returns to prefault level after a certain time. BFCL has lower current rise in comparison to SDBR but BFC-NSFCL and BFC-NSFCL with controller outperform the previous all of three and BFC-NSFCL with controller has the lowest current rise and minimum fluctuations.

Fig. 4.15. shows the stator current profile of the DFIG. SDBR comparatively has the lower current peak and fluctuations in compare to no controller. Though BFCL has minimum current rise during fault but it has certain amount of fluctuations. It is easily noticeable that BFC-NSFCL and BFC-NSFCL has the smoothest response and outperforms the conventional ones in all scenarios.

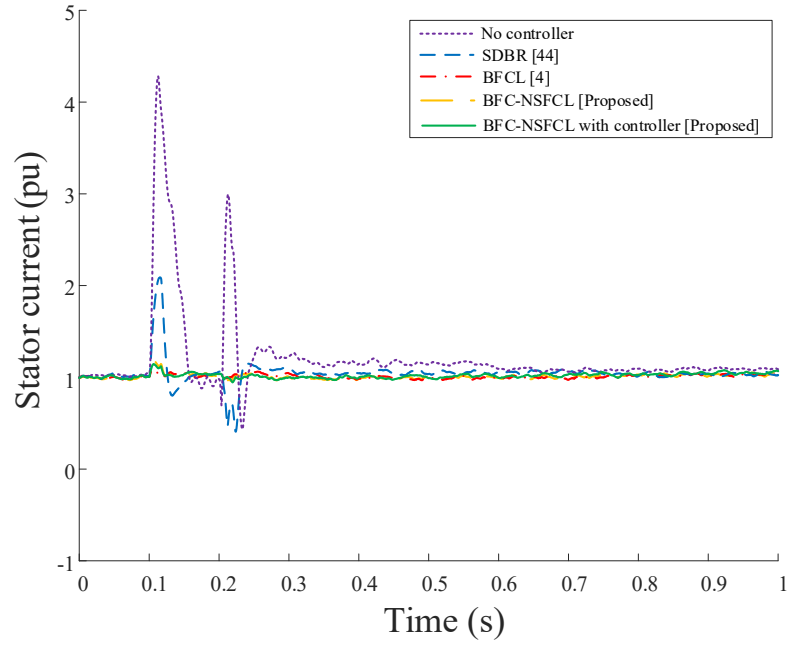


Fig. 4.15 Stator current for 3LG fault

4.5.2 Unsymmetrical Fault Responses

When the system experiences a temporary unsymmetrical 1LG fault, the responses of the six considered scenarios are depicted in Fig. 4.16-4.21. The terminal voltage profile of the DFIG of the system at the PCC is represented in Fig. 4.16. Without any controller, terminal voltage goes to 60% of pre-fault level and recovers after the opening of the breaker. BFCL and BFC-NSFCL both outperforms SDBR in all aspects but the zoomed view clearly indicates that the BFC-NSFCL with controller has the lowest perturbation and minimum amount of sag.

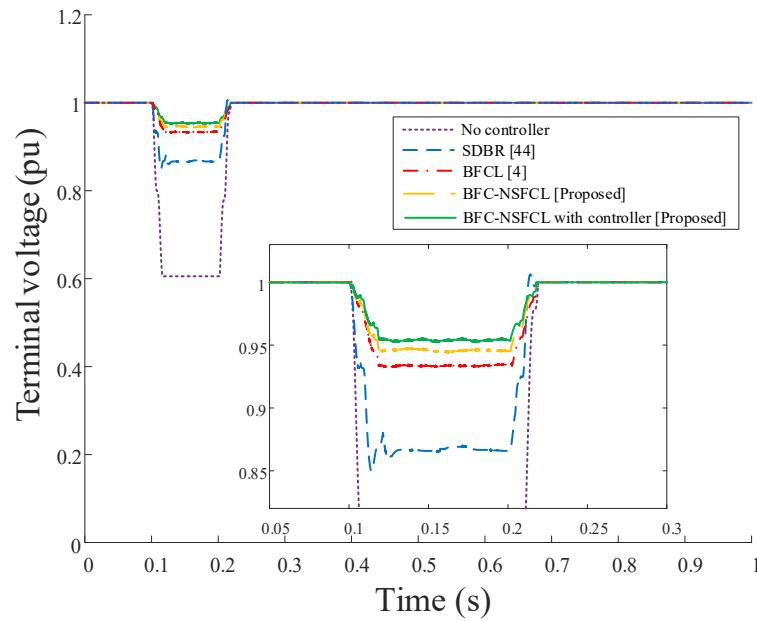


Fig. 4.16 Terminal voltage response for 1LG fault

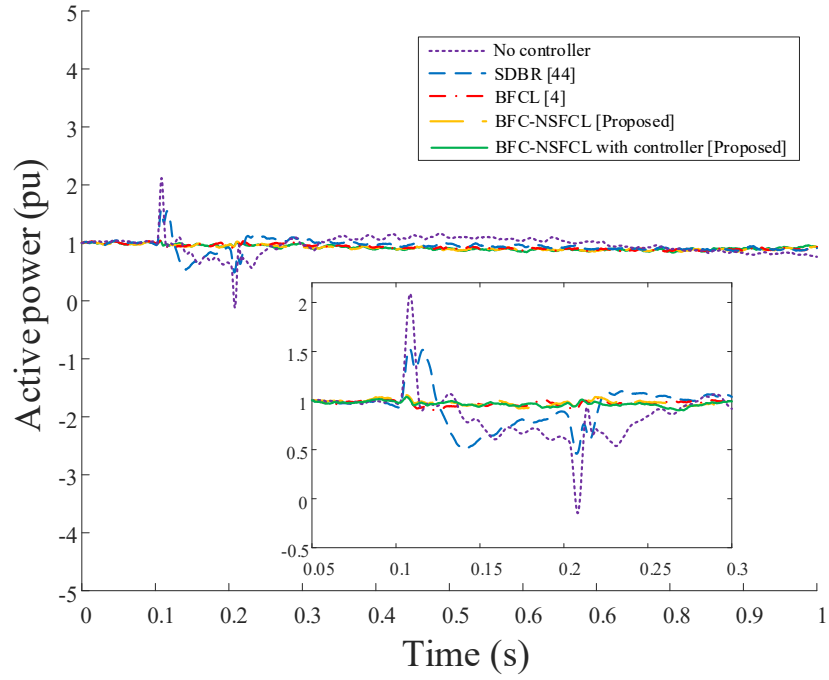


Fig. 4.17 Active power response for 1LG fault

Fig. 4.17 represents wind farm active power for 1LG fault. There is certain amount of deviations amongst all the methods but it is also noticeable that BFC-NSFCL with controller will be best candidate for retaining the stable operation of wind farm.

The dc-link voltage of the farm has no abrupt jump to a substantial value for 1LG fault shown in Fig. 4.18. The BFC-NSFCL and BFC-NSFCL with controller can hold the dc-link voltage fluctuation to the minimum.

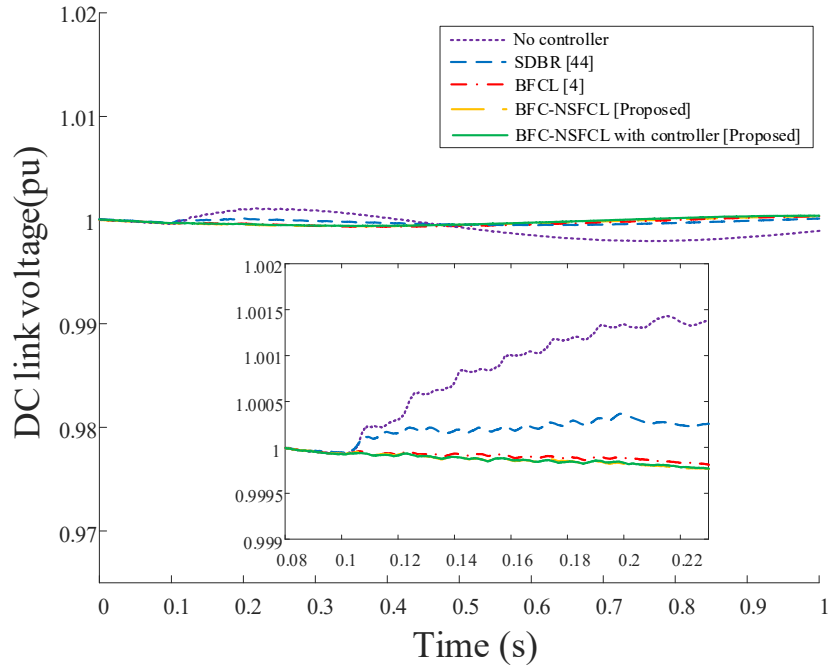


Fig. 4.18 DC link voltage for 1LG fault

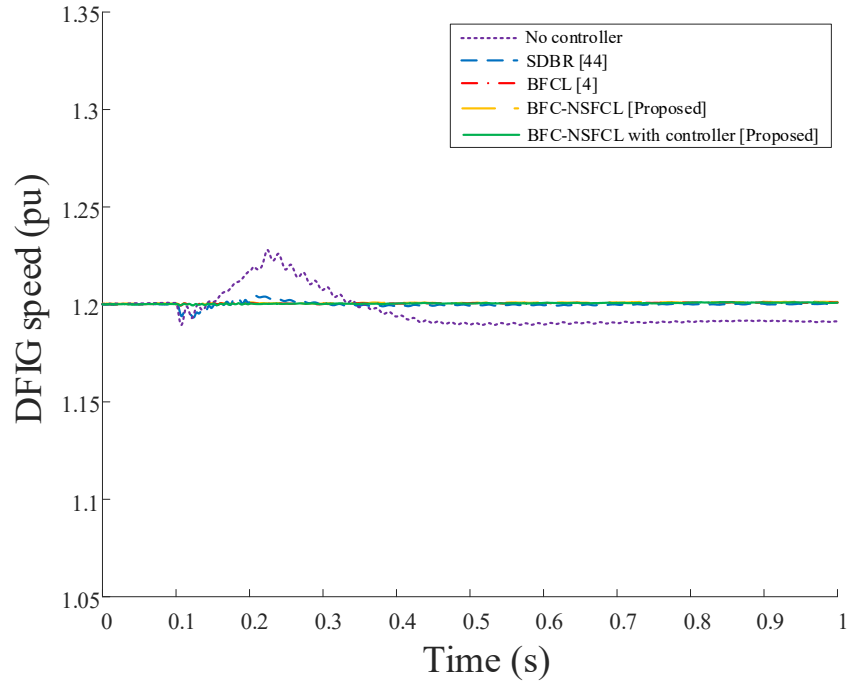


Fig. 4.19 Speed response for 1LG fault

The DFIG speed profile of the DFIG is represented in Fig. 4.19. for 1LG fault. In the case of no controller, it has certain amount fluctuations in rotor speed. As a result, the turbine generator electromechanical system confronts the minimum stress. BFCL and BFC-NSFCL has less fluctuations than SDBR but BFC-NSFCL with controller has the best response.

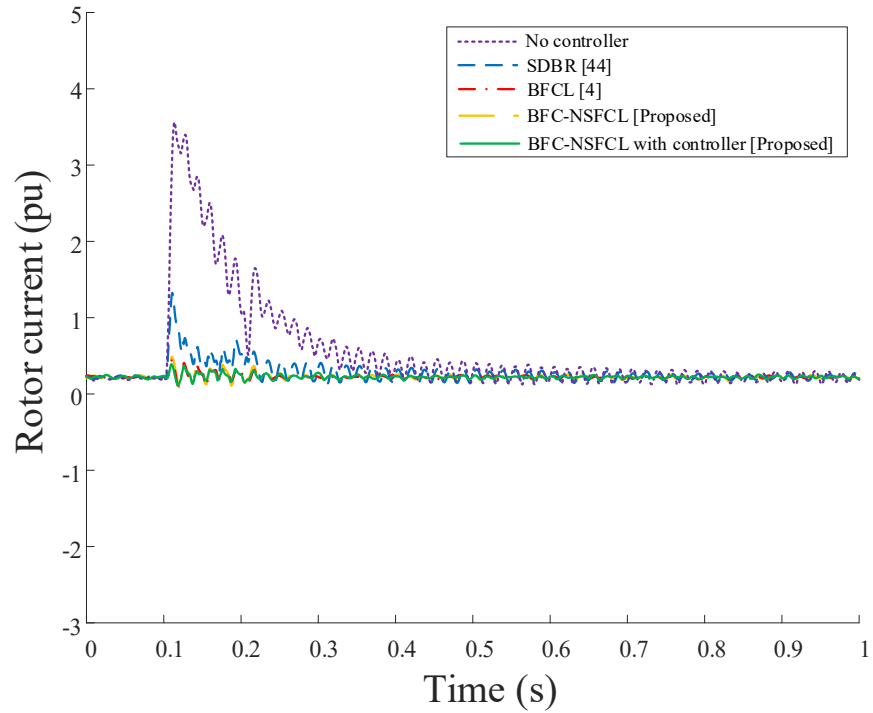


Fig. 4.20 Rotor current for 1LG fault

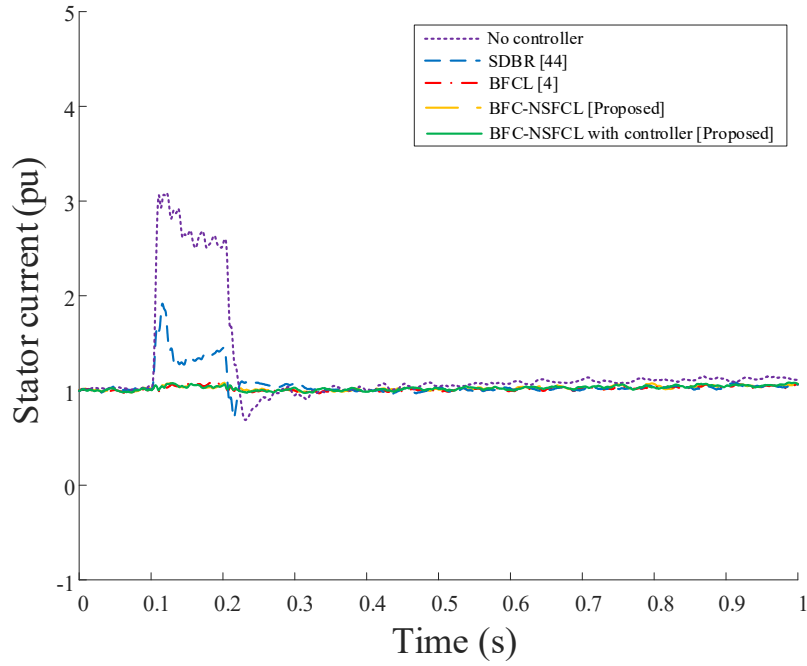


Fig. 4.21 Stator current for 1LG fault

It is evident from the Fig. 4.20 and Fig. 4.21 that, the rotor currents and stator currents are subdued to the minimum level by the BFC-NSFCL. Without any controller current becomes insignificantly high. Conventionally controlled SDBR and BFCL are also capable of current suppression but significantly inferior to the proposed BFC-NSFCL. The steady state operation of the DFIGs are guaranteed by the BFC-NSFCL with controller because it offers least stresses to the converters.

4.5.3 Index-based Comparisons

For the numerical verification, an index-based comparison was carried out to find out the performance of each fault current limiter. The indices are titled as $vlt(pu.s)$, $pow(pu.s)$, $dclink(pu.s)$, $spd(pu.s)$, $str(pu.s)$ and $rtr(pu.s)$. The indices were calculated with certain mathematical expressions which are stated from the equations (4.5) to (4.10).

$$vlt(pu.s) = \int_0^T |\Delta V| dt \quad (4.5)$$

$$pow(pu.s) = \int_0^T |\Delta P| dt \quad (4.6)$$

$$dclink(pu.s) = \int_0^T |\Delta V_{dc}| dt \quad (4.7)$$

$$spd(pu.s) = \int_0^T |\Delta \omega| dt \quad (4.8)$$

$$str(pu.s) = \int_0^T |\Delta I_s| dt \quad (4.9)$$

$$rtr(pu.s) = \int_0^T |\Delta I_r| dt \quad (4.10)$$

Here ΔV , ΔP , ΔV_{dc} , $\Delta \omega$, ΔI_s and ΔI_r are the deviations of PCC voltage, active power, dc link voltage, generator speed, stator current and rotor current respectively. The indices were measured within a time interval of T. In this work, the value of T was kept from 0 to 1 sec. Since the equations consist of deviations, the lesser the value of the indices the better wind generator's fault ride through performance. The performance indices for symmetrical (3LG) and unsymmetrical (1LG) faults are shown in the tables 4.3 and 4.4 respectively.

Table 4.3 Performance Indices for Symmetrical (3LG) Fault

Index Parameters (%)	Indices				
	No controller	SDBR	BFCL	BFC- NSFCL	BFC-NSFCL with controller
vlt (pu.s)	10.17	1.64	1.26	0.69	0.52
pow (pu.s)	8.03	7.94	5.51	5.26	5.18
dclink (pu.s)	0.0321	0.0089	0.0079	0.0037	0.0032
spd (pu.s)	0.371	0.393	0.069	0.03	0.028
str (pu.s)	12.98	5.04	2.42	2.09	2.01
rtr (pu.s)	162.13	15.33	4.03	2.56	2.34

Table 4.4 Performance Indices for Unsymmetrical (1LG) Fault

Index Parameters (%)	Indices				
	No controller	SDBR	BFCL	BFC- NSFCL	BFC-NSFCL with controller
vlt (pu.s)	4.01	1.38	0.69	0.48	0.39
pow (pu.s)	9.657	7.5329	5.085	4.851	4.45
dclink (pu.s)	0.0398	0.0261	0.0195	0.0179	0.0161
spd (pu.s)	0.5826	0.0424	0.0351	0.0301	0.026
str (pu.s)	11.997	4.949	0.734	0.078	0.056
rtr (pu.s)	116.82	18.69	0.5528	0.3388	0.2982

As it can be seen from the tables 4.3 and 4.4, the performance indices are maximum for no controller. The values reduced a lot when SDBR and BFCL were used. But for BSFC-NSFCL, the values of indices are reduced. This is true for both symmetrical and unsymmetrical fault. But with the use of the non-linear controller, the indices are the least. Since the performance of the FCLs are inversely related to their corresponding percentage indices, it can be said that the BSFC-NSFCL alone works great in improving the system dynamics. But with non-linear controller, it performs the best to improve system stability.

4.6 Chapter Conclusion

In this chapter, performance of different control schemes were discussed. Both graphical and index-based comparisons were provided. Apposite arguments about each of the comparisons were discussed in brief.

CHAPTER 5

CONCLUSION & FUTURE WORK

5.1 Conclusion

In this book, two different control schemes for the enhancement of FRT capability of a DFIG based wind farm are proposed. The first one is a new control scheme for the BFCL using active power. The performance of the proposed control scheme is compared with the performance of the previously proposed V_{pcc} and dq reference-based control schemes. The comparison leads to these certain conclusions.

- The control schemes using PCC voltage, dq reference voltage, and the active power can control the operation of the BFCL properly and successfully.
- However, the active power controlled BFCL performs better than the existing two control schemes.
- The response of active power controlled BFCL is faster and much more efficient.

The second work is the proposal of a bridge-type flux coupling non-superconducting fault current limiter to improve the stability of a grid connected wind farm. The performance of this FCL is compared with the performances of two of the other conventional FCLs. The system response in the absence of any auxiliary controller is also considered during the comparison. Observing the graphical responses and the numerical comparisons, the following conclusions can be reached.

- Without any controller, the system experiences unpleasant consequences during fault.
- FCLs offer a significant degree of improvement in the system responses.
- However, compared to other traditional FCLs, the BSFC-NSFCL offers better responses and takes care of the power loss as well.

5.2 Future Work

We can state the future works for each of the control schemes separately. The future work for the first control scheme would be the use of other control parameters such as the dc link voltage, turbine speed and reactive power to control the BFCL. The performance will be compared with the existing ones. Also, a prototype of BFCL will be made to test various control schemes practically.

For the BFC-HSFCL, a prototype of the BFC-NSFCL will be made to test the authenticity of this proposed FCL practically. Furthermore, the BFC-NSFCL is intended to be used in other grid connected renewable energy system i.e. solar PV system, ocean energy system etc

For both control schemes, a multi-machine environment will be considered instead of single machine system in the future.

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