IMPACTS OF GRID VOLTAGE DIP ON THE PERFORMANCE OF WIND TURBINE AND ITS POWER CONTROL DURING FAULT RIDE THROUGH (FRT) THE CASE STUDY OF DOUBLY-FED INDUCTION GENERATOR

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THESIS ORIGINALITY STATEMENT

I assert truthfully that as far as I know and on the basis of the search results of the various scientific papers, the scientific ideas and problems researched and reviewed in this Thesis are original from my thoughts. There are no scientific work has been submitted by others to obtain an academic degree in a college and Higher Education, and there is no work or opinion has ever been written or published by any other person except as expressly quoted in this Thesis and mentioned in the source of quotations and bibliography.

If it appears in the text of this Thesis can be proved there are elements plagiarism, I am willing to thesis canceled, and processed in accordance with the prevailing laws and regulations (UU NO .20 of 2003. article 25 of paragraph 2 and article 70)

FOREWORD

This thesis is concerned with electrical grid disturbances and their impact on the DFIG wind turbines connected to the power system, focusing on the codes and standards of the DFIG connected to the grid, the master aim in this study focuses on the requirements of the public grid during transient faults across the power system which is known as Fault Ride Through Requirements. with a view to increasing the interest in the codes and standards of the requirements of grid-connected wind turbines, which could be useful and contribute to future studies in this field in my country Libya.

ABSTRAC

The wind turbines equiped with doubly fed induction generators have been commonly used as the wind power generation connected to the public grid as a component of the power generation system. The grid-connected wind turbines are sensitive to the Grid disturbances, especially grid voltage dips caused by the transient faults of the power system. The DFIG is contacted to the Grid via conductors which use the grid voltage through an auxiliary transformer to perform the mechanism to switching on/off the DFIG to the power transmission system or public grid. In this thesis, the impact of the voltage dips on the wind turbine of DFIG and the main contactor of it is The interest of this study. The study concentrated on simulating the process of connecting the DFIG generator to the public Grid through its Main AC contactor and modelling of various symmetrical and asymmetrical voltage dips, and the impact of these failures on the process of connecting the generator to the power system via contactor contacts and also their impact on the performance of the generator. Thus, the voltage dip effect on the doubly fed induction generator connected to the public grid and its main Contactor is analyzed. The contactor is subjected to a range of voltage dips to analyze the maximum voltage dip possibility which is keeping the contactor still energize and its contacts still in close position. Due to sudden voltage drop has occurred to the system, the contactor voltage magnitude significantly dropped, Thus losing the ability to keep its contacts stay closed. As a result, the DFIG is disconnected from the grid. Consequently, a large transient in the rotor current is observed, as well as there is a voltage oscillation on the DC bus of the converter which greatly affects the rotor side converter of DFIG. Accordingly, some proposed protection has been added to both the contactor and the DFIG converter.

Based on the studies of properties and performance affected by the grid conditions for both the generator and main contactor, the simulated system is analyzed with and without proposed protection and compared at normal condition and different grid faults conditions. the results present the impacts of the AC contactor is effects the behaviour of DFIG as a result of its lost contacting to the power system due to the voltage dips impacts. In addition, the proposed protections is maintained the DFIG to stay connected to the grid during the grid transient, It was also controlled the converter DC voltage and the rotor. Finally, the results observed and interpreted with Matlab/Simulink simulation software.

SUMMARY

The wind energy playing a potential role in the establishment of a low -carbon and sustainable energy generation, Modern wind turbines have become an important economic clean energy source of renewable power generation. Although wind power generation has many environmental benefits, there are several technical problems to consider.

The problems are found in the wind power generation, especially on the grid-connected DFIG wind turbines, due to the conditions of the Grid, including the grid voltage fluctuations, which cause oscillations in the energy generated by the generators, therefore, these effects can have negative impacts on the power grid. Although there are mechanical and electrical methods to limit the impact of this grid disturbance, those measures result in a decrease of the total energy production through wind turbines. Moreover, the disturbance of grid voltage affects the other control devices responsible for connecting the wind turbine generator to the network such as Main contactors and converters which are significantly affected by these grid disturbances which affects the power productivity of the generators.

This study carries out an analysis of the impact of voltage dips during grid transients caused by power system faults on the wind generator and its main contactor. In addition, it also presents the addition of a time delay circuit on the contactor coils to ensure that the voltage dip will not affect the performance of AC contactor which means the contactor is continuing to connect the generator to the grid. The crowbar variable DC resistors are also added to the DFIG generator converter to ensure that the current of the rotor generator is not affecting the convertor during this type of network faults. Furthermore, The contactor continues to connect the generator to the grid without causing any interruption as a result of the proposed contactor protection, In addition to that, the DC input voltage of the converter will be controlled due to the proposed crowbar protection which also limits the effects of increased current and voltage on the rotor side converter during various Grid voltage dips which include the symmetrical and asymmetrical faults, Which connects two different types of devices that are affected by network disturbances to achieve safe operation of the generator during Grid disturbances, this is what the results of this research present.

CONTACTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 Research Background

Electricity plays a vital role in the modern life to supply institutions, factories and utilities with necessary energy. It supplies the communications, transportation and machinery factories, which require electric power to continue the production. However, the increase in energy demand as a result of the urban and industrial growth leads to the increase in the consumption of fossil fuel bringing along with the increase in the CO_2 in the atmosphere and environmental pollution. Thus, the interest in renewable energy has become urgent to reduce the pollution in the surrounding environment.

The wind turbines being the one of the most important and largest renewable energy sources which establishment of a low carbon sustainable energy. Libya is one of the countries which recently have focused on taking advantages of the investment in renewable energy. Its location has an advantage of being near to Europe, the one of the largest energy consumers. The distance between Libyan coast and Europe is about 360 kilometers. There are also power transmission lines, which are maritime cables linking Libya to the Europe and neighboring countries' electric grids. Thus, the investment in generating electricity using renewable energy, especially wind power projects is promising as it is potential to export the excess of energy to the neighboring countries. However, such projects are still under insignificant consideration in Libya (Mohamed, A et, al., 2016).

Nowadays, the wind turbines equipped with a doubly fed induction generators can be found among various ranges of different turbine constructions, especially in unstable wind-speed areas, due to the ease to control their speed during wind velocity changes, and its ease to connect to the public Grid and stability of power output, also easy maintenance and its appropriate prices (Morren, J.& Member, S, 2002).

Doubly Fed Induction Generator wind Turbines is transforming the wind kinetics through the blades and gearbox to generate a stable mechanical torque through inconstant wind speed, which gives potential to generate more stable electricity. However, their connectivity to the public grid through converters gives DFIG generator more tolerance to control the generation of power stability through the network voltage and frequency control. In other words, more stability in power generation increases the stability in the grid. The less expensive price, its low maintenance cost, its ability of maneuvering during the wind variety to generate stable electricity, and its connection to the public network make the DFIG wind turbine generators more efficient compared to other types of wind power generators. However, such sources of renewable energy have also disadvantages, where they are characterized by the intermittent generation of energy depending on wind conditions. Also, the wind turbines with DFIG is affected by grid disturbance at its point of contact which is caused by grid disturbance. Moreover, the most serious issue for the of power generation is the ability of the system to recover and return to the stable situation in a short time when the failure without affecting the stability of the process of power generation, which is defined as the capability of the machine to stay stable during a system disturbance such voltage dip (Kundu, 2004). Due to the effect of the direct connection of the wind turbines equipped with DFIG and the public Grid as a component of the power system, the DFIG is extremely sensitive to the grid voltage dips, which can cause power plant failure or wind turbine cut off grids that can influence the stability of the power system (Olguin, G. 2005).

The wind turbine DFIG is connected to the power system via two sides, the stator is directly connect to the grid and the rotor connected through converter to the power system, accordingly, the converter is divided into two parts, Grid Side Converter (GSC) Which is directly linked to the public network and Rotor Side Converter which is linked to the generator rotor windings through the slip rings, DFIG wind turbine is linked to the power system through two sides, the stator which is directly connected to the grid and the rotor which is connected through the converter to the power system, so the converter is divided into two parts, the Grid Side Converter (GSC) as directly related to the public network and the Rotor Side Converter which is connected to the rotor generator windings through the slip ring, it is expressed as the rotor side converter (RSC). The RSC converter is responsible for maintaining the grid voltage to manage the voltage in the rotor in order to suit the magnetization flux of the rotor and its speed or torque. The main disadvantage of grid connected DFIG Wind Turbines is the sensitivity to the grid transients, in particular the voltage dips caused by power system faults. This grid disturbance clearly effects the DFIG performance, especially the grid-related parts such as converters also, the wind turbine control components such programmable logic controller (PLC) and AC contactors. All these components of DFIG which is connected to the grid are clearly affected by sudden grid disturbance such voltage dips which sometimes cause the generator to be disconnected from its grid or effect on the generator parts (Bingham, 1998).

Voltage dip is a sudden drop in a voltage of power system which caused by power system disturbance or grid faults. This voltage disturbance directly affects the DFIG controls especially the converters. Therefore, analyzing the dynamic models of DFIG through simulation is necessary to be the reason of analyzing the behavior of DFIG and the difficulties derived the generator through the voltage dip grid disturbance. This disturbance is also applies to the contactors and relays that convert the magnetic flux generated by the grid voltage to a mechanical force that connects the electrical equipment to the power through the closing mechanism of their contacts. Thus, it can be assumed that the voltage dip affect the stability of DFIG Generators and their power controls.

However, the international standards and codes related to wind power generation do not allow the outage of wind turbine during the grid voltage dips. According to the international standards and cods, generators should stay ride of the grid during this type of sudden faults. This requirement is called Fault Ride through (FRT). Therefore, this study is concerned with the disturbances caused by the voltage dip on the grid-related generators and the contactors that are affected by the voltage disturbance, and the possibility to keep these generators safely connected during these faults (Priyanka, R., Bhole, A., 2017).

Most of the reviewed studies In this area have focused on the effect of the dips of a grid voltage on the wind turbines with DFIG and their converters. However, other parts are equally important as they are directly responsible control to connecting the DFIG generator to the power system. These parts, such as relays, programmable logic controllers (PLC) and contactors are also responsible for controlling the switching On/Off the DFIG generator into the power system, while it is also affected by the transient on the grid during the voltage dips. The most common devises are considered sensitive to the voltage sags is the personal computers, control devices, variable speed drives, contactors, converters, and microprocessors (Alena et, al, 2017).

Thus, through these previous studies of the wind turbine models, the aerodynamic and dynamic models based on space vector control can be used to increase the various speed of wind turbines to examine the DFIG generator characteristics when the Grid voltage dips occur. The model will include a crowbar protection to protect the converter during voltage transient and current disturbance. However, the previous studies presented in this research have neglected an important aspect, since it overlooked the impact of voltage dips on the main contactor which is responsible to switching on/off the DFIG generator to the grid.

In this proposed study there will be an attempt to integrate the strategy of DFIG fault ride through by limiting the rotor current using crowbar resistors and a contactor ride through strategy including under voltage DFIG generator protection. This fault ride through strategies will be simulated by using Simulink / Matlab.

1.2 Researches and Alternative Solutions

The DFIG generator control system is complicated than the controls of the variable speed induction motors, It requires a power electronic converters which has multiple different controls strategies to control the DFIG which including the control of rotor current and voltage of the generator. However, this DFIG generator is highly affected by grid voltage disturbances resulting in a high current disturbance on the Rotor Side Converter of DFIG. Since the wind turbines standards and grid codes are recommended to manage wind turbine linked to the grid when there is disturbance in the power system, many studies has been interested in obtaining safe and effective techniques to keep the DFIG generator stay connected and safely ride through during grid voltage dips. Several strategies to address this problem have been suggested by many researchers in this field.

Many researchers reported the harmful effects of current disturbances on the RSC Converter of DFIG during grid transients such voltage dip. Jun-Qing, L. and Ya-li,C. (2013) pointed out that the sudden dip of grid voltage can weaken the DC component of flux linkage which causes transient currents on the rotor side of DFIG generator. Additionally, Reddy, B. and Reddy, P. (2015) suggested that connecting different leakage inductances in series to the stator circuit could reduce the DC component during a symmetrical voltage dip thereby reducing the rotor current disturbances on DFIG. On the other hand, Xin, P., Huida, D. & Xiuli, L. (2017) found out that the voltage dip significantly increased the current on the rotor side converter during disturbance voltage dips. Also DFIG wind turbines using the crowbar resistor protection is the most popular and reliable scheme to relieve the problems of overcurrent in rotor side converter (RSC) and overvoltage at DC-link during a severe voltage dip. For DFIG the crowbar circuit is used as FRT protection method against sudden grid voltage dips during the period of fault.

All previous studies have been concerned with the DFIG generator as the most important part connected to the grid and affected by voltage disturbances. However, they neglected the main contactor which is greatly affected by the disruption of the grid voltage because it uses this voltage in the mechanism of switching On/Off to connect the generator to the grid. Even so, some studies have shown a significant impact of the voltage drop that causes disconnect of the equipment from the grid.

This study aims is to find out the related impact of the linking between two fault ride through (FRT) strategies, generator fault ride through and contactor FRT during voltage dips to perform a safe and successful fault ride through based on the grid codes.

1.3 Problem Statement

The voltage dips known as a sudden decrease in grid voltage for short duration about 150 msec which can affect many electrical devices, including control units, contactor latching coils, converters, generators, and motors. This sudden fault sometimes leads to the outage of generation or even instability of power grid. As a result, there may be blackout in the parts of the power system which may cover a village or a city. Therefore, as responding to the FRT requirements for wind turbines which recommends that the generators need to be staying linked to the power system when transient grid faults, happen which requires finding a safe method to keep DFIG connected to the grid to continuing safely perform during sudden faults like voltage dip. Since this study is concerned with wind turbines that use doubly-feed induction generators (DFIG), the research will be concerned with how to keep this DFIG generator stay uninterrupted and networked by controlling the disturbances that occur within the generator components such as a converter and contactors to reducing the disturbance effects on the generator ingredients. This study will implement the strategies and studies that have been conducted previously on this area. Hence, fulfilling study to the influence of the voltage dip on the converters of the wind turbines and the latching coils of the contactor should be considered because it is responsible to connecting the converters and generator to the grid and As a result of its obvious impact by the voltage drop. Therefore, the possibility of contactor to disconnect the generator from the network is greater.

Thus, this research will be conducted by answering the following research questions:

1. How it can keep the DFIG wind turbines is safely stay connect to the power system during grid voltage dips?
2. What are the appropriate strategies that used to control limiting the high current on the rotor side of the generator so as to protect the RSC converter?
3. How can a safe connection between generator and the main contactor be ensured during transient faults based on the FRT requirements?

1.4 Objectives of Research

The widespread use of wind turbines as a source of sustainable energy becomes a part of the main power grids. The DFIG is widely used in wind turbines for various speed winds area. Thus, the study aims to achieve a safe and successful strategy to achieve the target of this study that FRT requirement of the DFIG generator during the voltage dips.

1.4.1 Specific Research Objectives

This research will discuss the mechanism of the DFIG-based wind turbines to stay operationally uninterrupted during the grid disturbance by voltage dips by controlling the DFIG rotor current disturbance during voltage dips and protecting the convertor. Besides, it is also aimed to find out the way to curb the voltage dips impacts on the latching coil of the main contactor which connect the generator to the grid.

1.4.2 Significances of research

The results of this research are expected to provide useful information on the behavior of the doubly-feed induction generator by controlling the oscillating current in rotor convertor resulted from the voltage dips on the grid. It is very important to protecting the converter through crowbar which is variable set of DC resistors operating as a bypass for the rotor current transient during grid faults. This protection called the variable active crowbar protection. Besides, this study is beneficial to show results of the linking between rotor side protection and the main contactors using fault ride through strategy in order to reveal the behavior that binds between controls during these faults.

This type of DFIG generator which is the subject to study is widely spread and suitable to be used in the climatic condition similar to Libyan coasts. This study will give contribution and recommendation for the development of Libya renewable energy alternatives, especially wind power generation.

CHAPTER II

LITERATURE REVIEW

2.1 Previous Studies

The increasing demand for energy as a result of technological development has increased the problem of environmental pollution due to the fossil power generation. Global concern about environmental pollution led to the increased concern in renewable energy technologies for generating clean electricity generation, Wind Turbine with DFIG is one of the most common wind turbines in the wind power industries, especially for high potential power wind turbines estimated at megawatt size. For this reason, these DFIG wind turbines connected to the public grid are affected by disturbances caused by grid transient. Disturbances across the electricity grid significantly affect the electrical appliances and equipment connected to the grid even if these equipment are far from the fault site. This effect appears as a sudden and sharp drop in the general grid voltage known as the voltage dip. The wind turbines equipped with DFIG as synchronous generator is linked to the public grid to form groups called wind farms, they are affected by disturbances caused by grid transient. The voltage dip in electric network is able to influence the stability of power in the DFIG at the connection point of the wind turbine which makes these turbines vulnerable to affected by sudden changes in the grid during the transient faults.

Therefore, one of the most common drawbacks of DFIG wind turbines is its operation during voltage dips. The DFIG internal components are affected by these sudden voltage dips which affect the generator and its electronic components and causing a disturbance of voltage and current located on the rotor windings and stator of the DFIG. This condition results in a massive disturbance of the current and voltage on the rotor side converter, that possibly leads to the converter damage (Saad, 2015). Besides, the auxiliary control components of DFIG such PLCs and contactors are very sensitive to the voltage dips, although DFIG and its control units are sensitive to the voltage drop.

The grid codes and the requirements of the wind turbines state that the DFIG generator should remain connected during these transient faults, which are called fault ride through (FRT).

In order to achieve these requirements, several researchers began to develop several strategies for DFIG generators to pass through the faults when transient in the grid such as voltage dips happen. In this part of the research, a detailed review from the previous studies in the field of the DFIG generator behavior during grid transients such voltage dips is presented. The studies are including the technical articles from IEEE journals and few other sources (including websites).

In this chapter, consideration will be yielded to the previous studies that have been concerned with the impact of sudden voltage dips on the DFIG g`enerator connected to the grid. The literature review summarizes the work done previously that is related to modeling and controlling doubly-feed induction generator in general and transient fault ride-through during different power system status. As an important background for research, DFIG wind turbine modeling is importance in research. Therefore, this study is based on analyzing the simulations results of DFIG wind turbines through the Matlab Simulink software.

In order to study the doubly-feed induction generator behaviour during voltage dips in the power system, the use of dynamic models to accelerate the wind turbines equipped with DFIG connected to the grid. In a brief, a summary of some related studies concerned with this field will be presented.

Arantxa Tapia, A et. al. (2003) presented the induction machine model that illustrates the operating conditions at synchronous speed, in which the generator rotor is linked to the grid through the double sided converter. The *ds* and *qs* parts of the curret of the stator are represented at the reference frame of the stator flux. The vector control model of this stator is based on two PI controllers which are implemented in order that the active power is separated from the reactive powers. Ledesma, P. and Julio Usaola. (2005) have proposed a model of the DFIG to studying the grid transient on the power stability of the wind turbine where they assumed that the current controls process of DFIG is much faster than the effect of the transient on the electromechanical controls. The DFIG model was based on a set of algebraic equations is determined via the iterative method. The model is simulating the stability of DFIG controls during grid transient in order to demonstrate its feasibility. Abad, G. et. al. (2011) stated extensively about wind generators and mentioned that to control the increased mechanical effort during variable speeds and power generation, several controls must be available to do this without risks. The mechanical controls are the pitchable blades, gearbox, and power control via converters to provide variable speeds. They estimated various models to study the DFIG controls. An aerodynamic model was used to represent the electro mechanic torque as a function of the aerodynamic flow. The dynamic model is based on the space vector model which control the DC bus voltage to maintain the rotor flux linkages on the rotor then controlling reactive power exchange.

Recently, the grid standards and specifications recommended to keep the DFIG wind turbines stay connected and ride through the grid transient during voltage dip. Unless if the fault duration is greater than the allowable voltage dip period, which may affect the components of the generator, it allows disconnecting the generator from the grid (Al-Assaf, Y. et, al, 2013). Wang, W. and Jianlin, L. (2009) pointed out that DFIG wind turbine linked to the power system is clearly affected by the voltage dip, in particular, its converter which powered by the grid voltage. This effect relies on the voltage dip magnitude and grid status during fault accordance. This voltage disturbance causes the current turbulence and power generation instability. In addition, Wei Qiao, W et. al., (2006) have pointed that, the converter becomes a highly sensitive component in the wind turbine equipped with DFIG controls during voltage dip. While Salles, M et, al. (2015) have studied the DFIG though two sides, the Stator side, that links to the grid and the Rotor side, which is connected to the grid via a converter, they noted that the voltage dips on the grid side of the converter and rotor windings could cause high current may threaten the converter integrity. On the other hand, Pingle, T et. al. (2015) studied the modeling of a DFIG and its performance in a closed loop control model. Where they control the stator powers by using a vector control strategy with the stator flux orientation method. The topology of cascaded bridge inverter is used to study its effect on power quality. The simulated models are built via MATLAB software. The results are clearly appear the effectiveness of a vector control strategy.

Zhong Cheng and Yan Gangui (2015) in their study of doubly-feed induction generator performance during transient such voltage dips mentioned that transient analysis is the key for studying on DFIG wind turbine Subject to the ride faulty by the requirement. Besides, for the purpose to protect the DFIG converter during the grid voltage dips, crowbar protection generally added in parallel to the rotor windings of the generator. This protection acts as a current bypass to protect the converter from the troubled increase in the rotor current during the voltage. The paper also discussed the relationship between the crowbar resistance and the rotor current. Furthermore, DFIG wind turbines at the time of the grid disturbance have been studied by Duong, M. et al. (2016), studied the transient model of a resistive type SFCL based on the developed thermal model. The studies reported that the voltage transient occurrence in the grid increases the rotor current and may damage the rotor side converters. A crowbar which operates as a shunt resistor in parallel to the rotor windings and acts according to Kirchoff's law thus dampens the large current that causes the by grid transient on the rotor windings. For the purpose to increase the stability of power and to damp the oscillations on the DFIG wind turbine during grid transient, this paper proposed using the variable crowbar resistors as fault ride through solution.

Hannan, M. et al. (2012) had analyzed the AC contactor model and its ride through capability and behaviour during voltage sags. The study showed that the AC contactor as an electromechanical device is widely used in the industrial process such as switching or breaking of the load circuit for controlling the huge equipment. Due to the sensitivity of the AC contactor to the voltage dip, it is mentioned that the sensitivity of the AC contactor is exhibited in its voltage tolerance curves which predict the behavior and the failure area of the contactor.

Based on the previous studies and the fact that the wind turbines connected to the public grids in two sides, directly connect through the stator side and via converter at rotor side of generator, the grid connection is by the contacts of the main contactors which turn Off/On the DFIG generator to the power network. Figure 2.1 presents the connection of DFIG to grid.

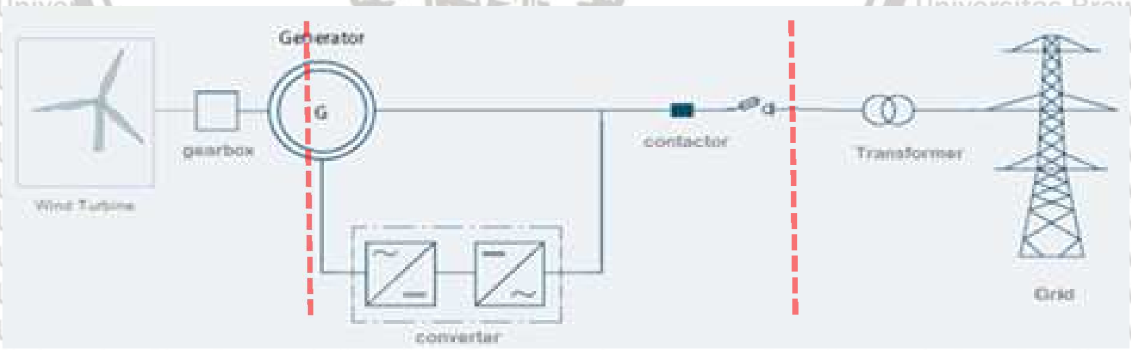

Figure (2.1) DFGI Generator connect to the power system

Therefore, to understand the effects of the voltage dip caused by grid disturbances on the wind turbine parts, the DFIG generator behavior with its main contactor should be studied at steady-state and transient grid states.

2.2 WIND TURBINES

Wind turbines are mechanical structures that transform the kinetic energy to mechanical energy through the blades, then the rotary energy drives the generator which produces electricity for consumption (Babypriya, B. & Anita, R. , 2009).

The operating regions of a wind turbine have minimum and maximum speed of wind velocity. The minimum speed is called cut-in speed. It is a wind speed less than the generator's nominal speed when the turbine stops working. Moreover, the turbine average speed is the wind velocity at which the wind turbine rotates at generator synchronous speed and generate its designated rated power. The cut-out speed occurs during the very high wind speed velocity. During the high speed of wind velocity, the most of wind turbines are shut down to avoid any damage to their mechanical parts.

Wind turbines have two main types, fixed and variable wind turbines, the main differences between these two types are the aerodynamic efficiency mechanism during the different wind speed conditions. There are several types of wind turbines, including:

a. Fixed Speed Wind Turbine. This is a type of wind turbine which has asynchronous induction generator directly linked to the public grid. This particular wind turbine is influenced by the wind variation velocity, which requires to switch the turbine off during low wind speeds since there is no speed or torque control. It also has a major drawback of the reactive power consumption because of the absence of power controls.

b. The DFIG Wind Turbine becomes commonly available because of the flexible characteristic to manage its speed during a certain wind speed range to generate more stable electrical energy. This generator is directly linked to the grid via the windings of the stator, whereas the windings of the rotor are linked to the grid through converter.

c. Variable Speed Wind Turbine with Full-Scale Power Converter. These particular wind turbines generally employ a permanent magnet which is synchronous generator having power converter in the full-scale to relate to the public electricity system.

2.3 Variable Speed Wind Turbine

Variable speed wind turbines consist of two parts, mechanical part which includes the rotor hub, shaft, gearbox, aerodynamic brake and generator rotating mass, and the electrical part which consists of the generator and converter. These mechanical components of wind turbines which transform the kinetic energy to mechanical energy to rotating the generator where it is generating electrical power. The wind rotates on the blades of the turbine, causing them to spin. The shaft is transferring the mechanical energy to the gearbox which steps up in the higher speed. The shaft causing the generator to spin, hence generating electricity. This type of wind turbines can control the mechanical torque and the mechanical rotation speed by controlling the gearbox and the aerodynamic brake system. This generates an appropriate torque and a speed on the rotor of the electrical generator to produce a more stable electric energy.

2.4 Doubly fed Induction Generator

Wind turbines with DFIG are the most popular in the renewable energy applications. The use of DFIG technology can obtain stable energy from unstable wind velocity by controlling the wind turbine speed through blades and gearbox controls to reducing the mechanical stress on the turbine during wind blowing. This enhances turbine efficiency to produce the greatest mechanical energy, thereby increasing the produced electric energy.

The basic parts of DFIG-based wind turbines are wind turbines, induction generators and converters. The generator stator winding is directly linked to the grid, while the generator rotor winding is connected to the grid through the converter. The purpose of the converter is to set the frequency generated from the turbine rotation and the grid frequency, thus allowing the DFIG generator to operate at variable wind speeds. Indeed, the presence of the DFIG converter is to interface of the generator frequency variable and the grid's fixed frequency. Thus, the generator rotation is controlled by the pitch and gearbox controls, while the converter controlling the frequency in the DFIG rotor control circuit. Depending on the size of converter, the generator can operate during a deferent variation of wider range approximately ± 30% around the synchronous speeds of the generator.

The dual-fed induction generators converter has two parts, the rotor side converter that is called (RSC) is linked to the DFIG rotor side via the slip rings, and the converter of the grid side called (GSC) is linked directly to the grid.

DC-link capacitor it mediates the both of the converter sides to stabilizes the output voltage of the RSC converter which resulting in a stable voltage on the rotor windings.

2.5 Back to Back AC/DC/AC Converter

The converter is an electronic device which is used to convert voltage and current from one form to another. It mainly consists of controlled rectifiers which are built from either diodes or thyristor.

Converters are generally applied in DFIG, which is a two-sided back-to-back converter, rotor side converter connecting rotor windings and lattice grid-side converters connected to the grille. This converter consists of an inverter on a rotor called RSC and a rectifier on the side of the grid called GSC. There is a DC link capacitor located between the inverter and the converter. capacitors are used as energy storage to keep the DC voltage of the converter during voltage variations, thus keeping the steady voltage on the rotor windings to control the rotor current of the Generator.

2.6 Contactors

AC contactor is a main electro mechanic which is used to frequently connect and cut off the large-capacity-electrical devices. Moreover, due to its ability to quickly respond to On/Off and frequently switching the large loads electrical circuits, it is often used to control motors and machines. Besides, it can remotely control the power devices to connect and disconnect equipment to the power system. The contactor function is remotely switch on/off the main circuits during normal conditions and due to protection controls.

The contactor structure consists of four parts, including: 3 contacts which connect and disconnect the main power phases, iron core and attract coil which produce magnetic force to operate contactor and latch their contacts, and auxiliary contacts which control the contactor. Commonly, the contactor uses the grid voltage to feed the inner coil to operate and move its conductor mechanism, following that the related equipment is turned on or off. It is also common for the small AC / DC converters to be used to supply the contactor coil by DC voltage from the grid voltage to obtain a constant magnetism on the contactor latching coil.

The controls of wind turbine use contactors to connect the generator and its converters to the Grid.

2.7 Doubly fed Induction Generator Connected to the Grid

The wind turbines with DFIG generator is linked to the public grid in two sides, the stator side which is directly linked to the grid, and the rotor side which is linked to the grid through the converter. The generator parts are joined the grid via the main AC contactor, where the generator windings are managed by wind turbine controls that controlling the contactor switching mechanism which is closed its contacts to coupling the generator to the power grid once the operating conditions of the generator are available such the synchronize speed of the generator has been reached and the regularity of the Grid voltage and frequency (Antonio et, al, 2016).

The DFIG is linked to the grid at the grid frequency of constant, the stator will produce a magnetic flux on the rotor windings which will produce an induced voltage on the rotor windings during the synchronous speed of the machine resulting in the exciter current which generates an opposite electric torque on the rotor.

The converter is controlling the generated torque via controlling the rotor current and voltage, where the voltage control achieved by controlling the exciter current, this will be controlled by the dc-voltage. So the rotor shall be supplied by voltage through the converter of rotor side via the DC link capacitor, while the converter of grid side controls the DC link to keep its voltage constant.

2.8 Voltage Dips

The voltage dip is a sudden decrease in the grid at the short duration, which is caused by a short circuit or overload or startup of the huge electric machines. A voltage dip happens during the decrease of the rms voltage between 10 and 90 percent of the nominal system voltage for approximately one-half cycle to one minute. This sudden voltage dip affects many electrical devices, including control units, Relays, contactor latching coils, generators, converters, UPSs, and control systems. This sometimes leads to generation outage or even instability of the grid which may cause block out of the part of the network.

There are many reasons for a voltage dip, grid faults caused by short circuits in someplace of the grid with a power supply temporarily disconnected, the start of huge machines which sometimes caused heavy currents flow in the system or big transformers saturation during startup. Voltage dips caused by power system faults have two types, the symmetrical fault and asymmetrical fault. The symmetrical voltage dip usually caused by three phase faults and system startup. And asymmetrical voltage dip usually caused by single-phase or two-phase or two-phase-to ground faults or grid unbalance power distribution. Voltage dips are the cause of the majority of electrical devices trip. The magnitude of a voltage dip is due to types of grid faults, the distance to the fault point, and the system Components.

The converters of doubly fed induction generator is very sensitive to transient faults of grid, especially voltage dips which causing high current disturbance that may damage the electronic power components of converters (Xiao, S et, al, 2012). Since there is an effect of sudden voltage dips on the generator parts, the auxiliary controls such relays and main contractors are also affected by this voltage fluctuation. The magnetically AC holding contractors may drop out when the voltage is reduced below about 80% of the nominal for a duration of more than one cycle before the functioning of the under voltage protection (Kueck, 2011). Effects of grid voltage transient on DFIG will lead to voltage sudden drop on the generator compensates where the voltage dip will Cause sudden decrease in the magnetic force of the contactor coil used to close the contacts which connect the generator to the grid, at the same time the voltage dip causes oscillations in the DFIG rotor flux which affects the performance of the DFIG generator and the Grid connection module known as AC contactor.

2.9 Fault Ride- Through (FRT) Capability Requirements

The Grid codes and requirements are considered as foundations and standards prepared by the grid system administrators and operators for the power system based on previous experience and studies aimed to achieving the efficiency and safety of systems and electrical devices during operation Fault Ride-Through Requirements specifies the requirements for the operation of wind turbines under normal and transient conditions. Many organizations and countries with experiences in the rentable energy have improved their power system requirements and codes to include wind generators ride during sudden faults (FRT). These countries include European countries such as Germany, Holland and other countries interested in wind power generation or renewable energy. In particular, it describes the requirements and the behavior of wind turbines under grid distortions, such as voltage dips, frequency, grid interphase, and higher harmonic. In addition, it also describes various techniques which have been developed to make the wind turbines connected to the power plant at the time of the grid transient which caused voltage dip on the generator components. This ability is called Fault Ride through (FRT) capability (Morren, J. et al., 2007).

Therefore, to achieve a safe grid fault ride through during voltage dips by the DFIG generator, the generator converter and its main contractors must be subjected to FRT requirements.

2.10 Modeling of Doubly-feed Induction Generator Circuit Connection to Grid

Due to growing use of doubly-feed induction generators (DFIG) in wind farms, Studies interested in this field consider it necessary to understand the generator properties and its controls characteristics. Thus, the DFIG as a synchronous generator, Generate a real power depend on the magnitude of the rotor voltage $|V_r|$ and angle δ Like the induction machine (Jiao, et. al, 2005).

When the mechanical part of wind turbine speed reaches the generator rating speed as a function of wind velocity and Pitch angle, the electrical controls ordering the Main contactors to close their contacts then connecting the generator the grid, then the generator operates as part of the public Grid. Figure (2.2) shows the DFIG wind turbines components (ABB, 2010).

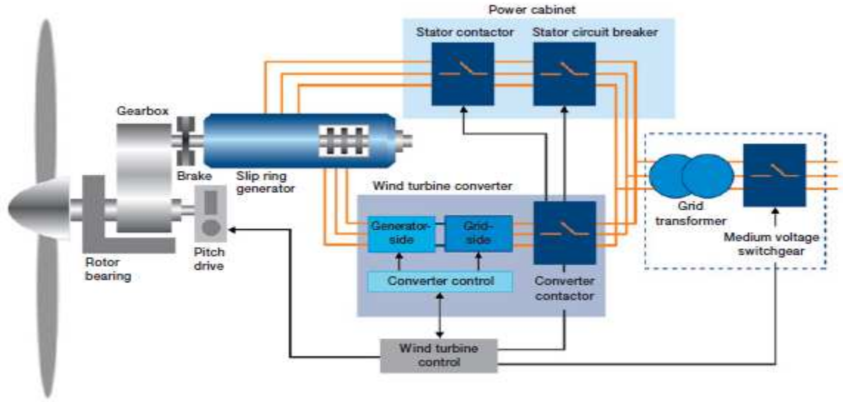

Figure (2.2) DFIG wind turbines components connected to grid (ABB, 2010).

As described in the figure above, Wind turbines mainly consist of two main components the turbine and the generator.

- The turbine consists of blades, which are responsible for generating kinetic energy through the variation of wind velocity, this blades rotation is controlled to be mostly a constant speed by the gearbox to transformed to mechanical torque drives the rotor generator.

- The DFIG generator is used to convert the kinetic energy produced by wind turbines into electrical energy via several procedures of the control process to generate stable power that rides the electrical grid. The generator contains two componets: the stator which is linked directly to the public network, and the rotor which is linked to the network through the converter.

DFIG's wind turbine operation mechanism and power production are controlled by several strategies that govern the mechanical work of the turbine and control the production of stable electrical energy. converters allow controlling generators to control speed, power and power factor, which provides a wider range control strategy of varying speeds to produce more stable power plants. The generator stator is connected to the grid through the main contactor to the stator generator cable to the grid. This is also in the grid side converter that connects to the public grid through the contactor. Thus, to understand the control processes in the DFIG generator on both sides of the Grid and rotor, it is necessary to simplify and model different control strategies of DFIG generators and wind turbines.

2.10.1 Aerodynamic Wind Turbine Model

The majority of DFIG wind turbines are equipped with a two-part rotor wound induction generator, the stator which is linked directly to the public network and the rotor which is linked to the power system through the converter. The occurance of a converter in a generator combination makes the DFIG able to handle the fraction (25% -30%) of the total power to reach full control of the generator. Wind turbine power generation depends on the interaction of wind turbine speed and generator rotation. Or the blades of the wind turbine extracts a part of the air flow from the wind velocity as kinetic energy during the blades movement which caused wind turbine rotation, then converts it to rotary energy, and supplies it to the generator via a mechanical drive (gearbox). The mechanical extraction of kinetic energy generated by wind blowing can be explained by the application of Bernoulli’s equation (Abad,G. et al., 2011).

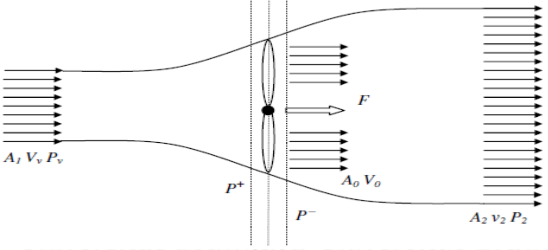

Figure (2.3) Schematic of fluid flow through a disk-shaped actuator

The power with the kinetic energy form produced by the wind velocity is described by the formula below:

$$P_v = \frac{1}{2}\rho_{A_1} V_v^3 \quad \dots\dots (2.1)$$

V_v is the wind speed and ρ known as air density

However, the wind turbine has the potential to recover only a part of this energy to convert it into mechanical energy which expressed as:

$$P_t = \frac{1}{2}\rho\pi R^2 V_v^3 C_p \quad \dots\dots (2.3)$$

Where

R is known as the radius of the wind turbine

C_p is known as the power coefficient, ρ_{A_1}.

The torque is generated via the rotor through mechanical rotation which determined as the following:

$$T_t = \frac{1}{2}\rho\pi R^3 V_v^2 C_t \quad \dots\dots (2.4)$$

Through this equation, an aerodynamic wind turbine model and speed control can be drawn. Thus the energy is produced by the turbine. The power curve which determines the capacity of the appropriate wind turbine can be analyzed.

2.10.2 DFIG Generator Model

The double-feed induction generator model includes two parts: the stator is coupled to the grid and the rotor connected to the grid through the converter (Figure 2.4), the stator supplied by a constant-frequency grid voltage, where the grid voltage creating a magnetic field on the stator windings. The rotor which supplied by the system voltages via a converter and takes a different frequency amplitude. The relations between the different frequencies of the path sides of the converter represent the grid frequency on the GSC converter and the rotor frequency which generated by the rotor rotation speed that on the RSC converter to the study of the electric equations of the DFIG.

The DFIG model is to determine the relationship between the rotor mechanism and the power produced at both grid sides of the generator, and clarify the different strategies for DFIG control (Abad,G. et al., 2011).

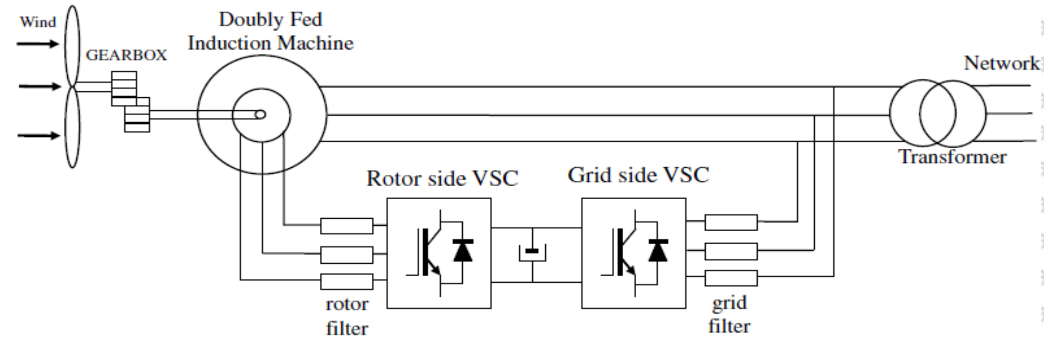

Figure (2.4) Schematic diagram of wind turbines based on grid connected DFIG

The rotating reference frames (α–β) are used to form the models of space vector for the DFIG. The stator reference frame represents the 3 windings of DFIG in the (*DQ)* spaces vectors where the rotor magnitudes are referred to the stator, where the voltage, flux and current sinusoid with a ω_s frequency which is the frequency of the stator. While ω_r is the frequency of rotor, clearly depends on the shaft speed ω_m. The rotor reference (*DQ*) represents two rotating coils at ω_m (rotor electrical speed), while the synchronous reference frame (*dq*) circles at ωs. These vectors are employed to show one space vector is referred to the stator. (Abu-Rub, H. et al. 2014).

2.10.3 α - β Model

In the α β model, dynamic, the electrical equations of induced generators are vector space theory. Figure (2.5) depicts three different circling reference frames that are usually employed to describe vector-based space models from DFIG. The stator reference frame (α - β) is a stationary reference frame. The rotor reference frame (DQ) rotates at ωm and the synchronous reference frame (dq) rotates in ωs.

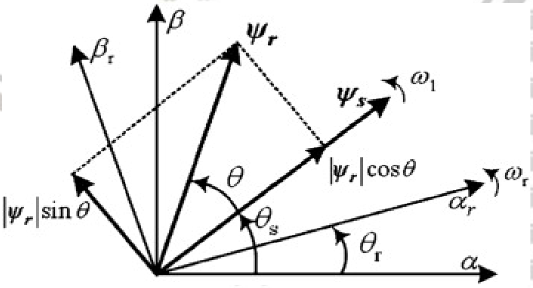

Figure (2.5) Different Reference Frames to Represent Space Vectors of the DFIG.

The space vector theory is represented by two stationary $\alpha\beta$ stator space frame to represent the stator coils and *DQ* frame to represent the two rotating coils, clarified via the following voltage equations:

$$\overrightarrow{v_s^s} = R_s\overrightarrow{i_s^s} + \frac{d\overrightarrow{\psi_s^s}}{dt} \quad \text{……………………………………………………(2.4)}$$

$$\overrightarrow{v_r^r} = R_r\overrightarrow{i_r^r} + \frac{d\overrightarrow{\psi_r^r}}{dt} \quad \text{……………………………………………………(2.5)}$$

If $\alpha\beta$ reference frame represented the rotor and stator voltage equations, then the rotor equation multiplied by $e^{j\theta_m}$ will be produces the following equations:

$$\overrightarrow{v_s}^s = R_s\overrightarrow{i_s}^s + \frac{d\overrightarrow{\psi_s}^s}{dt} \Rightarrow \begin{cases} v_{\alpha s} = R_s i_{\alpha s} + \frac{d\psi_{\alpha s}}{dt} \\ v_{\beta s} = R_s i_{\beta s} + \frac{d\psi_{\beta s}}{dt} \end{cases} \quad \text{……………………........................(2.6)}$$

$$\overrightarrow{v_r}^s = R_r\overrightarrow{i_r}^s + \frac{d\overrightarrow{\psi_r}^s}{dt} - j\omega_m\overrightarrow{\psi_r}^s \Rightarrow \begin{cases} v_{\alpha r} = R_r i_{\alpha r} + \frac{d\psi_{\alpha r}}{dt} + \omega_m\psi_{\beta r} \\ v_{\beta r} = R_r i_{\beta r} + \frac{d\psi_{\beta r}}{dt} - \omega_m\psi_{\alpha r} \end{cases} \quad \text{………..(2.7)}$$

by using a similar method, from $\alpha\beta$ frame, the stator and rotor flux equations are obtained in the stationary reference frame:

$$\overrightarrow{\psi_s}^s = L_s\overrightarrow{i_s}^s + L_m\overrightarrow{i_r}^s \Rightarrow \begin{cases} \psi_{\alpha s} = L_s i_{\alpha s} + L_m i_{\alpha s} \\ \psi_{\beta s} = L_s i_{\beta s} + L_m i_{\beta s} \end{cases} \quad \text{……………………………………(2.8)}$$

$$\overrightarrow{\psi_r}^s = L_m\overrightarrow{i_s}^s + L_r\overrightarrow{i_r}^s \Rightarrow \begin{cases} \psi_{\alpha r} = L_m i_{\alpha r} + L_r i_{\alpha r} \\ \psi_{\beta r} = L_m i_{\beta s} + L_r i_{\beta r} \end{cases} \quad \text{……………………………….(2.9)}$$

From these derived equations, the Figure (2.6) represents the $\alpha\beta$ equivalent circuit. Where its showing that, in $\alpha\beta$ space factor, all DFIG magnitudes of voltage, current and flux are sinusoidal with a ωs frequency. While the electromagnetic torque of DFIG is calculated by the equations:

$$T_{em} = \frac{3}{2}pIm\{\overrightarrow{\psi_r}\overrightarrow{i_r}^*\} = \frac{3}{2}\,p\left(\psi_{\beta r}i_{\alpha r} - \psi_{\beta r}i_{\beta r}\right) \quad \text{……………………………….(2.10)}$$

2.10.4 *dq* Model

In the *dq* reference frame, the 3 phase voltage of the DFIG generator are converted into a dq axes reference frame during rotating when the synchronous frequency ω_s. The stator voltages and flux equations for a DFIG became as the follows:

$$\overrightarrow{v_s}^a = R_s\overrightarrow{i_s}^a + \frac{d\overrightarrow{\psi_s}^a}{dt} + j\omega_s\overrightarrow{\Psi_s}^a \Rightarrow \begin{cases} v_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s\psi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} - \omega_s\psi_{ds} \end{cases} \quad \text{……………(2.11)}$$

$$\overrightarrow{v_r}^a = R_r\overrightarrow{i_r}^a + \frac{d\overrightarrow{\psi_r}^a}{dt} + j\omega_r\overrightarrow{\Psi_r}^a \Rightarrow \begin{cases} v_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_r\psi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} - \omega_r\psi_{dr} \end{cases} \quad \text{…………..(2.12)}$$

Similarly, the flux yields:

$$\overrightarrow{\psi_s}^{s} = L_s \overrightarrow{i_s}^{a} + L_m \overrightarrow{i_r}^{a} \Rightarrow \begin{cases} \psi_{ds} = L_s i_{ds} + L_m i_{dr} \\ \psi_{qs} = L_s i_{qs} + L_m i_{qr} \end{cases} \quad \text{……………………………………(2.13)}$$

$$\overrightarrow{\psi_r}^{a} = L_m \overrightarrow{i_s}^{a} + L_r \overrightarrow{i_r}^{a} \Rightarrow \begin{cases} \psi_{dr} = L_r i_{dr} + L_m i_{ds} \\ \psi_{qr} = L_r i_{qr} + L_m i_{qs} \end{cases} \quad \text{…………………………….……(2.14)}$$

Where:

v : Voltage (V) , R: the resistance (Ω), i: the current (A). ω_s : stator electrical angle velocity (rad/s), ω_r : rotor electrical angle velocity (rad/s), and ψ: the flux linkage. The *d* and *q* are indicated the reference frame direct and quadrature axis, *s* indicated the stator quantities and *r* indicated the rotor quantities.

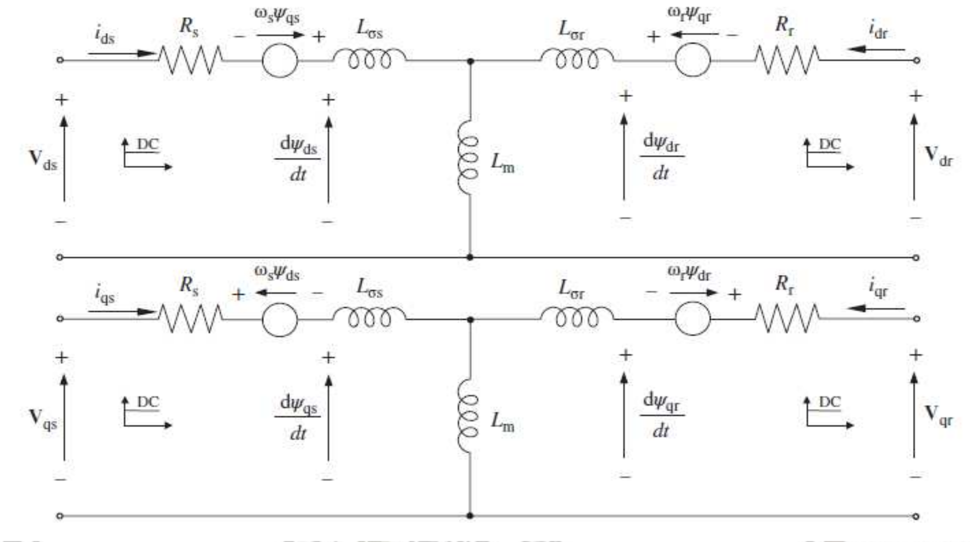

Figure (2.6) Model of the DFIM in dq Reference Frame (Abu-Rub, H. et al., 2014).

2.10.5 Vector Control Strategy

Vector control technique one of the extended alternative control method developed for the DFIG. It is easier to understand and handle, the control strategy of the generator is starting from the starting up method which explained by the current control loops, then the steady-state analyses methods, and it explains the stability state of the generator and finally the unbalanced grid voltage controls (Abu-Rub, H. et al., 2014).

The DFIG vector control strategy is defined through the synchronous dq frame, where the d-axis follows the stator flux space vector, as shown in Figure (2.6). Because of this alignment option, the rotor current will be proportional to the stator's reactive power, and the rotor current q is proportional to the torque or active stator power. Thus, from the DFIG model, the rotor voltage will be as a function of the rotor current and the stator flux (ψqs = 0) is reached. (Abu-Rub, H. et al., 2014)

$$v_{dr} = R_r i_{dr} + \sigma L_r \frac{d}{dt} i_{dr} - \omega_r \sigma L_r i_{qr} + \frac{L_m}{L_s} \frac{d}{dt} \left|\overrightarrow{\psi_s}\right| \text{……………………………}(2.15)$$

$$v_{qr} = R_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr} - \omega_r \sigma L_r i_{dr} + \frac{L_m}{L_s} \left|\overrightarrow{\psi_s}\right| \text{………………………………..}(2.16)$$

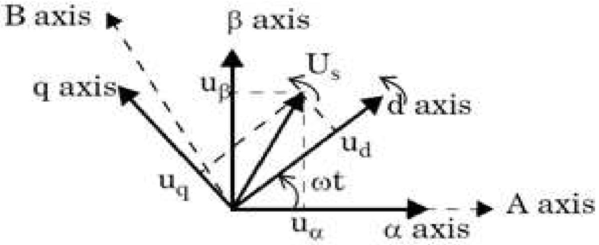

Figure (2.7) Synchronous rotating dq reference frame aligned with the space vector.

2.11 The Behavior of the Doubly Fed Induction Generator during Voltage Dips

To examine the DFIG control behavior at the time of the voltage dips, it is essential to analyze the performance of the generator and its behavior during this type of error. However, when the grid is temporarily occurring, the stator flux of the DFIG simultaneously and significantly falls. Therefore, it is necessary to analyze the characteristics of stator flux and magnitude to know the problems resulting from grid disturbance because of the dips voltage. Thus, through the following expression, the voltage drop effect can be determined. (Abu-Rub, H. et al., 2014)

$$\frac{d\overrightarrow{\psi_s}^{s}}{dt} = \overrightarrow{v_s}^{s} - \frac{R_s}{L_s}\overrightarrow{\psi_s}^{s} + R_s \frac{L_m}{L_s}\overrightarrow{i_r}^{s} \text{ ……………………………………………}(2.17)$$

In normal operation of the DFIG generator, the wind turbine transform the mechanical energy to electrical power. In this generation process, the electromagnetic torque of the DFIG will be controlled by the stator currents or rotor currents depends on the strategy used in the control, this is clearly shown in the equation (2.10), but these currents are generated as function of Grid voltage shown in the equation (2.11), in this case, the grid side converter is to control and sustain the input voltage stability through converter control strategies to be a constant under the operating conditions.

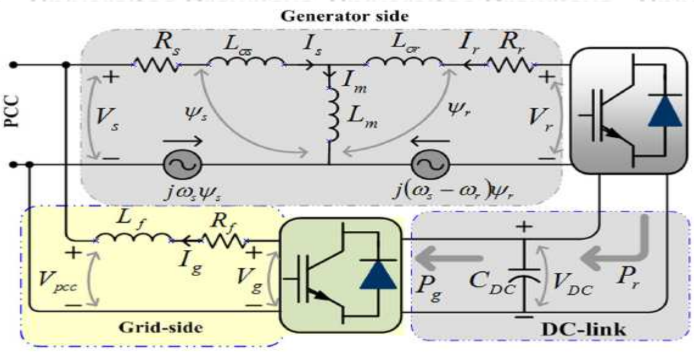

Figure (2.8) Equivalent circuit diagram of the DFIG based WT system

Figure (2.8) shows the relation between the Grid voltage and the flux and current of rotor side and stator of Generator, therefore any disturbance in the Grid voltage (V_{pcc}) will have an effect on the generator components. Therefore, when the Grid voltage fluctuates due to voltage dips, the DFIG generator parameters will be affected severely, this because the grid voltage is one of the references of generator control strategies. Thus, the grid voltage fluctuation, even for a short period of 150 ms. may causes a malfunction in the generator controls. Figure (2.9) shows the effect of the 80% of voltage dip on magnetic flux of the stator windings which in turn affects the electromagnetic torque of the generator, which causes a significant deterioration in the rotor current.

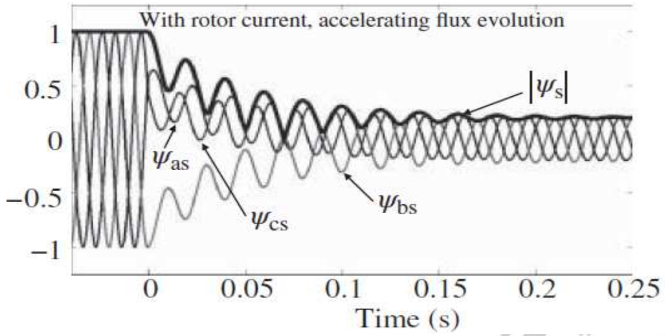

Figure (2.9) Stator flux evolution in p.u during an 80% voltage dip (Abu-Rub, H. 2014).

In view of this, the proposed solution strategy is controlling the disturbances current on the rotor by adding resistance in parallel with the rotor windings to protect RSC converter which known as the crowbar protection.

2.12 Fault Ride Through strategies for DFIG wind turbines

The impact of the grid voltage dip on the DFIG depends on its intensity and voltage dip duration. When the voltage dip appeared in the grid, the stator voltage will be suddenly decrease to a small value while the rotor current is significantly increased (Morren, 2007).

Based on the requirements of Fault Ride through (FRT) and standards of grid, the wind turbine must remain linked to the public network when Grid voltage dips. As reported in the previous research, to achieve safe driving fault through DFIG, the rotor current and overvoltage dc-link interference during voltage drop should be limited. These studies show that several strategies were found to fulfill the FRT requirements, and varied methods have been suggested to increase the DFIG performance during the transient grid of the dips voltage.

In this study, the active crowbar protection with variable DC resistors and chopper are proposed, where they will be activated according the DC voltage value of Link Bus exceeds the certain value. (Gabriela et. al, 2015).

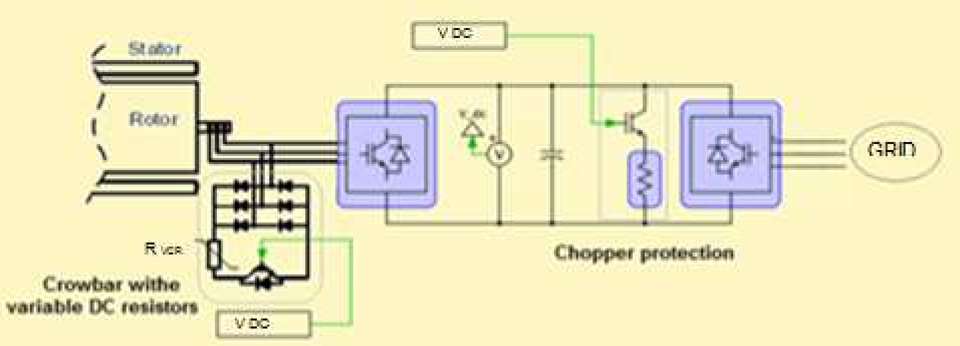

Figure (2.10) the crowbar protection connect to the rotor windings and convertor DC link

2.12.1 DC-Chopper

Chopper protection is a DC resistor that is connected in parallel with the DC capacitor of the converter to limit and control the excessive charge voltage during the voltage disturbance of the power system. Chopper resistors are used to protect the converter from overvoltage, but do not affect the disruption of rotor currents.

2.12.2 Crowbar DC variable resistance Protection

The crowbar protection is a set of dc resistors controlled by IGBT transistor and connected in parallel to the rotor windings via converter, where these resistors work during the occurrence of the voltage disturbance to damp the current increases and bypassing the RSC. The crowbar control scheme is increasing the dc resistors gradually according to the increase in the DC voltage value when necessary and disabled them to resume the DFIG controls.

RV crowbar control is activated by the insulated-gate bipolar transistors IGBTs to connect the variable dc crowbar and chopper to RSC and its DC link, thus connecting or disconnecting the protection is depending on the specific value of DC voltage Which is the reference to turn the protection on and off, these voltage limits control the crowbar and chopper to damping the current on rotor side converter.

2.13 AC Contactor model

AC contactor is used widely in the industrial field. It is used in the control operation of electric machines, especially to connect or disconnect the machines from the power system. Figure (2.11) shows the importance of the Main contactors to connect and disconnect (on/off) the DFIG to the power system. However, these contactors supplied through the Grid voltage, which powered its latching coils to generate a magnetic field resulting in a torque which move their contacts to close, then connect the generator circuit to the grid.

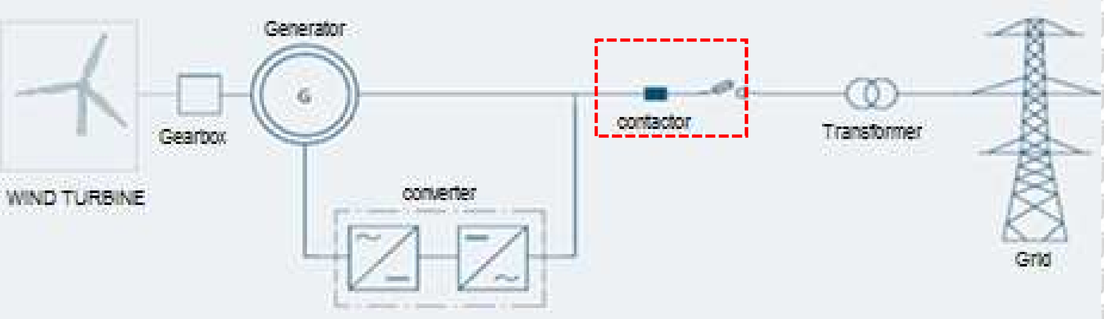

Figure (2.11) the Main contactor connect the DFGI Generator to the power system

In order to determine behave of AC contactor during the changes of grid conditions, to simulate the impact of its components, consequently, its effects on the machines connected to the grid via its contacts. Fig. 2.12 shows the mechanism of the contactor which is operated by the coil, spring sets and the contacts and its power supply the ac voltage.

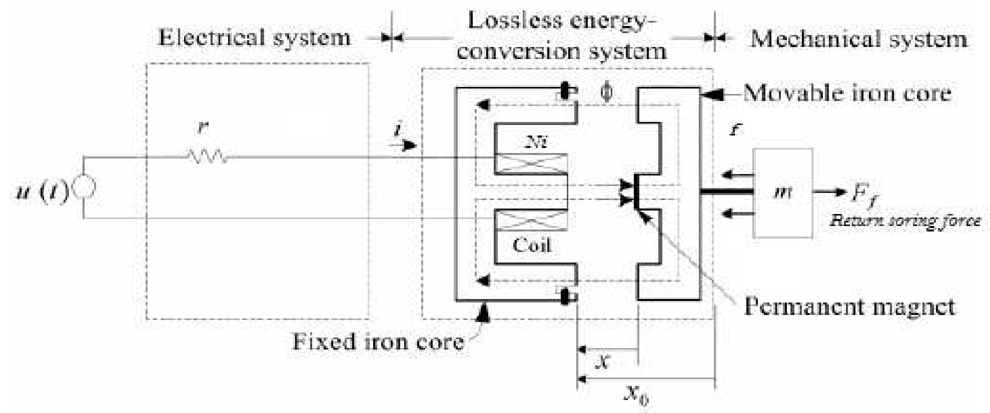

Figure (2.12) Structure of Magnetic Contactor

The contactor with 240 ac voltage 5000 turns coil is taken into account, in the electromechanical model. The ac voltage is applied the contactor coil to produce magnetic flux with respect to time $d\phi/dt$ and also related to the number of coil turns N (Iyoda, I. et, al., 2008).

The terminal voltage equations are

$$u = r\,i + N\frac{d\phi}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.18)$$

Where u is system voltage, ϕ is the flux linkages per turn of the exciting the coil, i is the current for the exciting coil, r is the resistance for the exciting coil

The current passing through the contactor coil generates an electromagnetic force that moving the movement parts of the contector (armature and contacts), That electromagnetic force moving the contactor armature is defined as follows

$$F = -\frac{\partial W}{\partial x} = -\frac{1}{2}\emptyset^2\frac{\partial \mathcal{R}}{\partial x} + f_f \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.19)$$

Where W is the magnetic energy, ϕ is the flux generated on the contactor coil, $\mathcal{R}$ is the total magnetic circuit reluctance and x is the air gap distance between the active armature and fixed core.

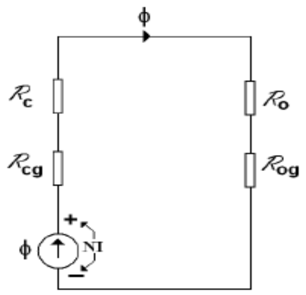

Figure (2.13) the Reluctance equivalent circuit for the contactor

In figure 2.14 the resulting magnetic reluctance caused via the magnetic flux where R_c fixed iron part reluctance is and R_{cg} is the air gape, and R_o is the movement armature reluctance and R_{og} is the air gap. The reluctance is presented as total Reluctance which can be expressed as:

$$\mathcal{R} = \frac{1}{\mu_r \mu_0 A} + \frac{2x}{\mu_0 A} \quad \text{...} (2.20)$$

AC contactor acts as a magnetizing switch depending on the coil magnetic force and electrical contacts position. The contacts are open/close based on the current supplied to the coil which generates the magnetic force to produce mechanical force which in turn opens and locks the circuit of the DFIG generator. The dynamic behavior of the contactor mechanism is expressed through the use of Newton's law of motion.

$$F = -m\frac{d^2x}{dt^2} + D\frac{dx}{dt} + K(x - x_0) \quad \text{...} (2.21)$$

The contactor model is developed according to the above mentioned equations

2.13.1 Voltage dip Effects on contactors

AC contactor is one sensitive equipment in voltage dips. The fundamental performance of the contactor is electromagnetic constriction on the movable bar. The momentum produced on this bar relies on the power of the magnetic field flux caused by the coil surrounding the fixed shell. It also relies on the electric power that supplies the coil (Jeong,S. et al., 2009).

2.13.2 Contactor ride through strategy during voltage dip

With the adding of an RC element in parallel to the Contactor coils to keep the contactor stay holding their contacts when the voltage source lasted, this through a capacitor discharge of its charge to resupply contactor coil if the voltage dip happened. the capacitor will start its discharge its charged voltage to supply the coil, and the resistor in series with the coil will limit the current to a safe contactor coil. So the contactor will stay energized for a few abrade of time during voltage dip. The RC energized time depends on the capacitors value, the resistance of the contactor coil and the voltage supplies the contactor coil during fault.

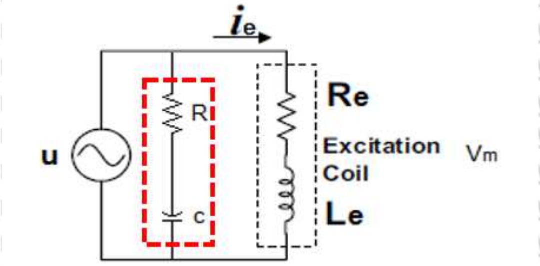

Figure (2.14) RC circuit add in parallel to the Contactor coil

If the coil resistance is known then the time delay will be approximately equal to:

$i(t) = \frac{u}{R}\ e^{-t/RC}$……………………………………………………………......(2.22)

$Ri(t) = V_m = u\ e^{-t/RC}$…………………………………………………………(2.23)

$-\frac{t}{RC} = \ln\frac{u}{V_m}$………………………………………………………………………(2.24)

$t = -RC\ln\frac{u}{V_m}$……………………………………………………………...…. (2.25)

Where, *R* =coil resistance, *C* is capacitance of capacitor, *u* is coil rating voltage and V_m is initial voltage across the capacitor (working voltage of the contactor's coil) (Hughes, 2005).

Via the relation between generator and the main Connectors in terms of contactor responsibility to control On/Off the generator connection to the grid. Since both are connected and use the Grid voltage as voltage sores to operate their mechanism, therefore, referring to the previous studies, which confirmed that path are affected through sudden grid voltage dips. Thus, the integration between fault ride through control strategies of bath generator and contactors during grid voltage dip which may give the generator a safe ride Through Grid voltage disturbance.

CHAPTER III

RESEARCH CONCEPT FRAMEWORK

This chapter contains problem analysis, research variables, and the solution concept. The concept of the solution is based on one of the technologies used to ride the transient faults through the public grid, which is fault ride through (FRT). In this proposed study, two technologies will be linked to work together to achieve a safe and successful DFIG fault ride through technology. It will be built to protect the DFIG converter from the high impact of rotor current disturbance during voltage influence. It is known as VR crowbar protection. It will be linked to the contactor ride through technology by giving an additional electronic circuit which operates as a battery to keep the main contactors stay connected during the period of voltage dips. This will enhance the fault ride through strategy, as the consideration in the research will prevent the effect of the main contactors from the sudden voltage dips. And meanwhile, the crowbar strategy will reduce the risk of current variation and DC voltage fluctuation within the rotor side converter of DFIG generator.

The generator will be simulated using the MATLAB by implementing several strategies to operate and control the electrical and mechanical components of the DFIG generator by the Simulink. The generator will be simulated in a normal condition. The asymmetrical fault condition, hence, the crowbar protection strategy will also be simulated on the DFIG rotor side converter. Moreover, the factors residing with the converter during voltage dips will be verified and analyzed to study the behavior of the DFIG during the adding of the crowbar protection. In addition, the main contactor as the main device to open and close the connection between the generator and the grid will also be simulated. This breaker or contactor consists of a mechanical interlock machine operated by magnetizing coils that generate a strong magnetic field that drives the axis of the interlock machine responsible for the interfacing process of breaker contacts. The breaker contacts open or close the contacts between the grid and the generator terminals. The internal coil of the main contactor is fed by the AC/DC converter which in turn is susceptible to voltage dip effects. Therefore, the operation mechanism of main contactor will also be simulated by MATLAB to study the voltage dip effects on the components of the circuit breakers and the effectiveness of the proposed strategy for the contactor ride through of voltage influences.

3.1 Solution Concepts

Basically, there are several methods developed to reduce the impact of voltage drop on the DFIG components. In general, the proposed technique is providing two strategies that are linked together and are related to the generator voltage protection. The first technique is the rotor protection strategy of current disturbances to limit the increase of the rotary current by crowbar resistors which will be connected in parallel with the DFIG rotor coils (Metatla et. al, 2014). The second strategy will be done by connecting the resistor and the capacitor in parallel with the operating coils of the main contactor interlock machine. It is aimed to add the time delay by discharging the charge of the capacitor to supply the coils during a voltage dip period. There is also a possibility of disconnecting the additional circuit to contactor coils during a normal operation by generator protection auxiliary contacts, connection or separation.

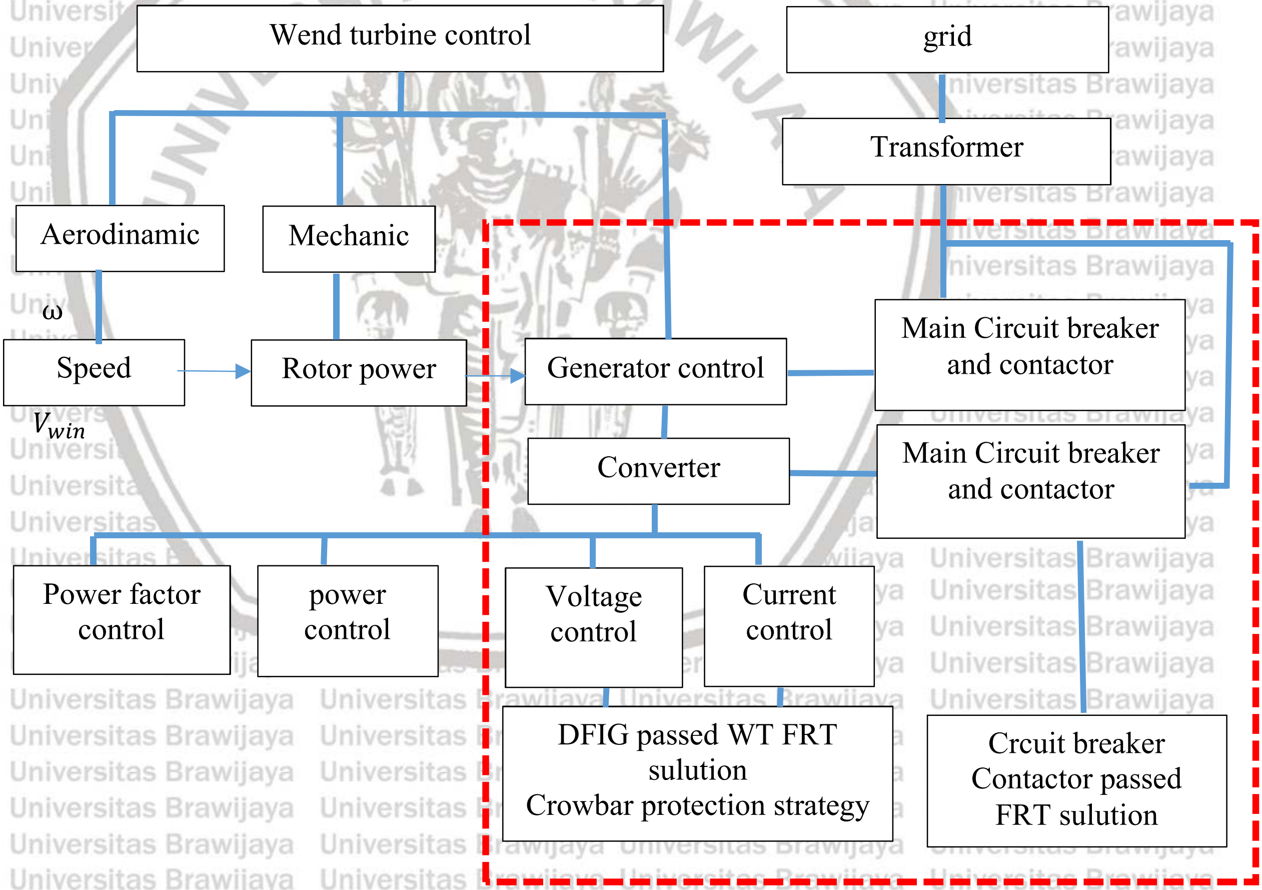

Figure (3.1) Flowchart of concept framework

3.2 Hypothesis

The hypothesis will be the possible results of the identification process of the simulation and the study of the planned model. Through the implementation of the planned strategy in this research, which is based on the hypothesis of the generator and its Main contactors during its effects by Grid voltage dip. Therefore, through this assumption, the study seeks to achieve a safe and successful stay connect to DFIG and its power system during Grid voltage dips.

CHAPTER IV

METHODS OF RESEARCH

The research is based on the Fault Ride Through (FRT) strategy. The idea is based on the link between the proposed crowbar protection for the DFIG generator and the main contactor FRT circuit which is proposed as a solution to ensure that the contactor mechanism remains connected during the grid voltage dips. Thus, analyzing the possibility of achieving FRT safely by controlling the rotor current at the time of voltage fluctuations can minimize the impact of voltage drop on the DFIG converter. During a network error, the crowbar resistor is activated to reduce the rotor current to reduce the flow to the RSC converter, leads to a very fast dc-link voltage increase, which necessitates the presence of chopper protection to limit the dc-link voltage value.

Therefore, the proposed crowbar protection in this research limits the increase of DC voltage and current on the converter, which protect the converter during grid transients, and also the added RC circuit provides a protection to ensure that the DFIG generator is not disconnected from the grid due to the sudden voltage dips occurs on the contactor coil.

The Matlab Simulink will be used to simulate the variable speed wind turbines with DFIG to analyze operation state of the DFIG wind turbine during normal grid connection. It also will subject the DFIG to a grid voltage dip at 80%, 60%, 40% and 20% respectively and separately for 150ms in order to study the behavior of DFIG generator during this type of fault. Besides, it also studies the effects of the voltage dip on the main contactor coils that operate the mechanism to connect DFIG to the grid. The modeled system under study will also be subject to symmetric and asymmetric phase faults, to study its effects on the generator and the contactor, and to determine the proposed protection performance resulting from Grid faults under study.

4.1 Method of Research Flowchart

The research method used in the fault ride through consists of several stages namely the definition of the problem to determine the research, data retrieval and system design to be implemented, the data simulated for a further process i.e. analysis and conclusions. The process is described in Figure 4.1.

4.2 Problem Identification

This stage is to examine the issues that will be raised in the system and to determine the characteristics that are important as the basis of problem solving through the needs analysis, design and implementation of system ride through strategy, in both of DFIG and contactor synchronously. The problem definition stage is conducted by reviewing the related research journals.

4.3 Data Collection

The data retrieval process is done using a primary source that is based on the data obtained from the original source, not through an intermediate medium, and from the result of simulation design with Matlab. Secondary data sources are data obtained from the second source. These data are the data that are explicitly correlated with the primary data sources, such as textbooks, journals, e-books, internet search results, and personal notes related to the research topic.

4.4 Simulation

The simulation of wind turbine models plays an important role for power quality analysis of wind turbine operation methods and their interaction with the grid Variables and the fluctuations in the power system. In this study, a wind turbine control models will be described in details to support the studies of the impacts of grid voltage dips on wind turbines and the performance of their power controls during symmetrical and asymmetrical faults before and after implementing the proposed fault ride through strategy, to obtain the results at steady-state and fault conditions on DFIG controls. The behavior of DFIG and its Main AC contactor performance during grid voltage dip will be simulated and analyzed by using a power system model simulated by Matlab/Simulink software.

The AC contactor mechanism to connecting the generator to the grid is modeled, to analyzing the impact of the grid voltage disturbance on the AC contactor which in turn maybe will affect the performance of the DFIG wind turbine.

In this simulation, the contactor operation mechanism to connect the DFIG generator to the public grid was simulated. A mechanism to connect and disconnect the generator to the network voltage through the contacts of the contactors was simulated to study the impacts of the conductor's behavior on the generator performance at the grid transient faults.

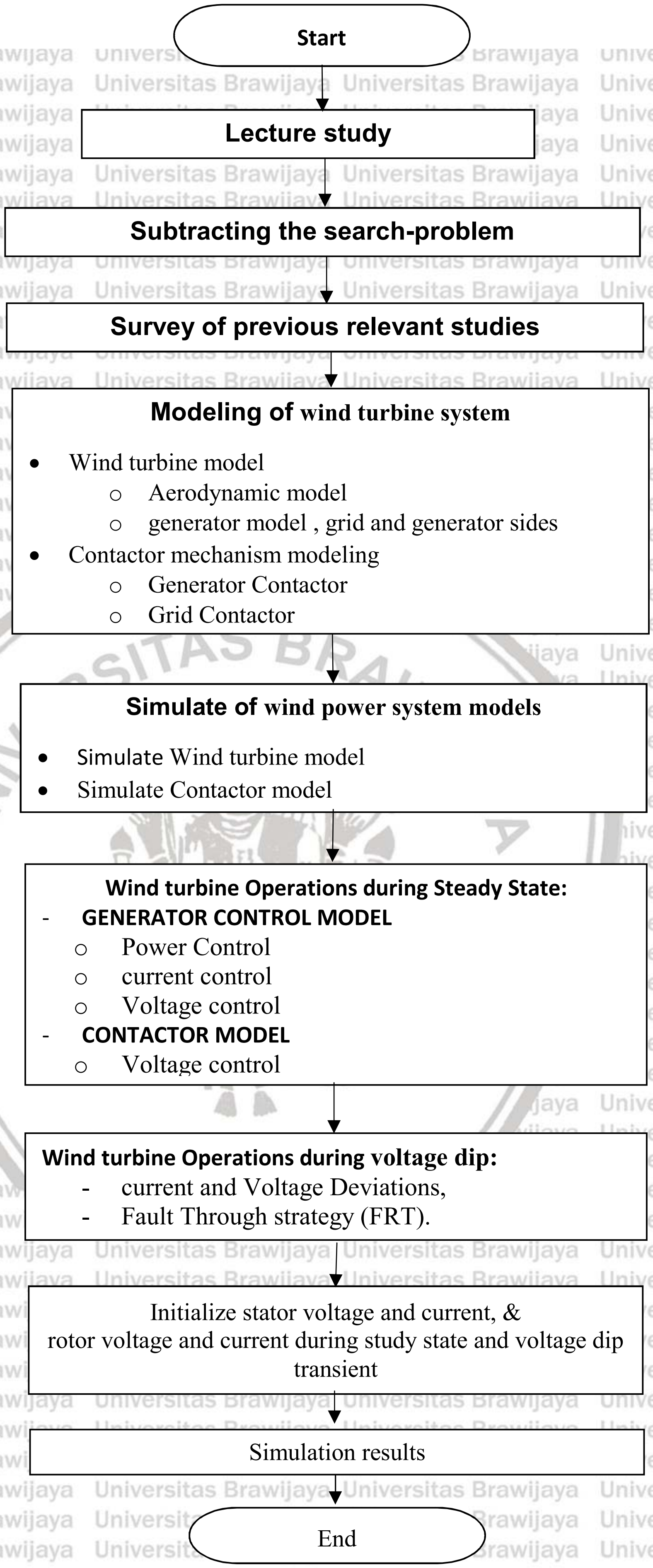

Figure (4.1) Research Methods

4.5 Analysis and Calculation

The following methodology is utilized in order to carry out the research works:

- To simulate the DFIG connected to the grid, complete wind turbine model with controls must be implemented, consequently, it's possible to determine the behavior of the generator and its interaction with the power system during transient and stable grid conditions..
- The steady state situation of the DFIG wind turbine during operation will be investigated during the simulationto to understand whether the generator is in the normal operation or is affected by the transient conditions.
- There are analyses of symmetrical and asymmetrical grid faults which caused voltage disturbance and the dynamic analysis of current loops in DFIG through space vector ∝β components.
- The Fault Ride Through strategy for DFIG wind turbine grid is developed to find out safe FRT to keep DFIG connect to the grid during power system grid faults and steady-state conditions.

4.6 Results and Conclusion

The impact reduction possibility of the voltage dips on the wind turbines prevent the transient effect on both the DFIG converters and the main contactor, resulting in a successful and safe fault ride through (FRT).

4.7 Timeline to finish the Research

The research activities are planned to be completed within 3 months or 12 weeks with details of activities as shown in Table 4.1. Analysis and simulation will take as long as approximately 7 weeks. Yet, the results and conclusions will take only 3 weeks. Meanwhile, the other activities on average will take about 3-6 weeks to complete.

Table (4.1) Research to finish the Research

No.	Activities	Weeks											
		1	2	3	4	5	6	7	8	9	10	11	12
1	Pre Research	🟥	🟥	🟥	🟥	🟥							
2	Identification, purpose and analysis		🟦	🟦	🟦	🟦	🟦						
3	System design					🟨	🟨	🟨	🟨	🟨			
4	Implementation								🟦	🟦	🟦	🟦	🟦

CHAPTER V

SIMULATION AND RESULTS DISCUSSION

The MATLAB Simulink has enabled the simulation users to combine the algorithms for further simulation analysis then export simulation results which give more realistic results. This is where Matlab Simulink comes in, which makes it simulate experimental reality, helping users take advantage of other MATLAB features. Thus, these simulations give great flexibility in testing, simulate experiment, analyzing results and improving performance, consequently increasing research and development (Krishnan, 2001).

In this chapter, the wind turbine based DFIG will be studied during steady state and under symmetrical and asymmetrical voltage dips with different protection techniques applied to keep the DFIG stay raid through the fault period safely and to compare their effects on DFIG. The study will include also various protection techniques in order to study the behavior of DFIG during grid normal operation and transient faults.

5.1 Power system with wind turbine Simulation model description

Doubly fed induction generator 1.5 MW that connected to power system via the Main contactor which is responsible for connecting/disconnecting the generator to the Grid. As shown in figure (5.1) The DFIG wind turbine is connected to system through Bus section number B575, which is connected to the 25/0.575 KV (1.7 MVA) transformer, Then its connected to 30 km transmission lines, out of Bus- bar number B25, it is connected 125/25 kV transformer which is connected to the Bus- bar number B125, and then to the main voltage source. The wind turbine system is modelled and simulated by modifying of the DFIG model in the MATLAB software. The detailed model includes a power source, transformers, overhead line and also wind turbine based DFIG with complete representation of power electronic converters.

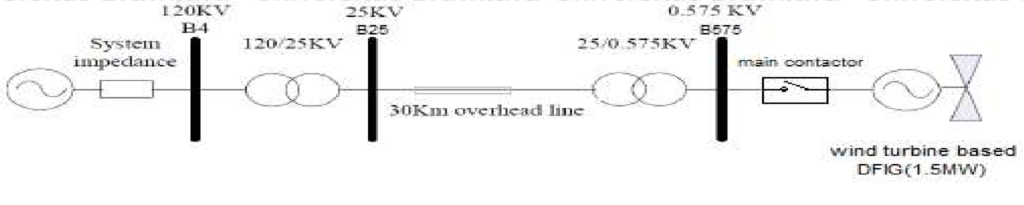

Figure (5.1) doubly fed induction generator 1.5 MW that connected to power system via the Main contactor

The Power system connect to wind turbine simulated model is viewed Figure (5.2) The three phase programmable voltage source connected to the bus bar B120 with three-phase balanced inductive to give balance to the simulated power system, 120/25 KV transformer which connected to Bus bar B125 to supply bus bar B25. The Grounding transformer is connected to the model in order to provide a neutral point in a three-distribution system. 30 km overhead line is modelled as an RL equivalent circuit to deliver the voltage to bus bar B25 through 25/0.575 KV transformer, the Main contactor model is simulated to study its behave during system simulation, the contactor is responsible to supply 575V to the wind turbine model through bus bar B25. The objective of the project is to build a transient model to study the performance of DFIG and its Main contactor during normal and transient status of the simulated system. Therefore, a fault model has been added at bus bar B25 before overhead line model to cause a transient in the Grid, resulting a sudden voltage dip to study the behavior of the DFIG generator and its Main conductor during this transient period.

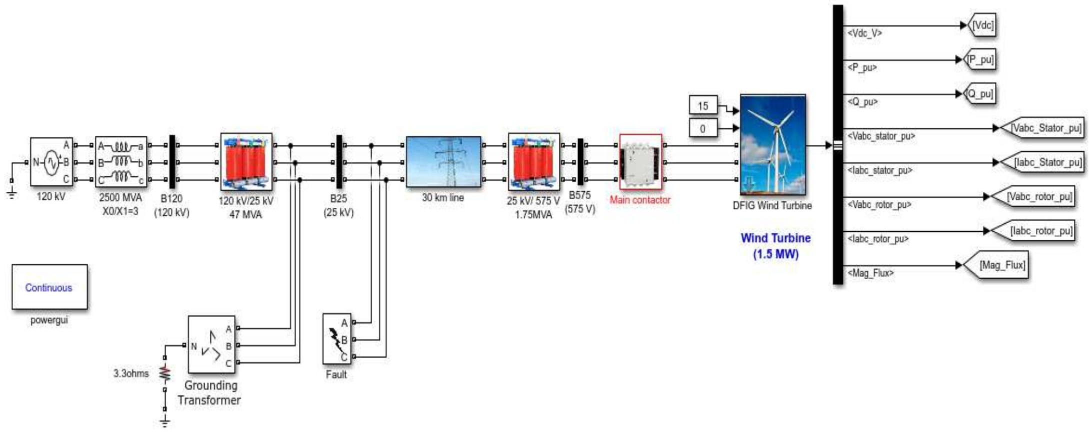

Figure (5.2) Power system connect to wind turbine simulation block diagram

In the block diagram of the Figure (5.2), a description of the used models from the Matlab Semolink Library to simulate the wind turbines under study in the several of Grid setuations. The study is incloding the normal Grid condition and all the faults under study, Which allows analyzing the contactor performance impacts on the of the behavior of DFIG generator during normal and transient power system conditions. And then study the effect of proposed protections in this study on the improved performance of the contector and DFIG and the feasibility of this addition.

5.1.1 Grid simulation blocks

This block shows a grid simulated components system used to model the power system to allow monitoring the status of grid conditions during simulation, the Grid side blocks are:

a) Three-phase source: The 120kv 3 phase voltage source is used to modeling the voltage system with possibility to program varying of voltage and its time variation. Where it can change the voltage amplitude, frequency of the Grid component at any time of simulation, to be able to study the Grid status at any time of the system variations.

b) Mutual Inductance: the Mutual Inductance is implemented a 3 phase balanced impedance. For balancing the simulated power systems, the 3 phase multi inductance block provides a suitable way to perform the system impedance.

c) Bus and V-I Measurement: The block is used to measuring the voltages and currents of the simulated power system and its connected elements through bus section, where it can be output the voltages and currents by in per unit (p.u) or in volts and amperes.

d) Transformer: This block is used to modelling the primary and secondary windings of the transformer to step-down the upstream voltages to suit voltage of the other side of the grid. The block provides the ability to specify the primary and secondary windings resistance and its inductance in per unit (p.u). The transformer power and voltage output values are based on its rated power, nominal frequency, nominal voltage and also its winding impedance.

e) Overhead line: The 3 Phase PI Section Line block is to representing the balanced overhead line model with their parameters. Where the line impedance is uniformly distributed along the distribution line. The model defined the line parameters with the assumption of the 3 phases are balanced, and also the phase impedance is deduced from the positive-and zero-sequence parameters where the line impedance is in ohms/ kilometer (Ω/km).

f) Phase Three Phase Source Block: This model consists of 3 individually circular and shutdown circuit breakers to model phase errors such as phase-to-phase disturbances, or phase-to-ground errors. This block is used to program a short circuit error between phase to phase or phase and ground

5.1.2 Contactor circuit specification

The contactor is an electromagnetic switch used to switching On/off the power electric circuit. Contactor has three components: the latching contacts, the movement of the armature and the electromagnet coil and movement spring. The figure (5.3) describe contactor components, this simulated model shows a contactor contacts with a return spring and magnetizing coil.

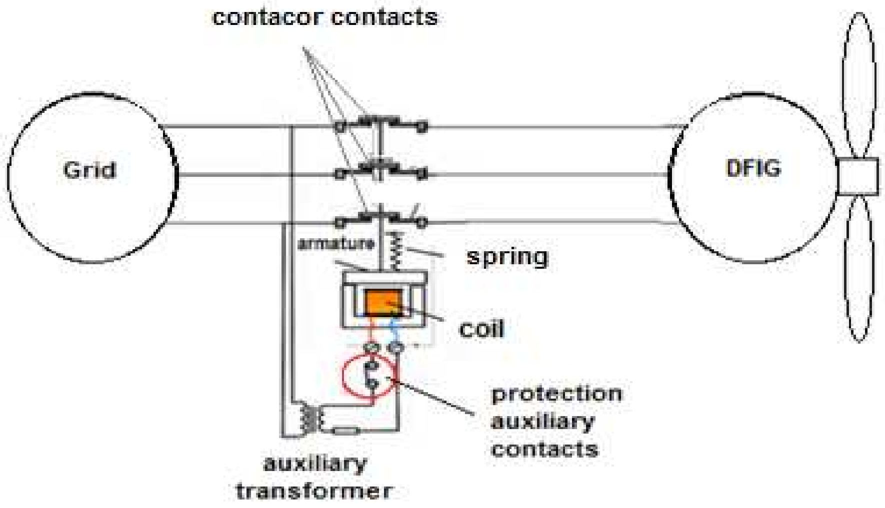

Figure (5.3) Contactor Components with armature and return spring

The contactor is modelled as a Reluctance and its number of coil turns where its movement force depends on the coil magnetic Flux, armature position and its return Spring Force. The coil generate electromagnetic force to magnetizing the armature and then move to close the contactor contacts.

5.1.2.1 Technical Specification of the Contactor

The contactor is a solenoid electromagnetic switching which is generally kept closed by a low current through the closing coils. Contactors are designed to carry out multiple switching operations which commonly controlled remotely by on/off pushbuttons, but the repeated operation cycles is standardized according to IEC 60947-4-part 4. The generator will be turned on/off constantly, this will require higher current loads and thus require a larger contactor, or contact points that have the potential to withstand these high currents during switching on/off. The specifications of any contactor are determined by the operating factors of the device to be connected to the electrical system, there for choosing the right standard code will increase the life time of the contactor.

Where the most important factors that help to choose the correct contector are:

- **Generator full Load Amperage at line to line Voltage**

  The first item to choose the right contactor is the load, which is the volume of current required to power the device at the system voltage, which is the value of current required to carry by contactor contacts during the device switching on/off at the system voltage. Therefore the nominal current of the generator and the operating voltage are the rated current and voltage of the chosen contector.

- **Contactor Coil Voltage**

  The control voltage to power the contactor, where the contactor typically use the system voltage to operate their contacts through the latching coil by generating an electromagnetic force by the network voltage applied to the ends of the coil. According to the factory requirements, generally, coil voltages are 250V or below for safety purposes. Coil operating limits according to IEC 60947-4-1 is 55 % of nominal line voltage.

- **Standard and code**

  The standard used to specify the type of electrical load and duty cycle of the load(s) to choose the correct type of contactor (ABB, 2014).

The selection of the appropriate contacto for the generator depends on the choice of the current intensity that the contactor contacts can carry during the operation of the machine which is called the Rated Operational Current of the contactor. This rated value is related to the nominal current of the generator that connected to the grid through these contactor contacts, the characteristics of these contacts are also related to the generator's operating voltage.

In this study, Contactor is used through the Matlab Semolink Library, which has been chosen according the specifications of the DFIG generator with a power capacity of 1.5 MW with a nominal current of 1800 Amp and 575 V AC.

The table (5.1) specify a three-phase contactor suitable for the applications such as Isolation and Distribution application up to max 1000 V, and its control coil operated with voltage range 100-250 V, AC/DC according to to IEC 60947-4-1

Table (5.1) The contactor specification (ABB, 2018)

No:	Description	Rate
1	Number of Main Contacts	3 No
2	Rated Operational Voltage	1000 V
3	Rated Frequency	50/60 Hz
4	Rated Operational Current AC	(690 V) 55 °C 1750 A
5	Rated Control Circuit Voltage (coil)	60 Hz 100 to 250 V

While the contactor Control Circuit is operating the mechanism of connecting and isolating the generator from the grid through controlling the contactor contacts. It is an internal operation of the contactor, which related to the contactor coil electromagnetic force that generated by 220V and armature return spring force Which is working to reopen the contactor contacts. Thus, the mechanism of the contactor depends on the magnetic field strength of the coils that depend on the nominal coil voltage and the return spring resistance force that keeping the contacts open.

The table (5.2) describe the contactor parameters. Since the contactor is isolating unit which responsible for connecting and disconnecting the generator to the public Grid when the operating order is taken from the control panel.

Table (5.2) The contactor simulation parameters (Nogueira, 2013)

Contactor Parameters	**Values**
Contactor Input voltage	220 V ac
Spring Force	3 N
No. of turns of contactor coil	5000 turns
coil resistance	600 Ω
μ_0	4π x 10^{-7}
μ_r	6001

Because the contactor is powered by an auxiliary transformer that transform the voltage from 575 volts to 220 volts ac to feed its internal coil that responsible to operate the contacts mechanism. The contactor mechanism depends on coil magnetic force that produced by transformed grid voltage. This coil magnetic flux generate a force to attract the contacts armature and its spring to close the electric circuit contacts of the wind turbine DFIG and then connect the generator windings to the Grid. The model in figure (5.4) is simulating the contactor mechanism to analysis its dynamic behavior of the electromagnetic force during normal and transient voltage source, where its behavior could interrupt the operations of the power generator.

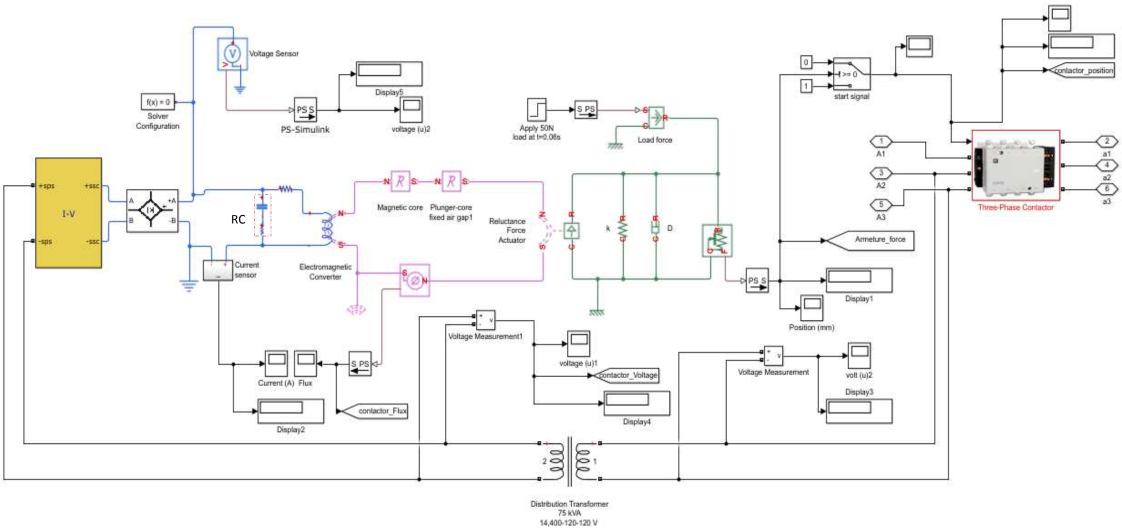

Figure (5.4) The contactor model in simulation

5.1.2.2 RC circuit add to the contactor coil as fault ride through

This proposed circout in this part of the research as a Fault Ride Trough solution according to FRT requirements to enable the contactor to keep the generator connected to the puplic network during Grid transiant faults. Capacitor and resistor RC circout will be add in parallel to the Contactor coils Which is referred as the part surrounded by an intermittent red line on Figure 5.4 and symbolized by RC to keep the contactor stay holding their contacts when the grid voltage source suddenly dip. So the contactor will stay energized for a few barude of time during voltage dip. The RC energized time depends on the capacitors value, the resistance of the contactor coil and the voltage dupplies the contactor coil during fault. According to equation (2.22), where coil resistanse and contactor voltage according to table Table (5.1) and the capacitance, C = 6 mF and the Vm= initial voltage across the contactor's coil during operation time.

5.1.3 Wind Turbine control system Block

Wind turbine transforms the incoming wind kinetic energy to mechanical energy through Gearbox, where the gearbox is the controlling mechanical power generated by the turbine input parameters (wind speed and pitch angle) to generate controlled torque rotate The generator, thus, to optimize the wind turbine torque, the turbine controller is feedback with signal representing the angular speed of the generator.

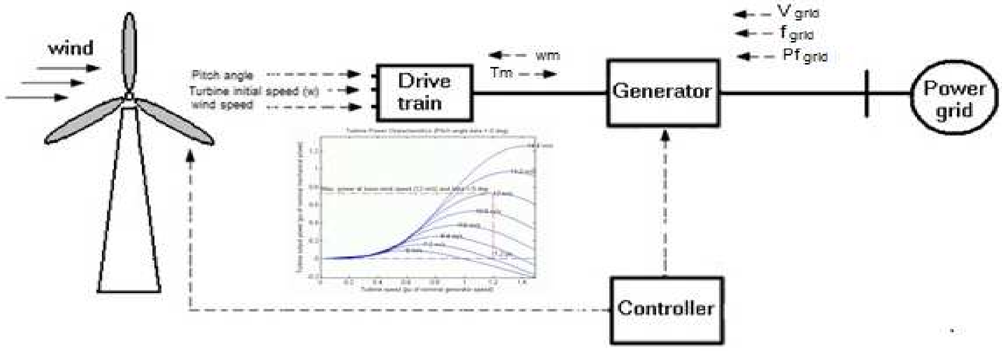

Figure (5.5) Overview of wind turbine

Figure (5.5) representing an overview of wind turbine mechanical and electrical parts that are modeled in this work. The figure shows the mechanical parts of the turbine that represented by Turbine drive train and the electrical generator which represented by Generator block, these parts are connected to the public Grid. It also shows the variables that act as control signals to complete the process of wind turbine controls. The simulation model used in this study is a modified version of the wind turbine with DFIG detailed model in the MATLAB/Simulink. Figure (5.6) representing the simulation which consists of Turbine drive train model that representing the mechanical parts of the wind turbine, and Double Squirrel-Cage Induction Generators model which representing the 1.5 MW doubly-fed induction generator with his power electronic converters.

The vector control technique is used to control the DFIG converters. The simulation studding the steady-state and instability in the grid that supply the DFIG generator, so the protection techniques (chopper, Dc Crowbar variable Resistor) are applied in this model. Table (5.3) describe 1.5MW wind turbine with DFIG simulated generator Parameters. Where the generator will be simulated in normal operation passing the steady-state to simulating the reality, and then the generator will be simulated in transient conditions represented by Grid faults. Through a fault duration simulation time, The model will simulate the system and analyzing the effects of the Fault transient occurring in the Grid and their impact on the voltage magnitude, current, flux and the power consumption of both contactor and generator, and then adding the proposed protections in this research and operating of the simulated system to study the impacts of these protections on the transient system and its effectiveness to achieve safe Ride through of the generator during Grid failures.

Table (5.3) 1.5MW DFIG Parameters (Gabriela, N et. al, 2015)

DFIG Parameters	**Values**
Rating	1.5 MW
Rated stator voltage (volt)	575 V
Rated voltage(volt)	1975
Number of pair pole	3
Stator resistance	0.023pu
Stator inductance	0.18 pu
Magnetizing reactance	2.9 pu
resistance	0.016 pu
inductance	0.16 pu
inertia constant of the generator	0.685 s

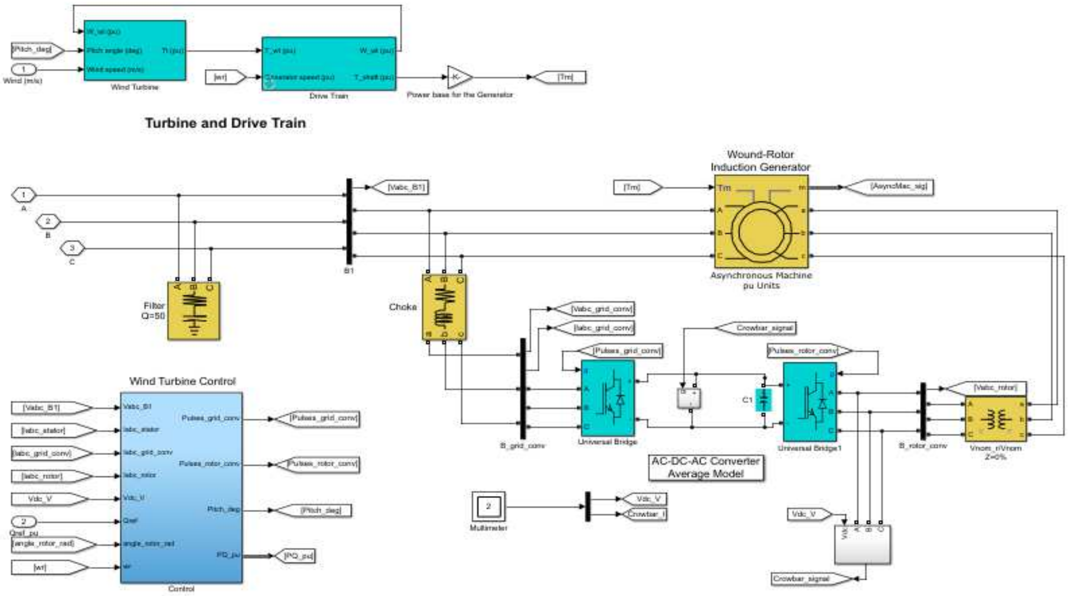

Figure (5.6) Simulation model of wind turbine with DFIG

The model in the figure (5.6) is a DFIG-based wind turbine based on the rated power characteristics under steady conditions, where the generator parameters are three inputs, engine speed, pitch angle and wind speed. This parameter is analyzed by Drive train model to get the turbine mechanical torque. The DFIG model consists of the Squirrel-Cage Induction Generator model and the converter. The stator windings of the DFIG generator are directly connected to the power grid and the DFIG rotor side is supplied by the PWM converter, where the converter must be side, rotor side (RSC) and grid side (GSC).

5.1.3.1 Turbine drive train controls

In the modeled of wind turbine, the dynamics of the conversion of wind velocity and wind rotation angle are not studied in this work, but they are applied as constant inputs that are mathematically analyzed and appeared in the model as a single gain. Also the pitch angle is constant until the active power reached to its rated value. Then, the PI-controller controls the rotating speed to achieve the highest gain of mechanical power from the kinetic energy of the wind velocity, and through the pitch angle control It is controlled and limiting the electromechanical torque to reach the synchronous speed of DFIG generator. The output of drive train model is the torque applied at the generator shaft.

5.1.3.2 Dublay fed induction Generator and its converter controls

Most DFIG wind turbines consist of a Double Squirrel Cage Induction machine that connects to public networks from two sides. The stator side is linked directly to the windings stator grid, while the rotor side is connected to the grid via the converter. DFIG converter has two sides, one connected DFIG to a power system channel called (GSC) converter and second side connected to DFIG rotor winding via a so-called ring slip (RSC) converter. The GSC converter is used to regulate the voltage of a DC link capacitor that supplies an RSC converter used to control and maintain the rotor voltage that supplies the rotor windings to produce a stable magnetic flux that excites the stator windings of DFIG to generate stapling power on the grid.

5.1.3.3 Grid side converter control

RSC converter functions to set DC voltage from DC bus capacitor to supply RSC converter with stable voltage. The vector control scheme has been used to control the voltage of the GSC converter, where the d-axis reference frame with d-q transforms to set the positive sequence of the grid voltage to control the current. Therefore, the DCC output DC Link voltage is controlled according to the current controller where the PI controller is used to obtain the current reference value to compare with the original dq value of the grid current, the resulting signal is again converted to the αβ reference to obtain the voltage grid and then fed to a PWM controller to generate a Grid side converter control signal.

5.1.3.4 Rotor Side Converter Control

The voltage controller is made to regulate and keep a constant terminal voltage value, so, the DFIG wind turbine system can be achieved at variable wind speeds. The strategy of a vector control is implemented to control the RSC converter, in which the voltage is reached as a function of the current and the approximate stator flux. Additionally, the phase model of locked loop (PLL) is used to increase the stator voltage and estimate the angle. Due to the *d* current is proportionally to power and torque of the stator. thus, the voltage control is subjected to the variation in torque and generator power. In this controls, because the current is referred to the stator, so the Rotor components are referred to stator measurement stage. Therefore, the voltage and current will be in *dq* coordinates, then the values will be transformed back into *abc* reference during converter control process.

5.1.4 Proposed variable Crowbar specification

In this section, two types of protection have been modelled, the first protection is chopper resistor controlled via GPIT thyristor has added in parallel to the Voltage link capacitor converter where the chopper resistor = 1 ohms, the second protection is crowbar with DC resistor in parallel to the rotor windings, the crowbar resistor is consists of 3 resistors series, each Resistor is connected in parallel to an ideal switch working via a gate that makes the resistors Perform variable resistance function and increasing according to the value of the gate determined by the DC voltage link. This proposed protection is added in parallel to rotor windings. The purpose of these two baths, which has suggested to be added together in this study, is to protect the convertor during transient grid faults.

5.1.4.1 Crowbar protection specification

the active crowbar is a sit of DC Resistors placed in parallel to the rotor winding of DFIG to damp the increase of the current when the transient is appeared in the power system to resume normal operation during and after fault duration. The crowbar circuit consists of 3 phase diode rectifier with IGBT thyristor and set of DC resistors controlled on/off by IGBT switches. the DC resistores must be larger than the rotor windings to function as shunt resistor on the rotor side of the generator to limit the transient current on rotor windings and also to avoid a high voltages in the RSC converter. There is no specific value for the crowbar resistance, but it ranges from 30 to 400 ohms according to previous studies and some wind power generators factories that use this type of protection. Gabriela N.& Sonia L(2015) suggested in their study crowbar Resistor = 50 times the DFIG stator resistance, while some Vendors such ABB using crowbar Resistor = 200 and 400 Ohms depending on the converter used on the wind turbine (ABB, 2011).

5.1.4.2 Chopper protection specification

A chopper is DC resistor connected to the DC bus of the converter to prevent its uncontrolled increase voltage during grid disturbance, the value of this resistance is 1 Ohms (ABB, 2011).

This study combines these two types of protection, chopper with a value of 1 ohm and a variable crowbar resistor that varying according to the DC voltage variation caused by the voltage dip. The values of resistors are 50 times stator resistance to increase due to DC bus voltage to reach 300 times starter resistance of the starter depending on the severity of the grid voltage dip.

5.1.5 Wind Turbine electric protection

Wind turbine protection system is electronic device used to monitoring of the voltage, current and machine speed to protect the system from any disturbance in these variables that may causing the damage to the generating unit or the whole system. Which requires protection in accordance with the manufacturer's recommendations and the requirements of the system linked with this equipment. Table (5.3) describes the settings of turbine protection.

Table (5.3) DFIG wind turbine protection settings (Markiewicz, H, 2004)

Parameter	Setting Value	Trip Time Delay
Instantaneous AC Overcurrent	140%	Instantaneous
AC Overcurrent (positive-sequence)	10 times	instantaneously
AC Current Unbalance	110%	$T = K\ relay\ seting/({}^{i}/_{I_{fl}})^2$ sec
AC Overvoltage (positive-sequence)	40%	0.2 seconds
AC under/over (Voltage)	35% / 110%	0.15 seconds
AC Voltage Unbalance (Zero-sequence)	5%	0.2 seconds
DC Overvoltage	1900 V dc	1ms

5.2 Simulation Results analyses

In this part, the model for a two-fold induction-driven wind turbine connected to the power system through the main Contactor will be operated during the normal and temporary power system state, where the simulation will analyze the operating state to study the behavior of the FFIG model. The simulation system is connected to 120 kV, a three phase source connected to a 1.5 MW wind turbine through. Lower the transformer, error protection and 30km transmission line, where the system is simulated during normal operation to analyze steady conditions of wind turbine and main contactor. Then, the system is simulated at symmetrical and asymmetrical voltage dips to analyzing the behavior of the wind turbine and it's Contactor in each case of Grid faults. The impact of the faults on the model under study is analyzed and determined the extent of their effects on the simulated system. The suggested protection will be applied to both the generator and the contector to determine the feasibility of the proposed FRT protection solution to achieve the safety fault ride through for DFIG generator during different status of voltage dip. The sequence of a study conducted that followed in this chapter was as follows:

First part, the case of Power system normal conditions, to determine the behavior of the generator and its Main contactor during normal Grid conditions.

Second part, in case of symmetrical fault, where (80%, 60%, 40% and 20%) voltage dips is generated by the main voltage source, and then respectively applied to the simulated system. These ratios of the voltage dips on the DFIG wind turbine were adopted as a case of study to indicate the different grid conditions affecting the behaviour contector to show the effect of the contector disturbances on the generator performance.

Third part, symmetrical three phase faults and asymmetrical fault case, two phase to ground, two phase, and single phase to ground are respectively applied at bus (B25) .

The duration of the applied faults in all study cases (symmetrical and asymmetrical faults) is 150 ms (Naderi, 2015). All the protection techniques were applied and removed in a predefined time irrespective of the DFIG readings. The following sections show the simulation results and its discussions.

5.2.1 Simulation Result of wind turbine under Normal Grid Conditions

Grid-connected simulation DFIG is a study under normal power system operation, to study the basic behavior of DFIG wind turbine and its control under normal operating conditions. Wind turbines connected to the Grid are simulated during normal network conditions, before an error occurs on the grid. Because the induction generator is directly connected to the grid, the main contactor is required to ensure connection and disconnection during controls and protection purposes, where the main contactor between transformer and DFIG generator is mandatory. In the simulation, the Main contactor is modeled, and simulated to connect and disconnect the DFIG from the grid to study its behavior during normal power system operation. During wind turbine operation characteristics and When the wind turbine mechanical controls giving order to generator to connect to the Grid, The contactor will operated to close its contacts, In this case, its lurching coil will be supplied by grid voltage via the 575/220 volt axillary transformer to generate magnetic force to move its armature to close its contacts and then connect the DFIG generator windings to the grid. This contactor On/Off status and DFIG generator operation mechanism are simulated. This section is concerned with studying the effect of the Grid voltage on the main conductor mechanism, and then the effect of the contector Behavior on the performance of the DFIG generator.

During simulation, the system was completely stable because of the system is clear from any faults. The wind turbine reached its Steady state at 2.8 seconds of simulation time, when the power output of the wind turbine generator is near to 1.5 MW. The figures below shows the simulation Results of DFIG under normal operation during 0.6 seconds.

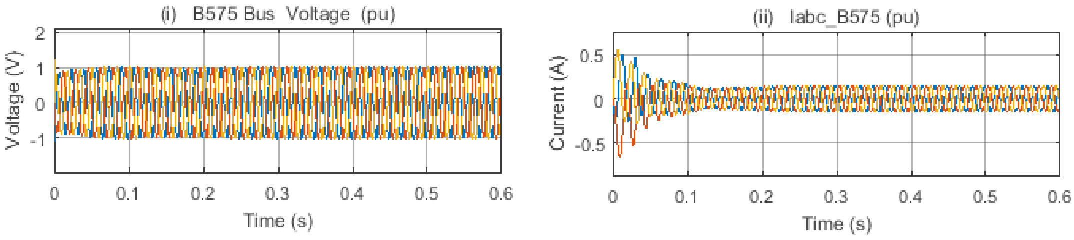

Figure (5.7) simulation results of DFIG bus B-575V (i) voltage of the DFIG bus B-575V (p.u), and (ii) current of the Bus B-575 current (p.u)

During normal operation of simulated system, as showed in figure (5.7) the bus B575 voltage is closed to 1p.u. And the Iabc bus B575 current is greatly increased as a result of the start-up time, Which simulates the starts of operation time of the DFIG generator, where the current on bus B575 is fluctuated between 0.6 to 0.2p.u for an interval time of 0.1sec, Then it returned and settled at 0.15 p.u within the remaining simulation time. At the startup time of the simulation of Main contactor is operated to connect the DFIG to the Grid. Where the 575/240 auxiliary transformer fed the contactor coils 240 V ac to generate an electromagnetic force that magnetizing the contactor contacts to close, thereby lnking the windings of the generator to the grid and begin the process of generation by the generator.

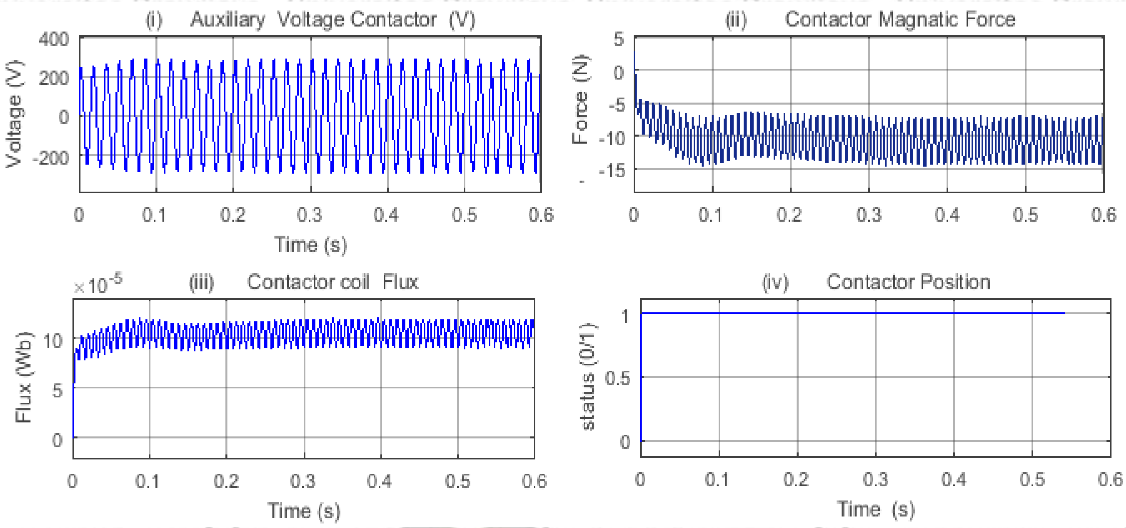

Figure (5.8) simulation results of contactor statues at normal operation of DFIG connected to the Grid when figure (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor.

After startup condition, when the wind turbine reaches its desired wind speed, at syncronouse speed of DFIG, the turbine controls orders the DFIG generator to connected to grid via its main contactor, then the contactor close its contacts to connect generator windings to the grid. Figures (5.8) shows the contactor voltage, contactor coil generated flux, the contactor armature movement and its contacts position during normal operation. As shown in the voltage curve Fig. 5.8 (i), thus, the voltage is existing the magnetic coil to generate a magnetic flux, Fig. 5.8 (ii) shows the magnetic flux that generated a magnetic force that moves contactor armature to move its contactor contacts, then closed. Fig. 5.8 (iii) describes the changing of armature positions as a result of its attraction has magnetized to close its contacts due to the coil electromagnetic force. The armature is connected to the contactor contacts and its spring. Thus, the magnetic force of attraction affecting the armature also works to change the position of the contacts from opening status at 0 to the closing position at 1, Fig. 5.8 (iv) describes the statues of contactor, when in position 0 is open contacts and thus the generator is disconnected from the Grid and the 1position is close contacts, therefore the contactor connect the generator to the Grid.

During normal operation, the modeled DFIG generator is being connected to the Grid to start its running process automatically. Wind turbine is generated power at synchronous speed, when the generator used the grid voltage to produce constant voltage on the winding to produce electromagnetic torque, to reach the point of system stabilization, which called steady state, which is when the generator produced its nominal active power. Thus, to steady the behavior of system values, such as the DC-Link voltage and stator flux As well as the active and reactive power. The figure (5.9) shows the performance of the DFIG wind turbines during normal operation where there were disturbances due to start-up and wind turbine is operating normally.

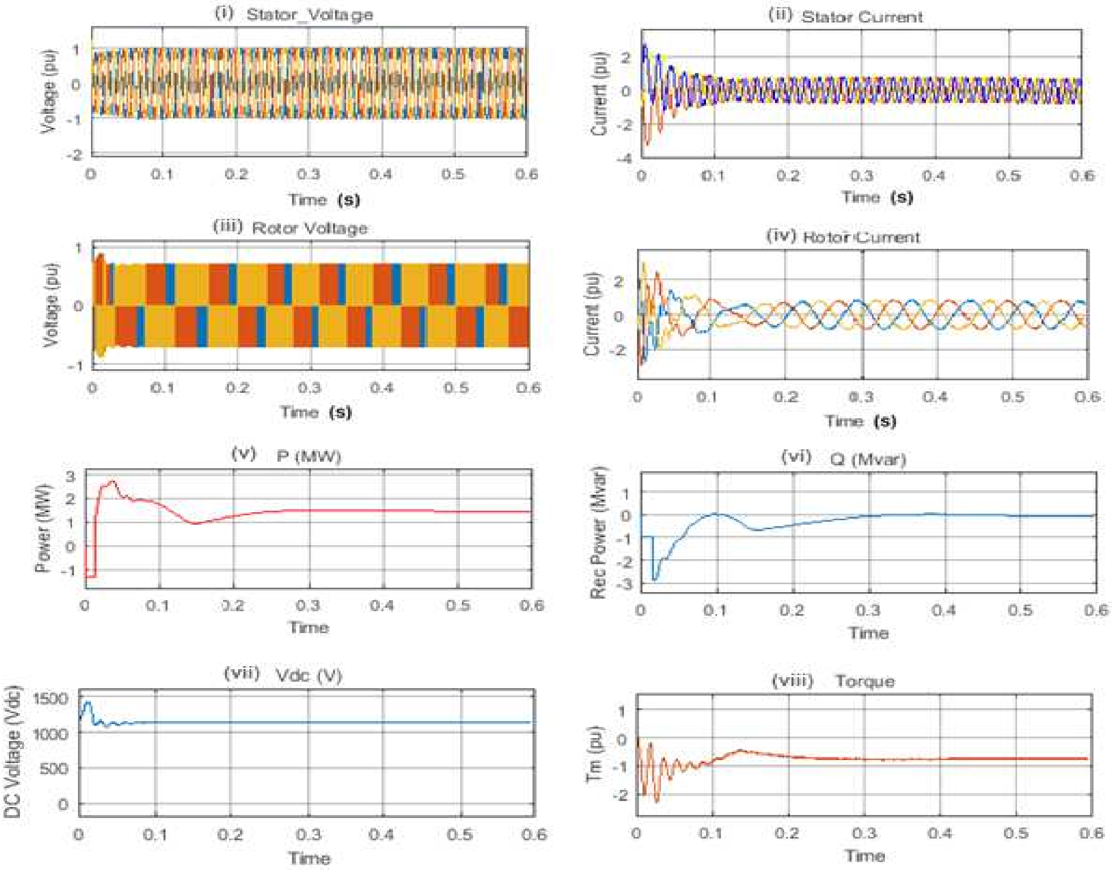

Figure (5.9) the simulation results of DFIG connected to the Grid at normal operation, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current. The (v) describe the active power statues, the curve (VI) describe the reactive power statues, curve (vii) shows the Dc voltage and the curve (viii) describe the electrical torque statues.

During the simulation time, the stator voltage is settled as 575 V which is measured and shown in Figure 5.9 (i), the voltage is constant at 1p.u. And stator current is measured and shown in Figure 5.9 (ii), the current is fluctuate between 3 to 1p.u for an interval time of 0.1sec. Then returned and settles at 0.8p.u for 6sec. The voltages is settled as 1975 V, megured and showed in figure 5.9 (iii), its value is constant at 1p.u. The currents of DFIG also measured and shown in 5.9 (iv), where fluctuated between 3 to 1p.u for an interval time of 0.1sec. Then returned and settles at 0.8p.u for simulation time 6sec. Wind turbine is generated power at synchronous speed, when the generator used the grid voltage to produce constant voltage on the winding to produce electromagnetic torque, to reach the point of system stabilization, which called steady state.

During simulation, the system reach its steady state condition near the nominal generator power which is 1.5 MW. This condition is appeared in figure 5.9 (v) where the active power extracted from the wind turbine DFIG and stabled at 0.28 second of simulation time. It is marked that the active power generated is injected into the Grid and the reactive power is controlled to zero. It is also observed in Figure 5.9 (vii) that the DC bus voltage is set at 1100 V. The electric torque is also set at 0.2 p.u as shown in Figure 5.9 (viii). All parameter stability of the DFIG generator is observed when it reaches steady state. Thus, these studied states are presented in figure (5.9) is being a reference point for the following simulation works where these system parameters are analyzed under grid fault conditions.

5.2.2 Simulation Result of DFIG under symmetrical and asymmetrical Grid fault conditions

In this part, the behavior of ac contactor and its impact on the wind turbine and its DFIG genera during power system transient faults is studied. Where the contactor behavior during Grid faults on occasion effect the generator and disconnect it from the Grid, which was necessitated studying the effect of this outage in the generator.

5.2.2.1 Simulation Result of DFIG under symmetrical Grid fault Conditions

Assumed a voltage dip occurs by voltage source at 0.3 sec and cleared at 0.45s of simulation time. Where the wind turbine starts its operation possess normally and the main contactor closed its contacts to connect the DFIG generator to the Grid. After the generator reach the steady state and started injecting power into the Grid, the simulated voltage source is started to create symmetrical voltage dip at 0.3sec, The fault continue for 150 milliseconds and then disappeared at 0.45s of simulation time, where the DFIG start recovered to its normal statues. In the meantime, the behavior of the generator and its contactor studied during (80%, 60%, 40% and 20%) of grid voltage symmetrical dips. The contactor voltage, contactor coil magnetic flux and its latching contacts status was monitored. As well as the Bus B575 its voltage and currant and the DFIG Wind turbine starter voltage, starter current, voltage, current, DC-voltage and output active and reactive power Were subject to study and observation.

5.2.2.2 Simulation Result of DFIG under 80% symmetrical voltage dip

In this part, the simulated voltage source is applied 80% symmetrical voltage dip at 0.3s, the fault continue for 150 milliseconds and then disappeared at 0.45s of simulation time.

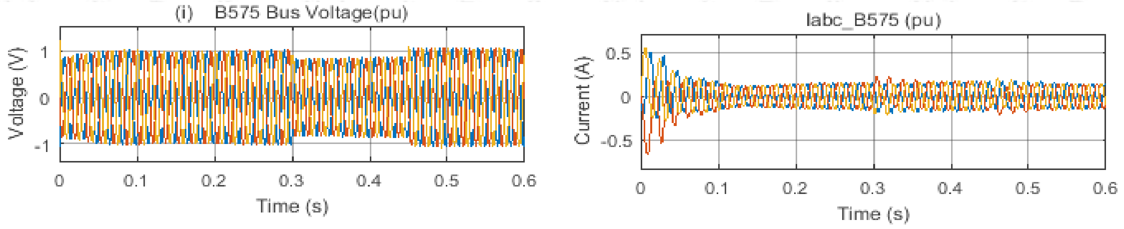

Figure (5.10) simulation results of Bus B575 at 80% symmetrical Grid voltage dip when (i) curve shows the Bus bar voltage, (ii) curve shows Bus bar current.

The figure 5.10 (i) shows that the bus voltage B575 is constant at 1 p.u until the voltage dip appeared then suddenly decreased at 0.3 sec of simulation to recover at 0.45s to reach its normal condition 1 p.u. Figure 5.10(ii) the Bus B575 current is fluctuate at startup for an interval time of 0.1sec, then stabilize at 0.15p.u until the voltage dip appeared at 0.3s, then the current fluctuated between fluctuate between 0.23 to 0.17p.u until transient disappeared at 0.45s to stabilized after that to 0.15p.u.

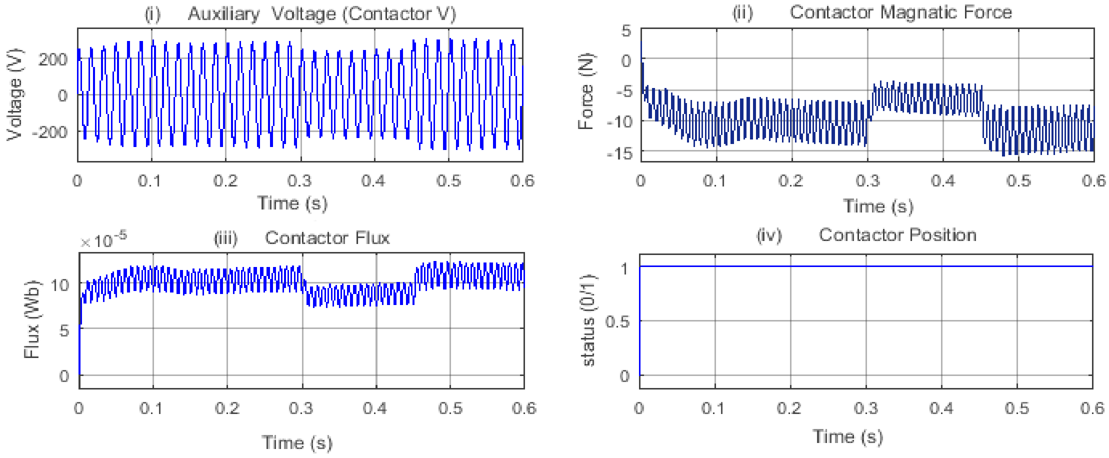

Figure (5.11) simulation results of DFIG Main Contactor statues at 80% symmetrical Grid voltage dip when (i) curve shows the auxiliary contactor voltage, (ii) curve shows contactor coil flux value, (iii) describe the contactor coil electromagnetic force, and (iv) describe the statues of contactor (on or off).

The figure 5.11shows 80% Grid voltage dip impact on the main contactor responsible for connecting the DFIG generator to the power system. When Figure 5.11(i) shows the auxiliary contactor voltage is constant at 240 V until the voltage appeared then suddenly decreased at 0.3 sec then suddenly decreased to 210V to recover at 0.45s when the voltage dip appeared to reach its normal condition. Figure 5.11(ii) shows the contactor coil flux where its value stabled at 12 x10^{-5} Wb, then voltage suddenly decreased at 0.3 sec suddenly decreased to Followed by magnetic flux to decrease to 9 x10^{-5} Wb until voltage dip disappeared at 0.45s to stabilize at 12 x10^{-5} Wb again. Figure 5.11(iii) describes the changing of contacts positions as a result of coil attraction to close its contacts duo to the coil electromagnetic force. at 0.3 sec sudden voltage dib appeared, which affect the magnetic flux to decrease the coil magnetic force Thus, the armature distance traveled by this force decreases to 4N which still greater than the strength of return spring of the contacts thus the contacts remain close, after voltage dip disappeared the force recovered back to 10N at 0.45s. Since the contactor's contact movement force is still sufficient to remain closed during 80% of the voltage drop, the contacts mode remains in the close, (1) status, 5.11(iv) shows the state of the contactor contacts during the voltage drop where The contector still connected its contacts, thus the generator continues connecting to the grid.

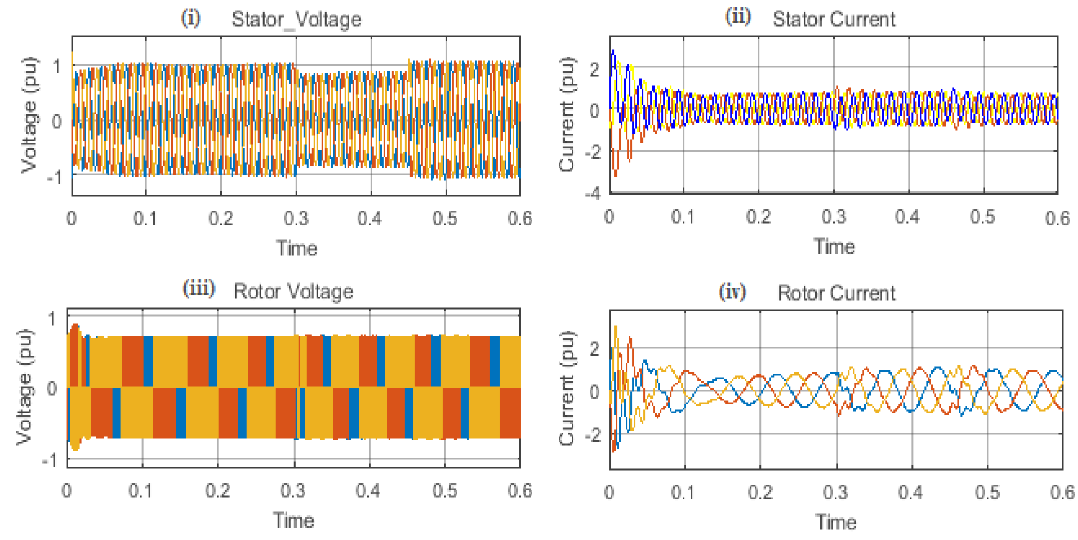

Figure (5.12) the simulation results of DFIG connected to the Grid at 80% symmetrical Grid voltage dip, when (i) the stator voltage, (ii) shows the stator current, (iii) the rotor voltage, (iv) shows the rotor current.

The figure 5.12(i) shows that the stator voltage is constant at 1 p.u until the voltage dip appeared then suddenly decreased at 0.3 sec to 0.8p.u until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.12(ii) the stator current is fluctuate at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3s, then the current increased to 1p.u until transient disappeared at 0.45s to stabilized after that at 0.8p.u. The figure 5.12(iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared then suddenly disturb between 0.72 to o.75 p.u at 0.3 sec until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. Figure 5.12(iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, then the current increased to 1p.u until transient disappeared at 0.45s to stabilized after that at 0.8p.u.

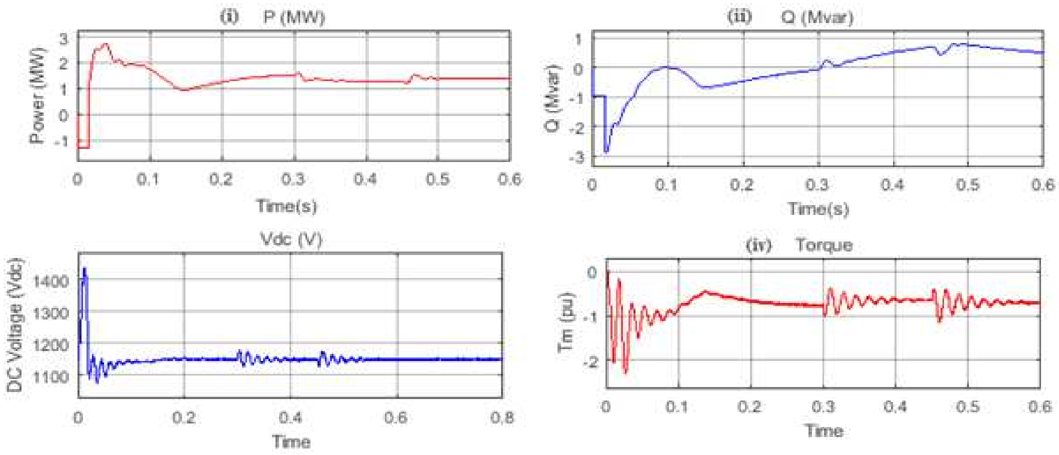

Figure (5.13) the simulation results of DFIG connected to the Grid at 80% symmetrical Grid voltage dip, when The (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in the figure 5.13(i) is describe the statues of active power, when the active power overshot during the startup time to reach 2.8MW then drops nearly to 1MW to stable to 1.5 MW at 0.28 s, when the voltage dip appeared at 0.3sec, Active power drops nearly to 1.3 MW, then start recovered at 0.45s. as its shown in the Figure 5.13(ii) Reactive power is interrupted during startup time the reactive power interrupted between -3 to 0 Mvar at o.1 sec then stabled near to zero at 0.28, when the 40% voltage dip appeared at 0.3s, the generator start to absorbs a reactive power from the grid to reach 0.8 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. Figure 5.13(iii) shows increase in the DC voltage which reach a value 1500 Vdc at startup to stable to 1150 Vdc, at voltage dip duration DC-link voltage interpreted but that not exceeding the rating of capacitor which is acceptable. The Figure 5.13 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u pu which is still acceptable.

5.2.2.3 Simulation Result of DFIG under 60% symmetrical voltage dip

In this part, a 60% voltage dip takes place in the system at 0.3 sec. to 0.45 sec. of simulation time.

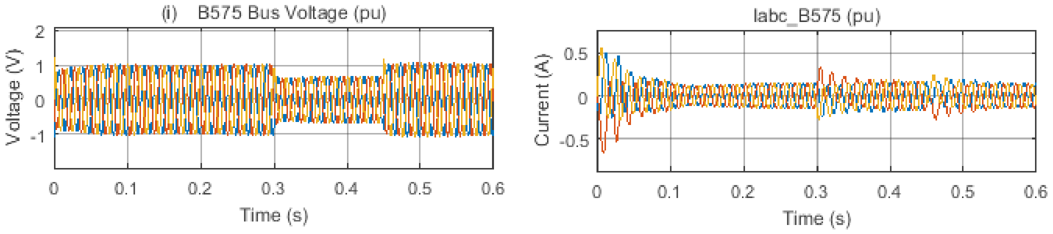

Figure (5.14) simulation results of Bus bar number B575 at 60% symmetrical Grid voltage dip when (i) the Bus bar B575 voltage, (ii) the Bus bar B575 current.

Figure 5.14(i) shows that the bus voltage B575 which has constant at 1 p.u until the voltage dip appeared, then voltage suddenly decreased to 0.6 p.u at 0.3 sec of simulation to recovery at 0.45s to reach its normal 1 p.u. again. Figure 5.14(ii) shows the Bus B575 current, its fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.15p.u until the voltage dip appeared at 0.3sec, then the current fluctuated between fluctuate between 0.35 to 0.2p.u until transient disappeared at 0.45s to stabilized back after that to 0.15p.u.

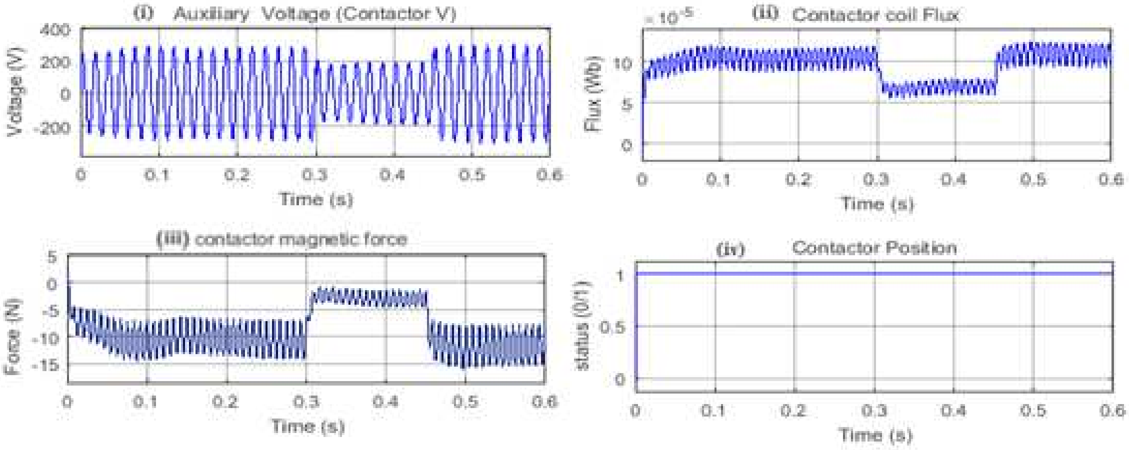

Figure (5.15) simulation results of DFIG Main Contactor statues at 60% symmetrical Grid voltage dip when (i) the auxiliary contactor voltage, (ii) contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor.

The figure 5.15 shows 60% Grid voltage dip effects the main contactor of the DFIG generator. When Figure 5.15 (i) shows the contactor voltage is constant at 240 V until the 60% voltage dip appeared in the system, then the voltage suddenly decreased at 0.3 sec to 180V to recover at 0.45s when the voltage dip disappeared. Figure 5.15 (ii) shows the contactor coil flux where its value stabled at 12 x10^{-5} Wb, during voltage dip at 0.3sec, the magnetic flux decreased to 7.5 x10^{-5} Wb until voltage dip disappeared at 0.45sec to stabilize at 12 x10^{-5} Wb again. Figure 5.15 (iii) shows the contactor coil magnetic force, during voltage dip at 0.3sec, the armature magnetizing force is at 2N to recover back to 10 N at 0.45sec after voltage dip disappeared. Since the contactor's contact still sufficient to remain closed during 60% of the voltage drop, the contacts statues remains in the close, (1) status, figure 5.15 (iv) shows the state of the contactor contacts during the voltage drop, where the contector still connected its contacts, thus the generator continues connecting to the grid.

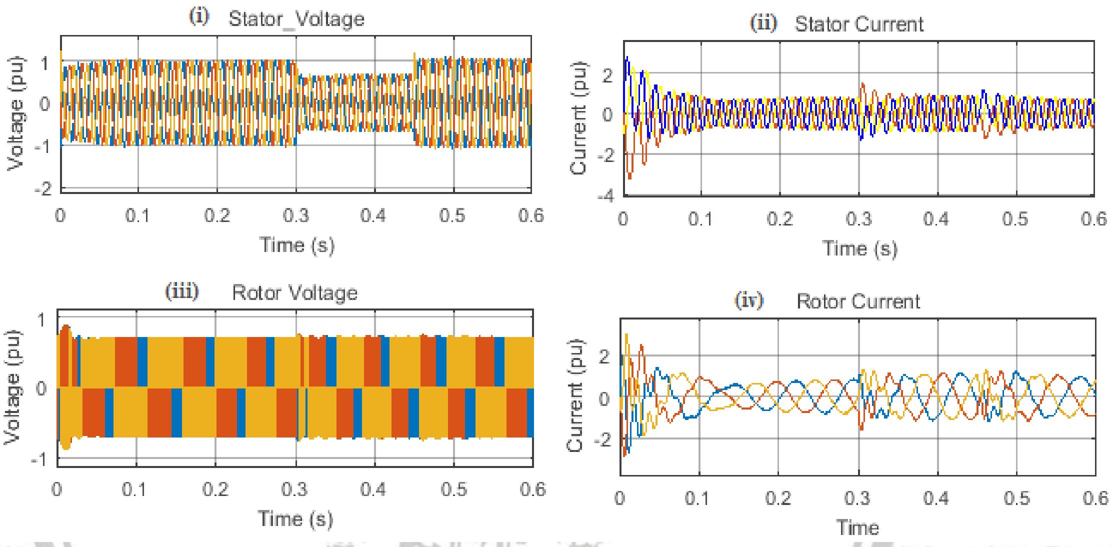

Figure (5.16) the simulation results of DFIG connected to the Grid at 60% symmetrical Grid voltage dip, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.16(i) shows the stator voltage, where it was constant at 1 p.u until the voltage dip appeared, and then the stator voltage suddenly decreased to 0.8p.u at 0.3sec until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.16(ii) the shows that stator current is fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.8p.u until the voltage dip appeared at 0.3s, after it, the current increased to 1.1p.u until transient disappeared at 0.45s to stabilize at 0.8p.u again. The figure 5.16(iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared at 0.3sec, then suddenly disturb between 0.7 to 0.72 p.u until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. Figure 5.16(iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, then the current increased to 1.1 p.u until transient disappeared at 0.45sec to stabilized after that at 0.8p.u.

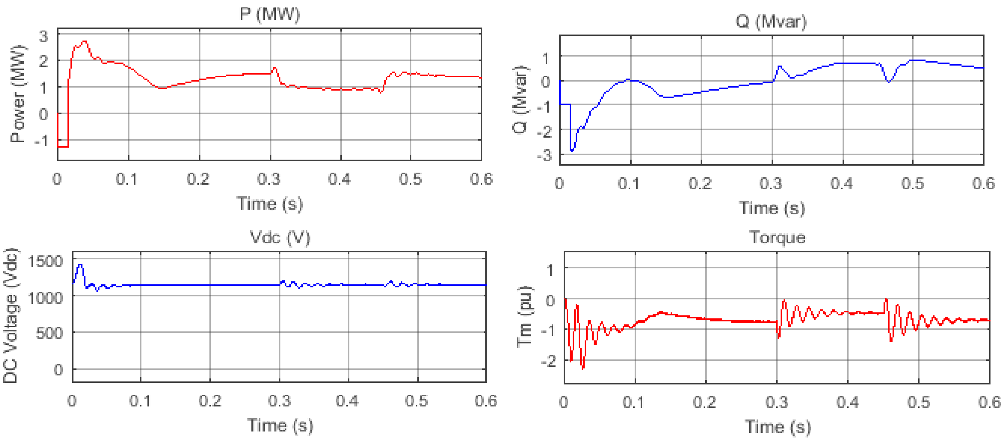

Figure (5.17) the simulation results of DFIG connected to the Grid at 60% symmetrical Grid voltage dip, when The curve (i) describe the active power statues, the curve (ii) describe the reactive power statues, curve (iii) shows the Dc voltage and The curve (iv) describe the electrical torque statues.

The simulation results in figure 5.17 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 1MW, then start recovered at 0.45s. In Figure 5.17 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the 40% voltage dip appeared at 0.3s, the generator begins to absorb the reactive power of the grid up to 0.8 Mvar before the voltage drop disappears, at 0.5 seconds the system begins to recover. Figure 5.17 (iii) shows an increase in DC-link voltage to achieve a value of 1500 Vdc at startup stable to 1150 Vdc, at a voltage dip the duration of the DC-link voltage is interpreted but it does not exceed the acceptable capacitor rating. The Figure 5.17 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u pu which is still acceptable.

5.2.2.4 Simulation Result of DFIG under 40% symmetrical voltage dip

In this part, 40% voltage dip takes place from 0.3 sec. to 0.45 sec.

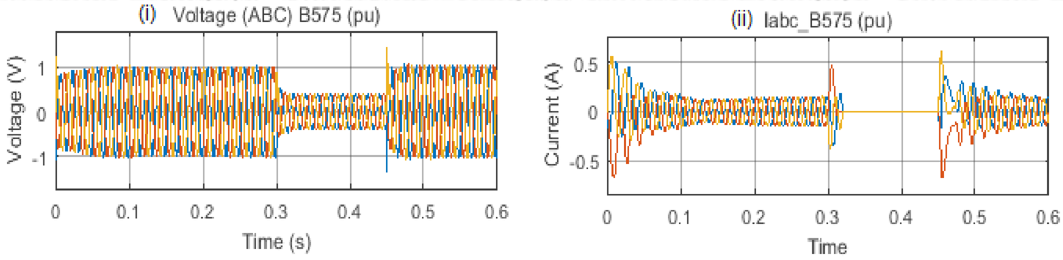

Figure (5.18) simulation results of Bus bar number B575 at 40% symmetrical Grid voltage dip when (i) curve shows the Bus bar voltage, (ii) curve shows Bus bar current.

As shown in Figure 5.18 (i), at 0.3 sec the voltage on Bus B575 is dipped to 0.4 p.u, this leads to current transient in the bus B575 as shown in figure (ii), Currents disturbed to 0.5 p.u then stabled at 0 until the voltage dip disappeared to disturb gain to reach 0.6 p.u, then start recovery.

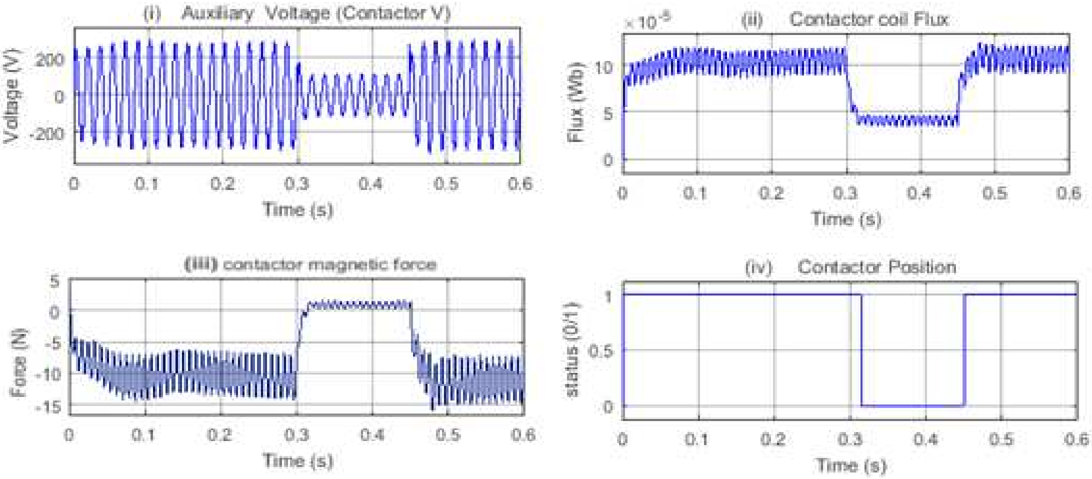

Figure (5.19) simulation results of DFIG Contactor statues at 40% symmetrical Grid voltage dip when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor(on or off).

The figure 5.19 shows 40% Grid voltage dip is effect the main contactor coil terminals. Figure 5.19 (i) shows the contactor voltage is decreased at 0.3 sec to 100V, this caused a sharp drop in the electromagnetic force of the coils as shown in figure 5.19 (ii), which led to the opening the contacts as a result of the armature return spring movement force is greater than the coil magnetic force, This situation caused the contactor opening its contacts then cutoff the DFIG generator from the power system. At 0.45sec the grid voltage recovered and fault disappeared. Therefore, the contactor force stabilized at 12 x10-5 Wb again then contactor close its contacts to connect the generator to the grid then wind turbine recovered.

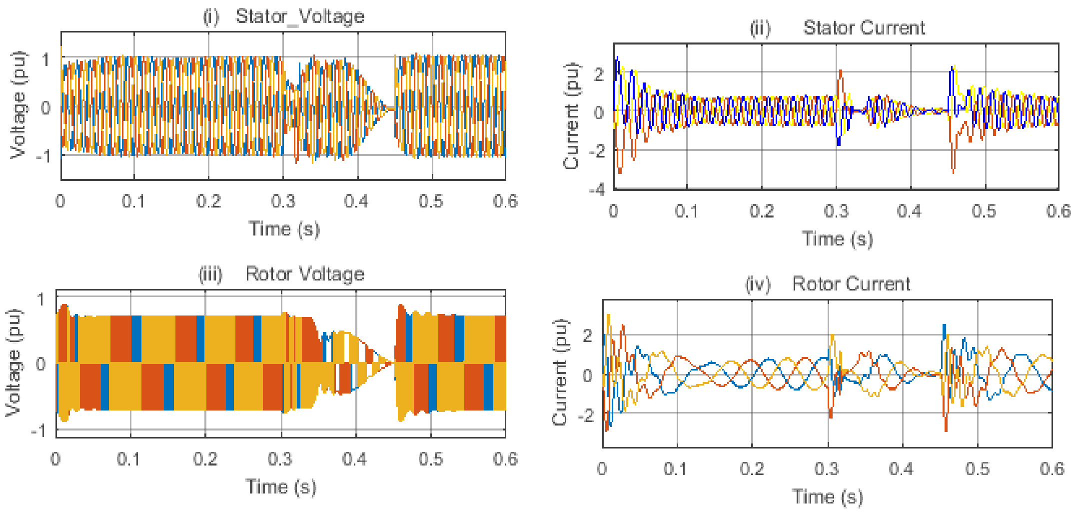

Figure (5.20) the simulation results of DFIG connected to the Grid at 40% symmetrical Grid voltage dip, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.20 (i) shows a voltage going regularly until the 40% Grid voltage dip appeared in the system at 0.3sec of simulation time, then stator voltage disturbed, but this voltage is very short, therefore it does not cause the generator to be protected. During voltage dip affects, the stator voltage appeared at 0.3 to 0.1sec as a result of the presence of DC link voltage with the turbine rotated at a synchronous speed, this situation leads to oscillations of the stator voltage imbalance. As well as the stator current has significant deterioration as shown in Figure 5.20 (ii) , when the current disturbed to reach up to 2 p.u then stabled at 1.1 until the voltage dip disappeared to disturb gain to reach 2.4 p.u, then voltage dip disappear and start current recovery. Figure 5.20 (iii) shows a voltage fluctuation in rotor, it also as a result of the DFIG generator is disconnected from the grid in case of contactor fault effects. At 0.3, short v disturbance in the voltage made it reach its value 0.78 p.u. During voltage dip affects, the voltage appeared at 0.3 to 0.45sec as a result of the presence of DC link voltage with the turbine rotated at a synchronous speed. At 0.45, the voltage fluctuated again to reach its highest value 1.1 p.u for short time. After voltage dip disappeared, the voltage recovery to its operation value. Figure 5. 20 (iv) shows the impacts of current, when the current disturbed to reach up to 2 p.u then stabled at 0.8 p.u until the voltage dip disappeared at 0.45sec to disturb gain to reach 2.4 p.u, then the current recovery.

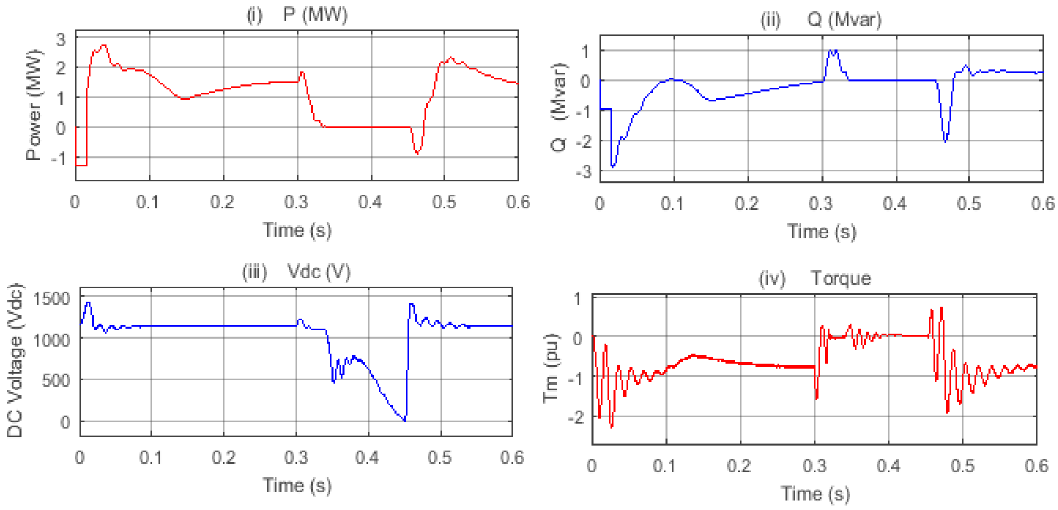

Figure (5.21) the simulation results of DFIG connected to the Grid at 40% symmetrical Grid voltage dip, when The curve (i) describe the active power statues, the curve (ii) describe the reactive power statues, curve (iii) shows the Dc voltage and The curve (iv) describe the electrical torque statues.

The simulation results in figure 5.21 (i) shows the active power is significantly reduced to Zero MW as a result of the generator outage from the Grid due to the impact of the contactor by the voltage drop. And also the reactive power affected this reason, as shown in 5.12 (ii). In Figure 5.21(iii), the DC-link voltage gradually discharged during the time period of the fault and rises rapidly as the fault disappeared. This voltage discharge explains the presence of voltage on the rotor and stator during the fault. The Figure 5.21 (iv) show the torques is significantly reduced to Zero at voltage dip period, After the fault is disappeared, the torque momentum appears to be disturbed but at the allowable range, and then begins to recovery.

5.2.2.5 Simulation Result of DFIG under 20% symmetrical voltage dip

In this part, 20% voltage dip takes place at 0.3 sec. to 0.45 sec.

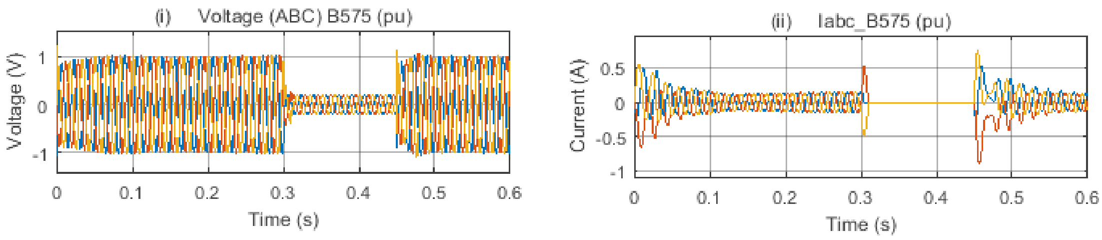

Figure (5.22) simulation results of Bus bar number B575 at 20% symmetrical Grid voltage dip when (i) curve shows the Bus bar voltage, (ii) curve shows Bus bar current.

The results Figure 5.22 (i) shows that the bus B575 voltage is dipped to 0.2 p.u, this leads to current transient at in the bus B575 as shown in figure 5.22 (ii), the current reach 0.5 p.u at the beginning of volte transient then immediately drop to zero in the bus B575, then, Currents disturbed again at 0.45 sec to reach its Highest value 0.76 p.u then then start recovery.

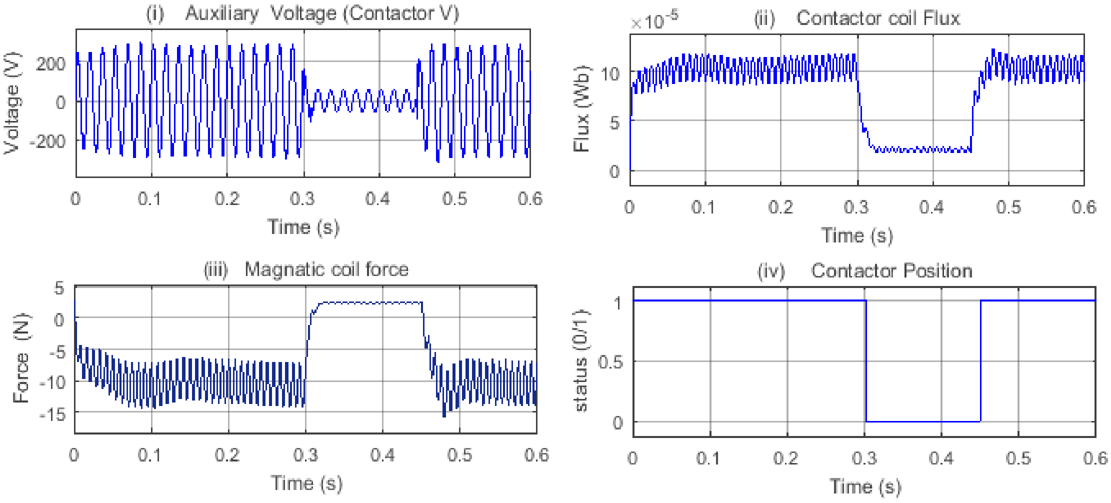

Figure (5.23) simulation results of DFIG Contactor statues at 20% symmetrical Grid voltage dip when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor(on or off).

The figure 5.23 shows the effect of 20% Grid voltage dip on the main contactor coil terminals. Figure 5.23 (i) shows the contactor voltage is decreased at 0.3 sec to 56V, this caused a sharp drop in the electromagnetic force of the coils as shown in figure 5.23 (ii), which led to the opening the contacts as a result of the armature return spring movement force is greater than the coil magnetic force, this appeared in Figures 5.23(ii) and (iii), This situation caused the contactor lost its magnetic force then opened its contacts then cutoff the DFIG generator from the Grid. At 0.45sec the system fault disappeared.Therefore, the contactor magnetic flux recovered to stabilize at 12x10-5 Wb again then contactor close its contacts to connect the generator to the grid then wind turbine recovered.

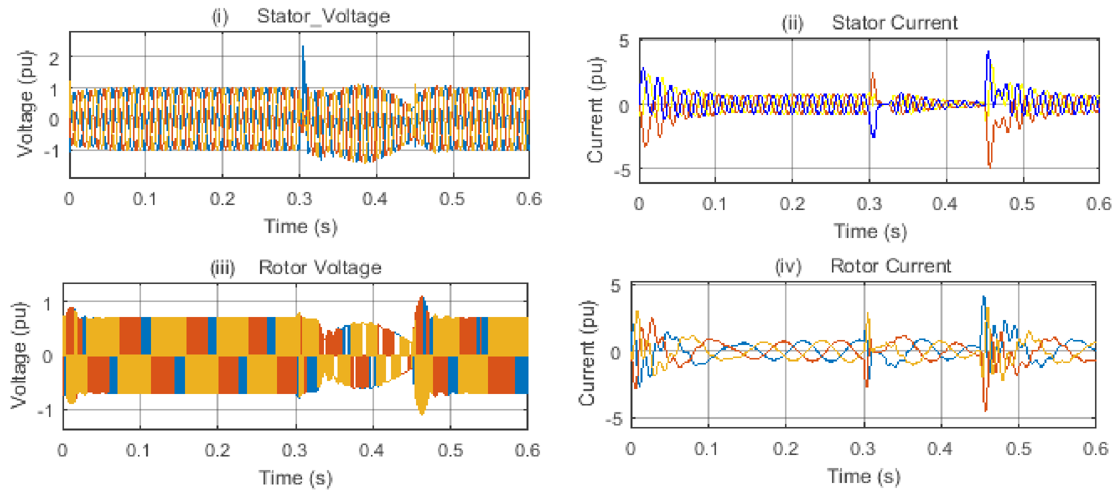

Figure (5.24) the simulation results of DFIG connected to the Grid at 20% symmetrical Grid voltage dip, when (i) curve shows the stator voltage, (ii) curve shows the stator current, (iii) curve shows the Rotor voltage , curve (iv) shows the rotor current.

Figure 5.24 (i) shows a voltage going regularly until the two phase to ground appeared in the system fault at 0.3sec of simulation time, then stator voltage disturbed to reach its highest value - 2.3 p.u, but this voltage is very short, therefore it does not cause the generator to be protected. During voltage dip affects, the stator voltage appeared at 0.3 to 0.45sec as a result of the presence of DC link voltage with the turbine rotated at a synchronous speed, then the stator voltage recovery after voltage dip disappeared. . Figure 5.24 (ii) shows the impacts of stator current, when the current disturbed to reach up to 2 p.u then disturbed at 0.8 to 0.2 p.u until the voltage dip disappeared at 0.45sec to disturb gain to reach 4 p.u, then the start current recovery. Figure 5.24 (iii) shows a voltage fluctuation in rotor, it also as a result of the DFIG generator is disconnected from the grid in case of contactor fault effects. At 0.3, short v disturbance in the voltage made it reach its value 0.78 p.u. During voltage dip affects, the voltage appeared at 0.3 to 0.45sec as a result of the presence of DC link voltage with the turbine rotated at a synchronous speed. At 0.45, the voltage fluctuated again to reach its highest value 1.1 p.u for short time. After voltage dip disappeared, the voltage recovery to its operation value. Figure 5.24 (iv) shows the impacts of current, when the current disturbed to reach up to 2.8 p.u then stabled at 0.8 p.u until the voltage dip disappeared at 0.45sec to disturb gain to reach 4 p.u, then the current recovery.

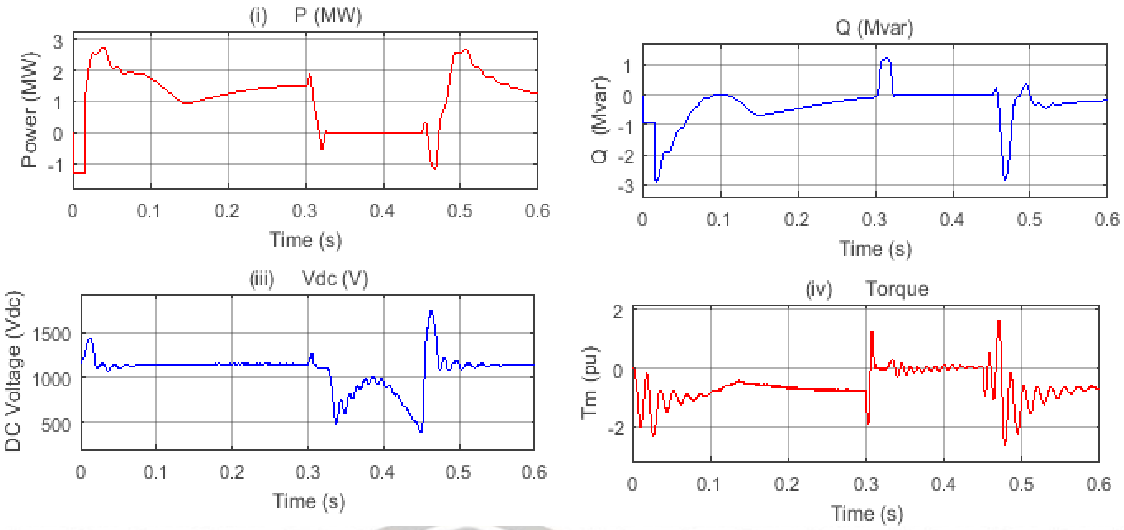

Figure (5.25) the simulation results of DFIG connected to the Grid at 20% symmetrical Grid voltage dip, when The (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.25 (i) shows the active power is significantly reduced to Zero MW as a result of the generator outage from the Grid due to the impact of the contactor by the voltage drop. And also the reactive power affected this reason, as shown in 5.25 (ii). Both active and reactive power curves oscillate similarly to the operating time of simulation time 0.45 sec, this giving the impression that reconnecting the contector to the grid and the return of the DFIG generator giving a statues of generating worst then the startup time of the generator. In Figure 5.25 (iii), the DC-link voltage gradually disturbed between 500 to 1000 V dc during the voltage dip, and then rapidly rises to 1750 Vdc as the fault disappeared. This dc voltage distortion explains the presence of voltage on the rotor and stator during the fault. The Figure 5.25 (iv) show the torques is significantly reduced to Zero with a momentum distortion at starting of voltage dip period, after the fault disappeared, the torque is disturbed at 0.45 to 0.5 with allowable rate, and then begins to recovery.

5.2.2.6 The results Summary

Through the investigating of symmetrical voltage dips under study in this part of simulation, the effects of the conductor behavior during the symmetrical voltage drops (80%, 60%, 40% and 20%) on the DFIG wind turbine operation state were studied.

The analysis of the simulation results showed that the contactor is not affected by symmetrical voltage up to 60% of the grid voltage, thus, the generator will stay connected to the Grid during symmetrical voltage dips above 60% grid voltage. The DFIG generator continues to produce active power with an appearance of reactive power and a slight disturbance in the electromechanical torque. The variations of stator current, rotor current, and DC-link voltage is acceptable and does not affect the performance of the wind turbine during these type of voltage transients.

In symmetric voltage dips below 40% of grid voltage, the analysis of the simulation results showed that the contactor is affected by this range of voltage dips. Thus, As a result of the voltage influence below 40%, the contactor is effected and open its contacts as a result of lost its coil magnetic force. This effect of voltage dip on the contactor caused the DFIG generator being disconnected from the grid. Therefore, the simulation results showed the effect of the conductor behavior on the generator, where the generator is lost its ability to produce electrical power during the time period of the voltage dip under 40% of grid voltage.

Thus, when the error is under a 40% voltage drop, the contactor opens its contact, the voltage on the DFIG generator decreases and causes a similar decrease in the stator voltage and electromagnetic torque and the active energy. In addition, the DC voltage decreases irregularly during interruption. At the momentum of fault release, large distortions excite in active, reactive, voltage and current also on torque and DC voltage. This instability is because the turbine generates a great potential similar to the start-up potential after the error is released and the contactor returns to connect the generator to the Grid, so this explains the turbulent increase in the DFIG current and torque as soon as the fault is gone.

5.2.3 Simulation Result of DFIG under voltage dip caused by Grid fault

In this part of simulation, the voltage dip caused by phase faults model is applied at Bus bar B25, where the simulated DFIG wind turbine without any Fault ride through protection methods. The effects of different type of faults on the system was studied in this simulation part, including the asymmetrical fault, asymmetrical two phase fault, single phase to ground fault, asymmetrical two phase to ground fault, and symmetrical three phase fault. These faults were simulated respectively one after the other, and the faults occurred at junction bus B25 and applied to the simulated system at 0.3 to 0.45 sec for duration of time 150 m sec according to the most of the new grid codes requirements. The following sections describe the simulation results and its discussions.

5.2.3.1 Result of DFIG under Unsymmetrical single phase to ground faults

In this part, the simulated system is applied phase to ground asymmetrical fault at 0.3sec the fault continue for 150 milliseconds then disappeared at 0.45s of simulation time

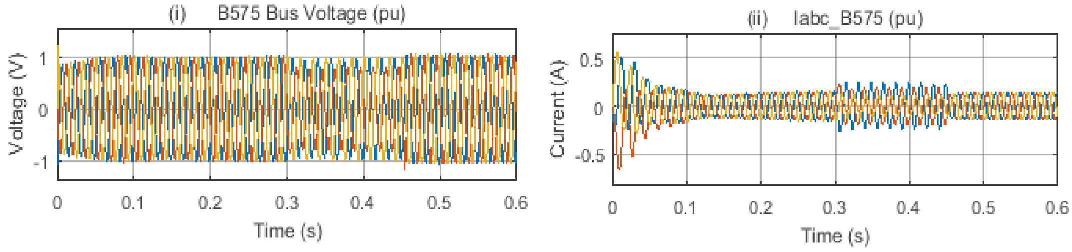

Figure (5.26) simulation results of Bus bar number B575 at single phase to ground faults when (i) curve shows the Bus bar voltage, (ii) curve shows Bus bar current.

As shown in Figure 5.26 (i), at 0.3 sec when phase to G fault appeared to the system, the voltage on Bus B575 is dipped to 0.8 p.u, this leads to current transient in the bus B575 as shown in figure 5.26 (ii), Currents increased to 0.25 p.u until the voltage dip then the current back to its normal operation value 0.15 p.u.

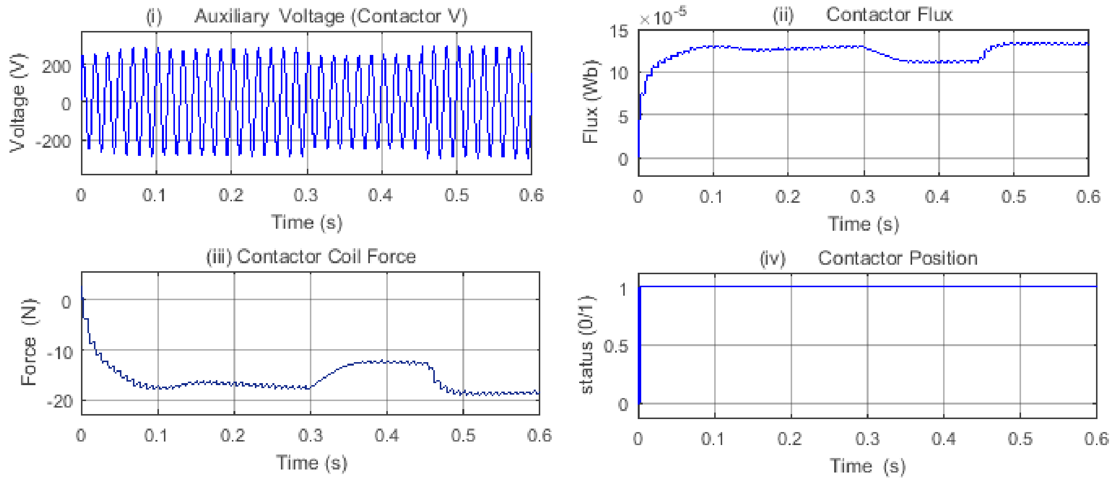

Figure (5.27) simulation results of DFIG Main Contactor statues at single phase to ground faults when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor(on or off).

The figure 5.27 shows phase to ground fault type effects the main contactor coil terminals of the DFIG generator. When Figure 5. 27 (i) shows the contactor voltage is constant at 240 V until the fault appeared in the system, then the voltage suddenly decreased at 0.3 sec to 210V then recovered at 0.45s after fault disappeared to recovered to 240 volt again. Figure 5. 27 (ii) shows the contactor coil flux where its value stabled at

12×10^{-5} Wb, during the fault appearance at 0.3sec, the magnetic flux decreased to 11×10^{-5} Wb until voltage dip disappeared at 0.45sec to stabilize at 12×10^{-5} Wb again. Figure 5. 27 (iii) shows the contactor armature placement, during fault at 0.3sec, the coil magnetic force is at -8 N to recover back to 10 N at 0.45sec after fault disappeared. Since the contactor's contact still sufficient to remain closed during the fault, the contacts statues remains in the close at (1) status, figure (iv) shows the state of the contactor contacts during the voltage drop, where the contector still connected its contacts, thus the generator continues connecting to the grid.

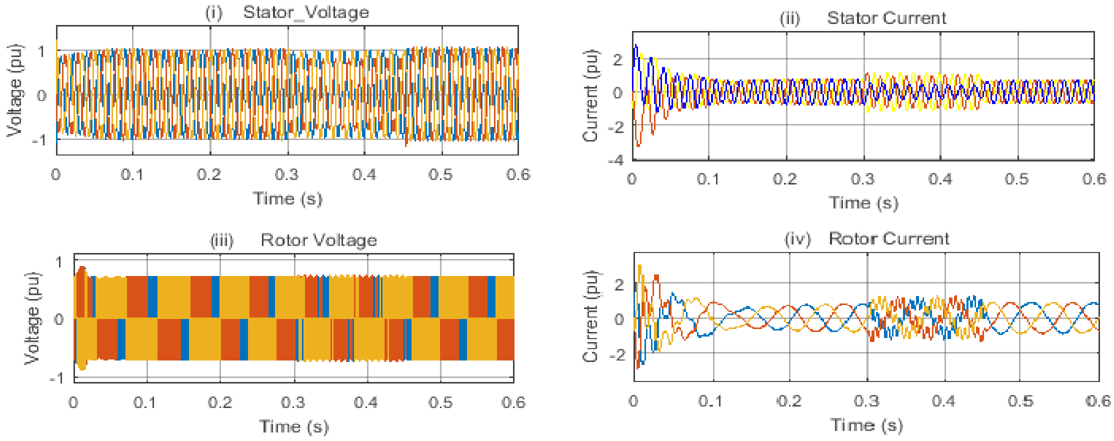

Figure (5.28) the simulation results of DFIG connected to the Grid at single phase to ground faults, when (i) curve shows the stator voltage, (ii) curve shows the stator current, (iii) curve shows the rotor voltage , curve (iv) shows the rotor current.

Figure 5.28(i) shows the stator voltage, where it was constant at 1 p.u until the phase to Ground fault appeared, and then the stator voltage suddenly decreased to 0.9 p.u at 0.3sec until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5. 28 (ii) the shows that stator current is fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.8p.u until the fault appeared at 0.3s, after it, the current increased to 1 p.u, after the transient disappeared at 0.45s the current back to stabilize at 0.8p.u again. The figure 5. 28 (iii) shows the rotor voltage which is constant at 0.7 p.u until the fault appeared at 0.3sec, then suddenly increased to 0.72 p.u until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. Figure 5. 28 (iv) describe the rotor current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, then the current increased to 1 p.u until transient disappeared at 0.45sec to stabilized after that at 0.8p.u. An inconsiderable imbalance on voltage and current is appeared during the time period of the phase to ground fault.

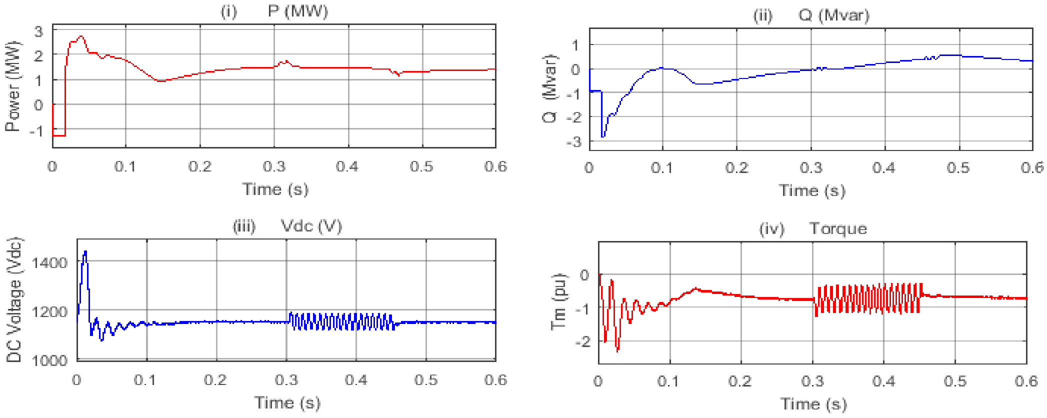

Figure (5.29) the simulation results of DFIG connected to the Grid at ingle phase to ground faults, when (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) The Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.29 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 sec. when the phase to ground fault appeared at 0.3sec, Active power has continued to 1.5 MW with slight disturbance at the beginning of the fault time, then start recovered at 0.45s. In Figure 5. 29 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28 sec. When the fault appeared at 0.3s, the generator start to absorb a reactive power from the grid to reach 0.8 Mvar before the fault disappeared, at 0.5 sec the system started recovering. Figure 5. 29 (iii) indicates a rise in the voltage of DC-link reaching 1500 Vdc at startup to stable to 1150 Vdc, at fault duration dc voltage softly disturb. The Figure 5. 29 (iv) show the torques variation when the voltage drops at the instant 0.3 sec to reach a value 0.7p.u pu which is still acceptable.

5.2.3.2 Result of DFIG under Unsymmetrical two phase to Ground fault

In this part, the simulated system is applied two phase to ground asymmetrical fault at 0.3sec the fault continue for 150 milliseconds then disappeared at 0.45s of simulation time.

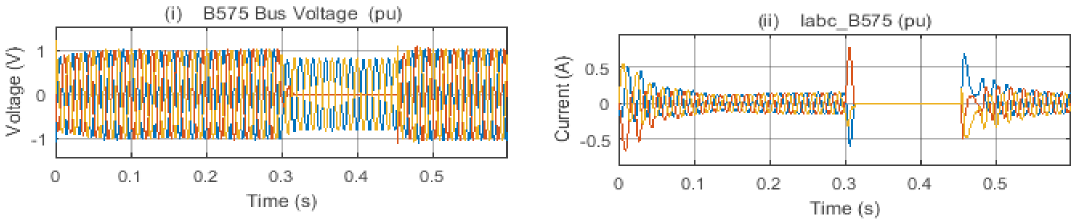

Figure (5.30) simulation results of Bus bar number B575 at two phase to ground faults when curve (i) shows the Bus bar voltage, (ii) curve shows Bus bar current.

The results of Figure 5.30 in (i) shows that the bus B575 voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared this leads to current transient, as shown in (ii), the current on bus B575 Suddenly increased to 0.78 p.u at the beginning of volte transient then immediately drop to zero, then the Currents disturbed again at 0.45 sec to reach 0.68 p.u then then start recovery.

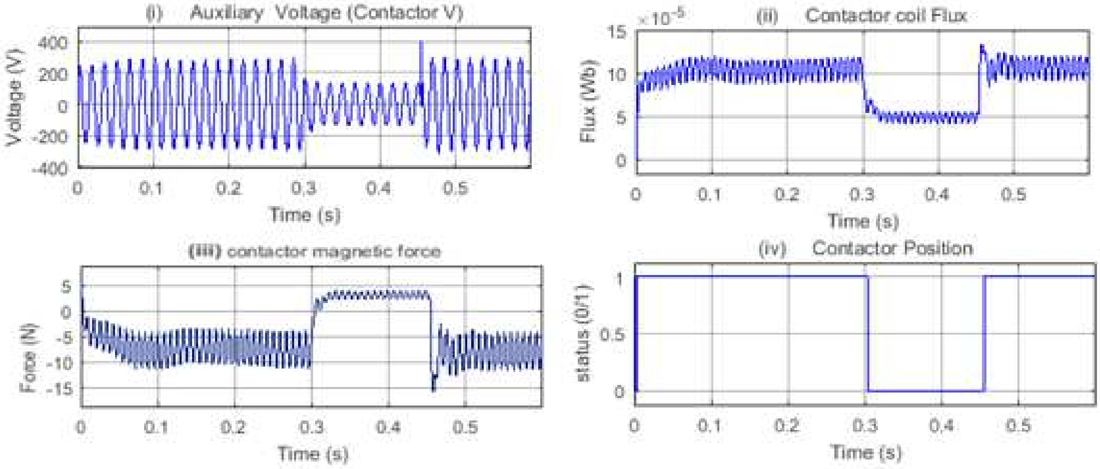

Figure (5.31) simulation results of DFIG Main Contactor statues at two phase to ground faults when (i) curve shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the contactor statues.

The figure 5.31 shows the effect of 2 phase to ground system fault on the main contactor coil terminals. Figure 5. 31 (i) shows the contactor voltage is decreased at 0.3 sec to 132V, this caused a sharp drop in the electromagnetic force of the contactor coils as shown in figure 5. 31 (ii), which led to the release the contactor contacts as a result of the armature return spring movement force is greater than the coil magnetic force, this appeared in Figures 5. 31 (ii) and (iii), where the situation caused opening contactor contacts then cutoff the DFIG generator from the power system. The grid voltage recovered at 0.45sec and fault disappeared, therefore the contactor force stabilized at 12 x10^{-5} Wb again then contactor close its contacts to connect the generator to the grid then wind turbine recovered.

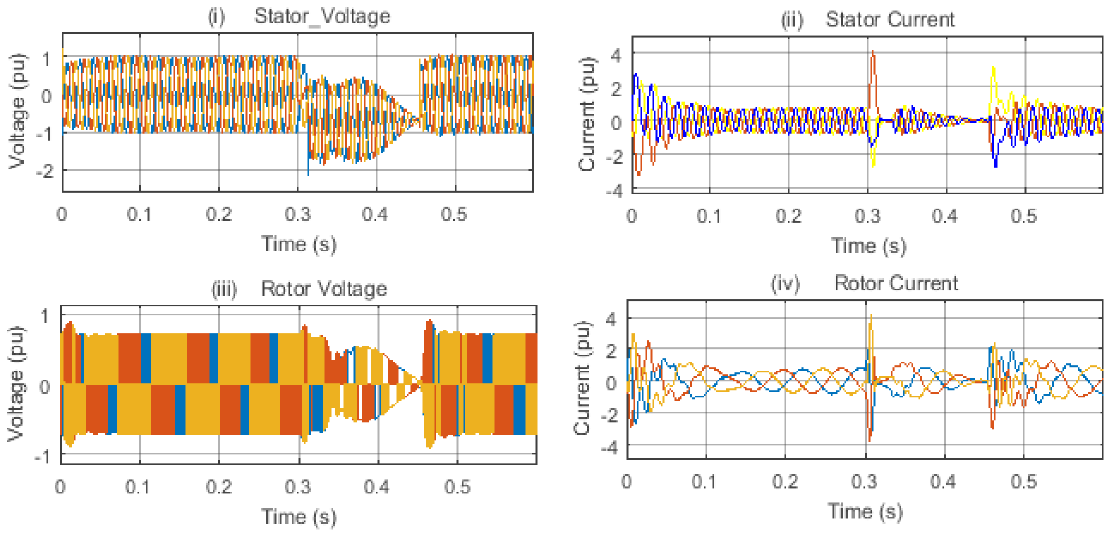

Figure (5.32) the simulation results of DFIG connected to the Grid at two phase to ground faults, when (i) curve shows the stator voltage, (ii) curve shows the stator current, (iii) curve shows the rotor voltage , curve (iv) shows the rotor current.

Figure 5.32 (i) shows a voltage going regularly until the two phase to ground fault appeared in the system at 0.3sec of simulation time, then stator voltage disturbed to reach its highest value - 2.3 p.u, but this deterioration time is very short, therefore it does operate generator protected. During voltage dip affects, the stator voltage appeared at 0.3 to 0.45sec caused by the exixtence of the voltage of DC link when the turbine rotated at a synchronous speed, but it has no influence on the turbine productivity. The recovery of the stator voltage after voltage dip disappeared. Figure 5. 32 (ii) shows the impacts of stator current, when the current disturbed to reach up to 4 p.u then disturbed between 0.8 to 0.2 p.u until the voltage dip disappeared at 0.45sec, then disturbed gain to reach 2.2 p.u, then the start current recovered. Figure 5. 32 (iii) shows a fluctuation in rotor voltage during fault time, it also as a result of the DFIG generator is discharged from the grid in case of contactor disconnected during fault effects. At 0.3sec, short disturbance in the rotor voltage made it reach its value 0.78 p.u. During fault appearance. The voltage appeared at 0.3 to 0.45sec is resulted by the presence of DC link voltage with the turbine rotated at a synchronous speed. At 0.45, the voltage fluctuated again to reach its highest value 1.1 p.u for short time. After voltage dip disappeared, the voltage recovery to its operation value. Figure 5. 32 (iv) shows the impacts of current, when the current disturbed to reach up to 4 p.u then stabled at 0.8 p.u until the fault disappeared at 0.45sec to disturb gain to reach 2.2 p.u, then the current recovery.

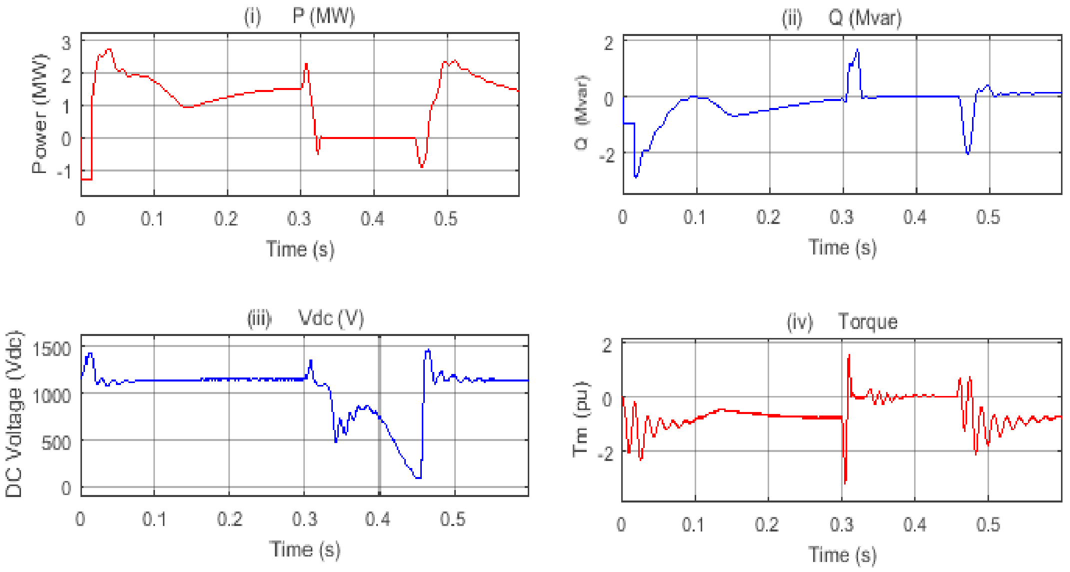

Figure (5.33) the simulation results of DFIG connected to the Grid at two phase to ground faults, when The (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.33 (i)) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. however, when the two phase to ground fault appeared at 0.3sec, the active power is significantly dropped to Zero MW as a result of the generator outage from the Grid due to the impact of the contactor by the voltage drop. Also the reactive power affected by this reason, as shown in 5. 33 (ii). Both active and reactive power curves oscillate similarly to the oscillation during operating time of simulation at 0.45 sec, this giving the impression that reconnecting the DFIG generator to the grid by contactor giving a statues of generating worst then the startup time. In Figure 5. 33 (iii), the DC-link voltage gradually disturbed between 100 to 1100 V dc during the fault, and then rapidly rises to 1500 Vdc as the fault disappeared. This dc voltage distortion explains the presence of voltage on the rotor and stator during the fault. The Figure 5. 33 (iv) show the torques is significantly reduced to Zero with a momentum distortion at starting of voltage dip period, after the fault disappeared, the torque is disturbed at 0.45 to 0.5 with allowable rate, and then begins to recovery.

5.2.3.3 Result of DFIG under Unsymmetrical two phase fault

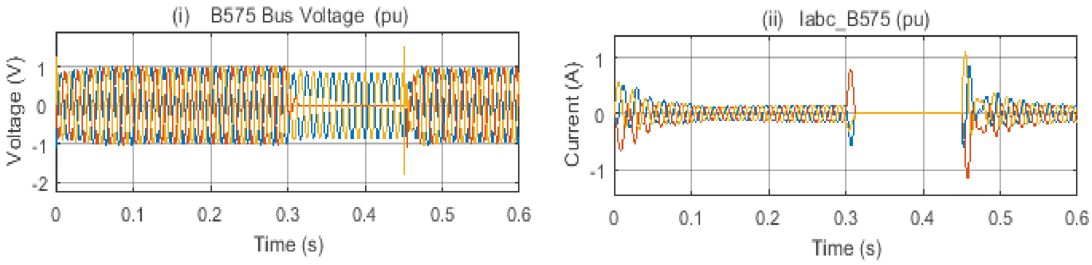

Figure (5.34) simulation results of Bus bar number B575 at two phase faults when (i) shows the Bus bar voltage, (ii) shows Bus bar current.

The results Figure 5.34 (i) shows that the bus B575 voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared this leads to current transient, as shown in Figure 5.34 (ii), the current on bus B575 Suddenly increased to 0.78 p.u at the beginning of volte transient then immediately drop to zero, then the Currents disturbed again at 0.45 sec to reach 1 p.u then start recovery.

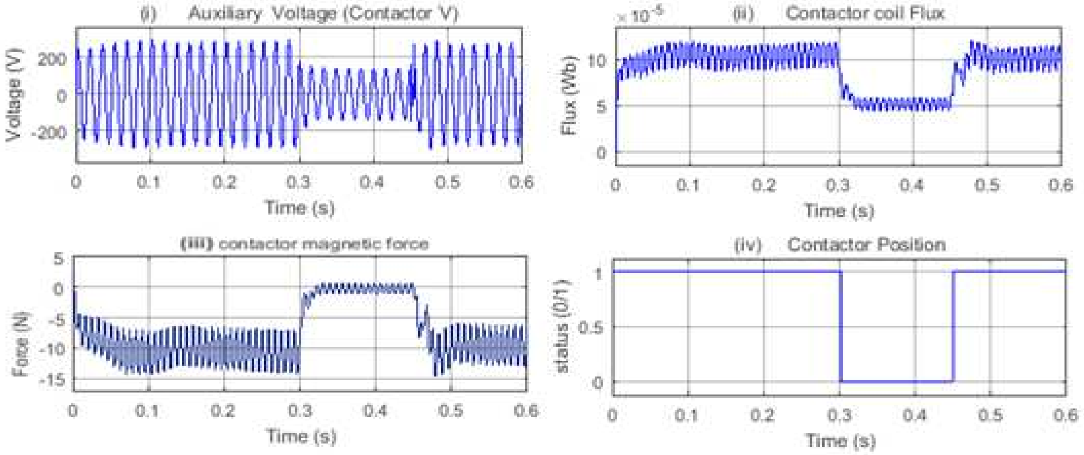

Figure (5.35) simulation results of DFIG Main Contactor statues at two phase faults when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor(on or off).

The figure 5.35 shows the effect of 2 phase fault affect the system which appeared as voltage dip on the main contactor coil terminals. Figure 5. 35 (i) shows the contactor voltage is decreased at 0.3 sec to 140V, this caused a sharp drop in the electromagnetic force of the contactor coils as shown in figure 5. 35 (ii), which led to the release the contactor's contacts as a result of the armature return spring movement force is greater than the coil magnetic force, this appeared in Figures 5. 35 (ii) and (iii). This situation caused the contactor opening its contacts then cutoff the DFIG generator from the power system. The grid voltage recovered at 0.45sec and fault disappeared, therefore the contactor force stabilized at 12 x10-5 Wb again then contactor close its contacts to connect the generator to the grid then wind turbine recovered.

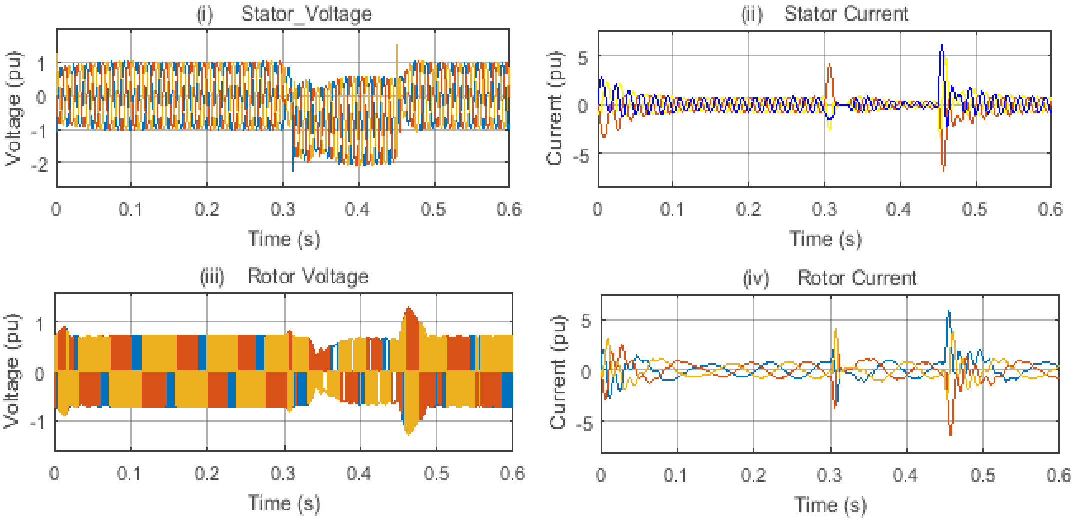

Figure (5.36) the simulation results of DFIG connected to the Grid at two phase faults, when (i) shows the stator voltage, (ii) curve shows the stator current, (iii) shows the rotor voltage, while (iv) shows the rotor current.

Figure 5.36 (i) shows a voltage going regularly until the two phase fault appeared in the system at 0.3sec of simulation time, then stator voltage disturbed to between o.5 to - 2.3 p.u for during voltage dip duration, the voltage which appeared on the stator at 0.3 to 0.45sec is a resulting of the presence of DC link voltage while the turbine rotated at a synchronous speed, but it has no influence on the turbine productivity. The recovery of the stator voltage after voltage dip disappeared. Figure 5. 36 (ii) shows the impacts of stator current, when the current disturbed to reach up to 2.2 p.u then disturbed at 0.8 p.u until the voltage dip disappeared at 0.45sec, then disturbed gain to reach 6 p.u, then the start current recovered. Figure 5. 36 (iii) shows a fluctuation in rotor voltage during fault time, it also as a result of the DFIG generator is discharged from the grid due to contactor condition during fault effects. At 0.3sec, short disturbance in the rotor voltage made it reach its value 0.78 p.u. During fault appearance. The voltage appeared at 0.3 to 0.45sec is resulted by the presence of DC link voltage with the turbine rotated at a synchronous speed. At 0.45, the voltage fluctuated again to reach its highest value 1.25 p.u for short time. After voltage dip disappeared, the voltage recovery to its operation value. Figure 5. 36 (iv) shows the impacts of rotor current, when the current disturbed to reach up to 4 p.u then stabled at 0.8 p.u until the fault disappeared at 0.45sec to disturb gain to reach 6 p.u, then the current recovery.

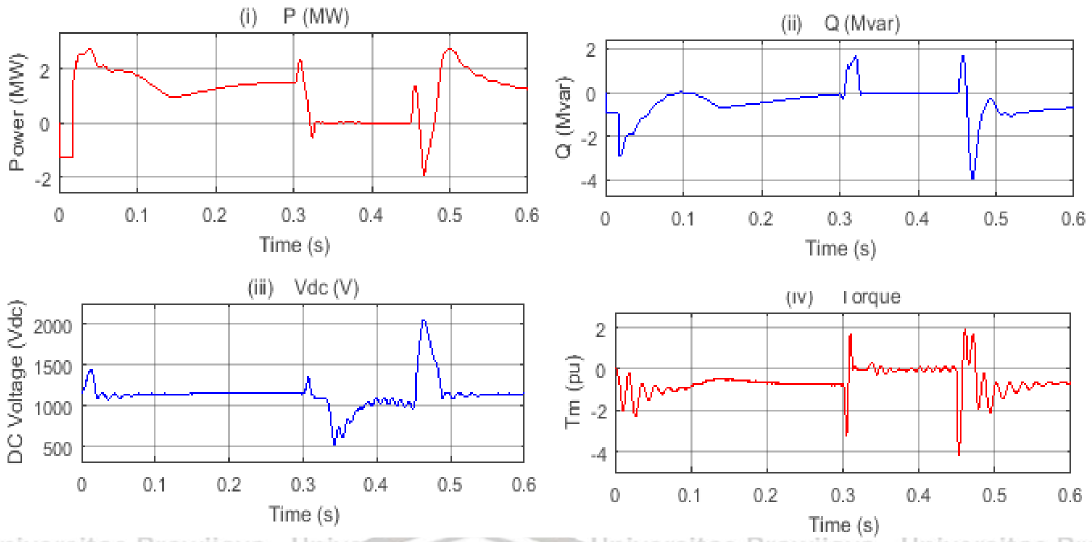

Figure (5.37) the simulation results of DFIG connected to the Grid at two phase faults, when The (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.37 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. however, when the two phase fault appeared at 0.3sec, the active power is significantly dropped to Zero MW as a result of the generator outage from the Grid due to the impact of the contactor by the voltage dip. Also the reactive power affected by this reason, as shown in 5. 37 (ii). Both active and reactive power curves oscillate similarly to the oscillation during operating time of simulation at 0.45 sec, this giving the impression that reconnecting the DFIG generator to the grid by contactor giving a statues of generating worst then the startup time. In Figure 5. 37 (iii), the DC-link voltage gradually disturbed between 500 to 1000 V dc during the fault, and then rapidly rises to 2000 Vdc as the fault disappeared, which is affect the voltage protection. This dc voltage distortion during fault explains the presence of voltage on the rotor and stator during the fault. The Figure 5. 37 (iv) show the torques is significantly reduced to Zero with a momentum distortion at starting of voltage dip period, after the fault disappeared, the torque is disturbed at 0.45 to 0.5 with allowable rate, and then begins to recovery.

5.2.3.4 Result of DFIG under symmetrical three phase fault

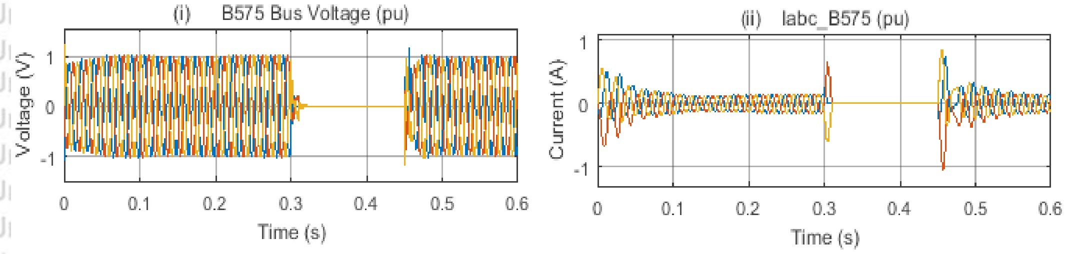

Figure (5.38) simulation results of Bus bar number B575 at three phase faults when (i) shows the Bus bar voltage, (ii) shows Bus bar current.

The results Figure 5.38 (i) shows that during three phase system fault the bus B575 voltage is dipped to zero p.u during fault duration, then voltage gets momentum overshoot to 1.1p.u, after that then start voltage recovery. In Figure 5. 38 (ii), the current on bus B575 Suddenly increased to 0.78 p.u at the beginning of volte transient then immediately drop to zero, then the Currents disturbed again at 0.45 sec to reach 1 p.u then start voltage recovery.

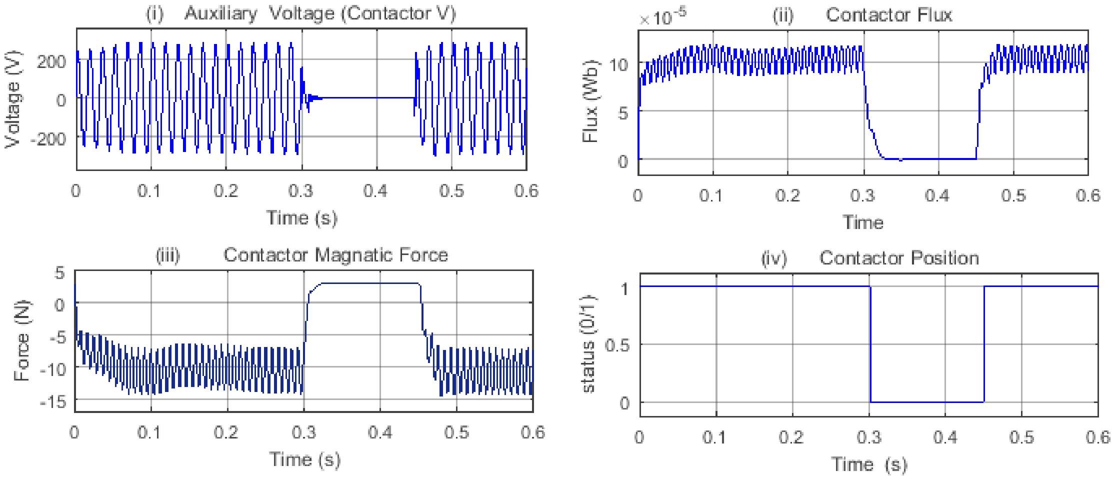

Figure (5.39) simulation results of DFIG Main Contactor statues at three phase faults when. (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describes the statues of contactor (On or Off).

The figure 5.39 shows the effect of 3 phase fault affect the system which appeared as voltage dip on the main contactor coil terminals. Figure 5. 39 (i) shows the contactor voltage is decreased at 0.3 sec to zero V, this caused a sharp drop in the electromagnetic force of the contactor coils as shown in figure 5. 39 (ii), which led to the release the contactor's contacts as a result of the armature return spring movement force is greater than the coil magnetic force, this appeared in Figures 5. 39 (ii) and (iii). This situation caused the contactor opening its contacts then cutoff the DFIG generator from the power system. The grid voltage recovered at 0.45sec and fault disappeared, therefore the contactor force stabilized at 12 x10^{-5} Wb again then contactor close its contacts to connect the generator to the grid then wind turbine recovered.

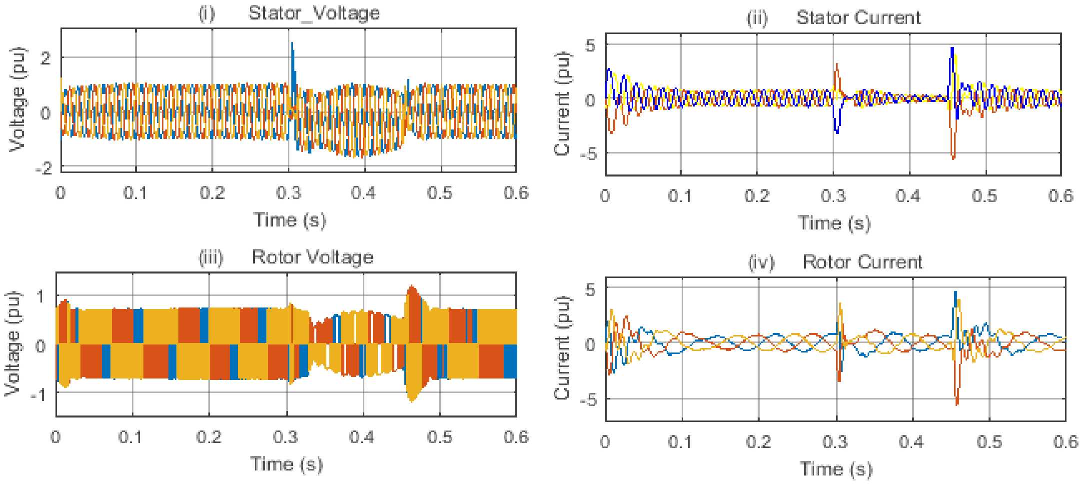

Figure (5.40) the simulation results of DFIG connected to the Grid at three phase faults, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.40 (i) shows a voltage going regularly until the three phase fault appeared in the system at 0.3sec of simulation time, then stator voltage disturbed to reach its highest value 2.3 p.u, but the deterioration time is very short. At voltage dip duration, the voltage appeared on the stator caused by the existence of the voltage of the DC link when the turbine circled at a synchronous speed, but it has no effect on the productivity of the turbine. The stator voltage recovered after voltage dip disappeared. Figure 5. 40 (ii) shows the impacts of stator current, when the current disturbed to reach up to 3.12 p.u then disturbed at 0.76 p.u until the voltage dip disappeared at 0.45sec, then disturbed gain to reach 4.7 p.u, then the start current recovered. Figure 5. 40 (iii) shows a fluctuation in rotor voltage during fault time, it also as a result of the DFIG generator is discharged from the grid due to the contactor condition when fault gives effects. At 0.3sec, short disturbance in the rotor voltage reaches 0.8 p.u. The voltage distortion appeared at 0.3 to 0.45sec is resulted by the presence of DC link voltage with the turbine rotated at a synchronous speed. At 0.45, the voltage fluctuated again to reach its highest value 1.15 p.u for short time. After voltage dip disappeared, the voltage recovery to its operation value. Figure 5. 40 (iv) shows the impacts of rotor current, when the current disturbed to reach up to 3.5 p.u then stabled at 0.8 p.u until the fault disappeared at 0.45 sec to disturb gain to reach 4.6 p.u, then the current recovery.

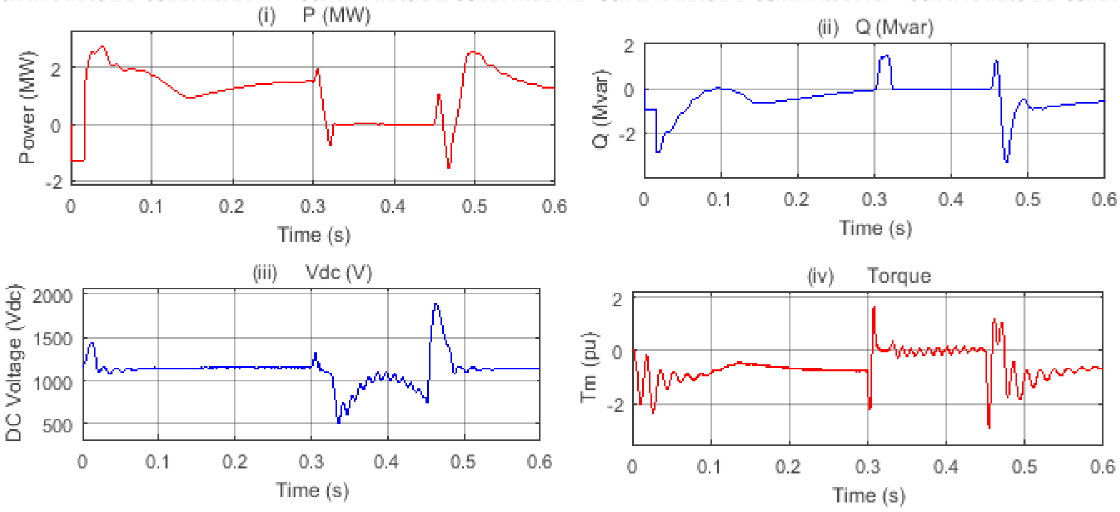

Figure (5.41) the simulation results of DFIG connected to the Grid at three phase faults, when The (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) shows the Dc voltage and (iv) describe the electrical torque statues.

The simulation results in figure 5.41 (i)) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. however, when the three phase to ground fault appeared at 0.3sec, the active power is significantly dropped to Zero MW as a result of the generator outage from the Grid due to the impact of the contactor by the voltage dip. Also the reactive power affected by this reason, as shown in 5. 41 (ii). Both active and reactive power curves oscillate similarly to the oscillation during operating time of simulation at 0.45 sec, this giving the impression that reconnecting the DFIG generator to the grid by contactor giving a statues of generating worst then the startup time. In Figure 5. 41 (iii), the DC-link voltage gradually disturbed between 500 to 1100 V dc during the fault, and then rapidly rises to 1800 Vdc as the fault disappeared, which is affect the voltage protection. This dc voltage distortion during fault explains the presence of voltage on the rotor and stator during the fault. The Figure 5. 41 (iv) show the torques is significantly reduced to Zero with a momentum distortion at starting of voltage dip period, after the fault disappeared, the torque is disturbed at 0.45 to 0.5 with allowable rate, and then begins to recovery.

5.2.3.5 The results Summary

Based on the observation of dips voltage caused by Grid errors examined in this simulation section, the effect of conductor behavior at the moment of the symmetric and asymmetric voltage dips which are caused by Grid error in the operating state of DFIG wind turbine studied. The error under investigation is an asymmetrical error that includes phase to ground, two phase and two phase to ground errors and three symmetrical phase error. The simulation result analysis shows that the contactor is not affected by the asymmetric voltage drop caused by the phase noise to the ground, so that the generator will remain connected to the Grid during this type of voltage dips. The DFIG generator continues to produce active power with the appearance of reactive power and little interference in electromechanical torque. Stator current variations, rotor currents, and DC-link voltages are acceptable and do not affect the performance of wind turbines during this type of transient.

In asymmetric voltage dips caused by two phase and two phase to ground grid faults, the analysis of the simulation results has shown that the contactor is effected and open its contacts as a result of lost its coil magnetic force, This contactor effect caused the DFIG generator being disconnected from the grid. Therefore, the simulation showed that the conductor behavior during asymmetrical voltage dip effected the generator performance, where the generator is lost its ability to produce electrical power during the time period of the voltage dip caused by grid two phase faults.

In voltage dips caused by symmetric three phase grid faults, the analysis of the simulation results has shown that the contactor is effected and open its contacts as a result of lost its coil magnetic force, This contactor effect caused the DFIG generator being disconnected from the grid. Therefore, the simulation showed that the conductor behavior during symmetrical voltage dip caused by three phase grid fault effected the generator performance, where the generator is lost its ability to produce electrical power during the fault time period. Also, the two phase and three phase faults resulting voltage and current unbalance may operating the wind turbine protection, this is also the case of DC voltage which may affect the performance of converter. As a result of the sudden reconnect the generator to the grid by the contactor after the fault disappeared, a disturbance in the electromechanical torque appeared as a result of greater potential produced by the turbine a to reach its generation stability again.

Thus, through the study of the grid voltage dip and the results demonstrated by the simulation, which showed the effect of some transient faults on the behavior of the contactor has caused to disconnect the grid voltage from the generator during synchronize speed of wind turbine, which affected the performance of the DFIG wind turbine. Therefore, for a more accurate study, RC circuit protection was added to the contractor coil to provide suitable conditions to keep the contact stay connected to the grid during the grid faults and then re-examine the system faults that affected the contector to analyze their effects on the DFIG generator and the proposed protection for the contactor.

5.2.4 Simulation Result of DFIG under voltage dip with proposed RC circuit for contactor coil

In this part, proposed solution of contactor fault raid through (FRT) is add to the contactor coil circuit, a capacitor with resistor are being added in parallel to the contactor coils to give a time delay to keep its contacts stay connect when a sudden voltage dip occurs on the grid, so the generator will not be disconnected during the sudden Grid faults. This part is concerned with the faults that affected the performance of the contactor in the previous simulation results. Thus, we will study 40% and 20%, voltage dips as well as two phase, two phase to ground, three-phase faults, in case of the contactor coil affected during these type of faults when there is no additional RC circuit. These simulation is done in case of study the effect on the generator when its stay connected to the system during these faults.

5.2.4.1 Result of DFIG under 40% symmetrical voltage dip with RC circuit

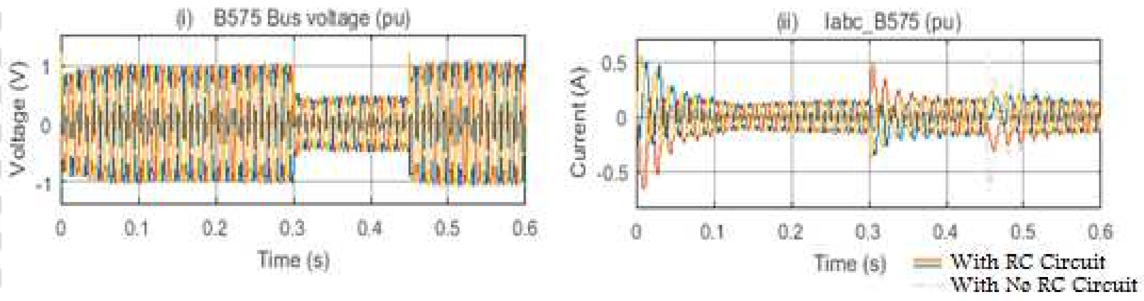

Figure (5.42) simulation results of Bus bar number B575 at 40 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) shows the Bus bar voltage, (ii) shows Bus bar current.

Figure 5.42 (i) shows that the bus voltage Bus B575 which has constant at 1 p.u until the voltage dip appeared, then voltage suddenly decreased to 0.4 p.u at 0.3 sec of simulation to recovery at 0.45s to reach its normal 1 p.u. again. Figure 5. 42 (ii) shows the Bus B575 current, its fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.15p.u until the voltage dip appeared at 0.3sec, then the current fluctuated between fluctuate between 0.35 to 0.2p.u until transient disappeared at 0.45s to stabilized back after that to 0.15p.u. The gray dotting on the figure 5. 42 (ii) shows the previous result of the current on the Bus B575at 40% voltage dip without RC circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

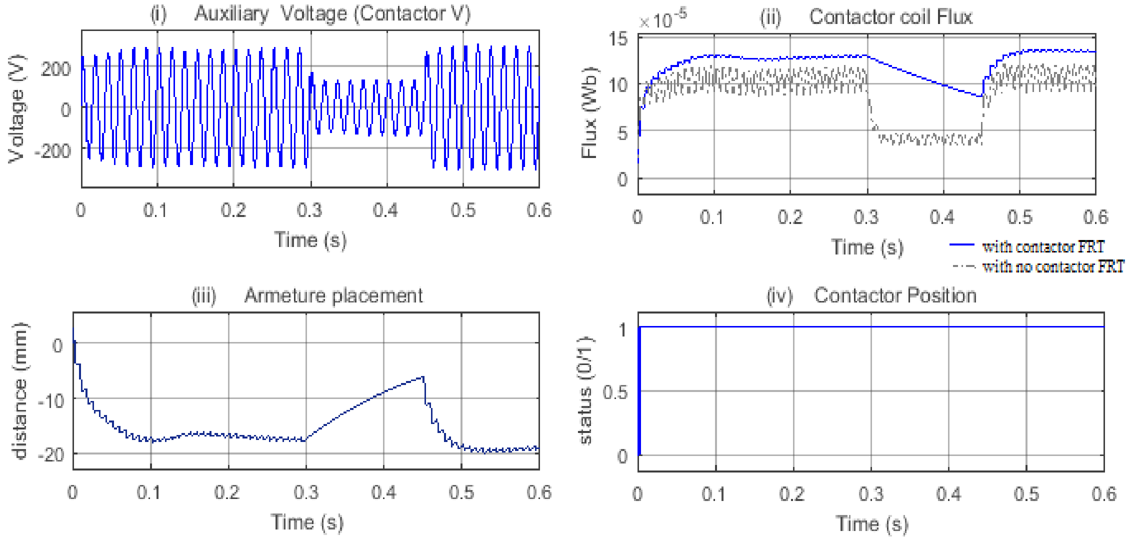

Figure (5.43) simulation results of DFIG Main Contactor statues at 40 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) curve shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor armature displacement, and (iv), describe the statues of contactor(on or off).

The figure 5.43 shows 40% Grid voltage dip is effect the main contactor coil terminals. Figure 5.43 (i) shows the contactor voltage is decreased at 0.3 sec to 100V, this supposed to cause a sharp drop in the electromagnetic flux of the coils, but as shown in figure 5.43 (ii), the flux decreases linearly as an function in time, which keeps the magnetic force strong enough to magnetize the armature then keep the contactor stay closing its contacts during the fault duration. The gray dotting on the figure 5. 43 (ii) shows the previous result of the contactor coil at 40% voltage dip, so with the proposed contactor RC circuit, the coil is recovered upon the fault disappeared. The figure 5.43 (iii) shows that the contactor armature still below zero indicating that the contacts is remained closed during the fault period. This is also shown in figure 5.43 (iv) which describe the opening and closing status of the contector, which in this status indicates 1, The generator is stay connected during the fault.

Figure 5.44 (i) shows the stator voltage, where it was constant at 1 p.u until the voltage dip appeared, and then the stator voltage suddenly decreased to 0.4 p.u at 0.3sec until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.44 (ii) the shows that stator current is fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.8p.u until the voltage dip appeared at 0.3s, after it, the current overshoot to 2 p.u then stabled at 1 p.u until transient disappeared at 0.45s to stabilize at 0.8p.u again.

The gray dotting on the figure 5.44 (ii) shows the previous result of the stator current during 40% voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

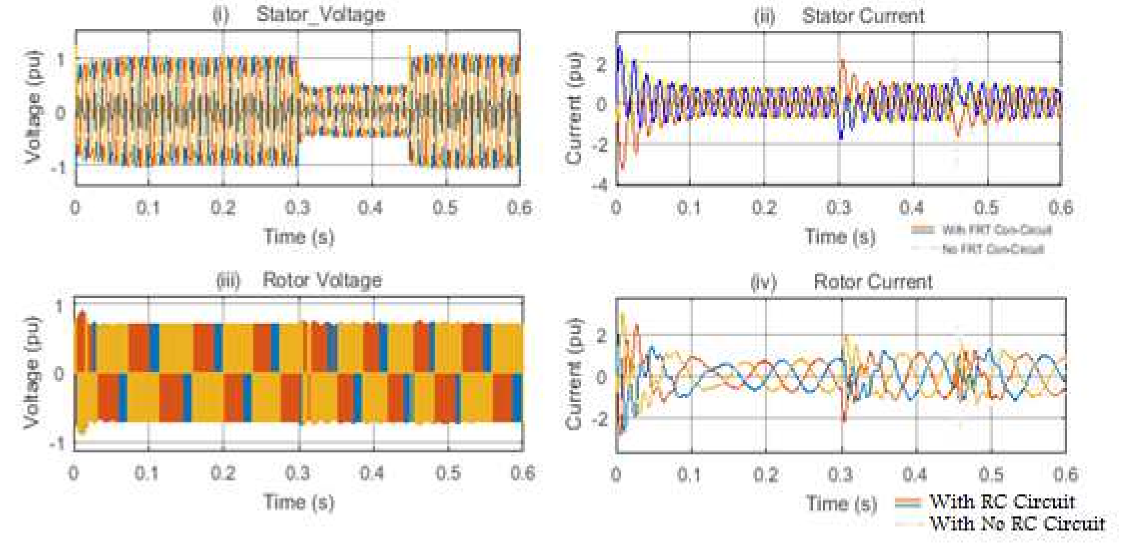

Figure (5.44) the simulation results of DFIG connected to the Grid at 40 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) shows the stator voltage, (ii) shows the stator current, (iii) curve shows the voltage , (iv) shows the current.

The figure 5.44 (iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared at 0.3sec, then suddenly disturb between 0.7 to 0.72 p.u then disturb between 0.7 to 0.72 p.u, Where the voltage appears in a semi-stable state on the rotor As a result of convertor mechanism, until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. Figure 5.44 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 2 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec to stabilized after that at 1p.u and recovering. The gray dotting on the figure 5.44 (iv) shows the previous result of the rotor current during 40% voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

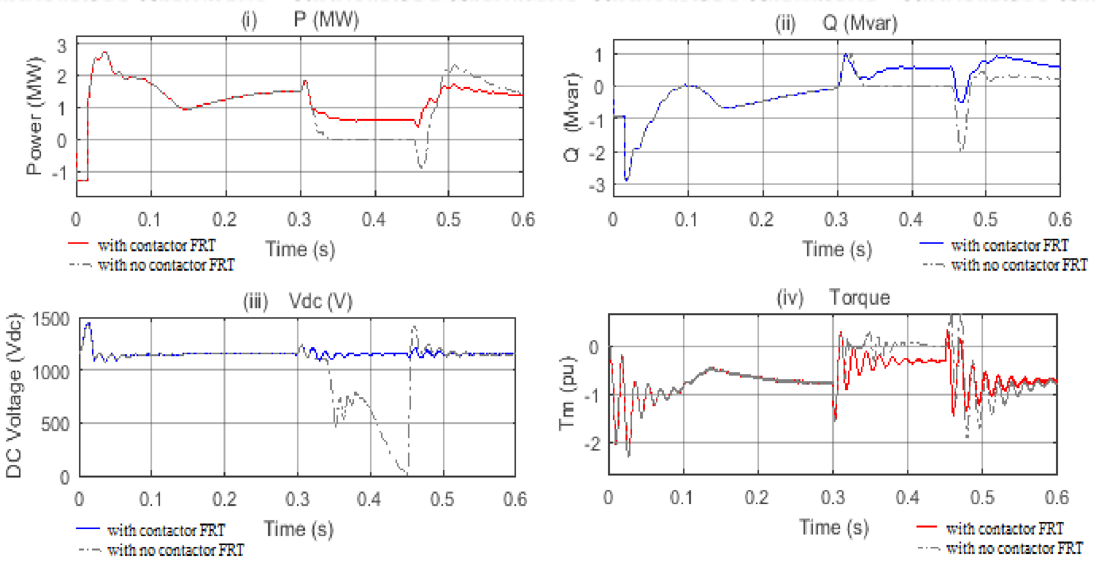

Figure (5.45) the simulation results of DFIG connected to the Grid at 40% symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) describe the active power statues, the curve (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.45 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 0.8 MW, then start recovered at 0.45s With time of fault disappearance. The gray dotting on the figure shows the previous result of the active power where it was at zero during fault impact of the contactor, however, when the RT circuit protection is added to the contector, the generator's performance is improved during the fault appearance, but it still showed a decline in power generation due to fault disruption. In Figure 5.45 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the voltage drops 40% for 0.3sec, reactive power caused disruption to 1Mvar suddenly and then the generator began to intake a reactive power from the grid to reach 0.8 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The gray dotting on the figure shows the previous result of the reactive power during 40% dip where the reactive power was at zero during fault effect of the contactor, however, when the RC circuit protection is added to the contector, the generator's performance is improved during the fault appearance, but the generator still absorbs the reactive power of the grid before voltage dip disappeared, at 0.5 sec the system started recovering. Figure 5.45 (iii) depicts a rise in the voltage of the DC-link up to 1500 Vdc at the beginning to reach the stable 1150 Vdc. At voltage dip, voltage duration of DC-link is described but it does not exceed the rate of the acceptable capacitor. The gray dotting on the figure shows the previous result of the DC Voltage during 40% dip where the voltage is suddenly decreased with significantly fluctuated during the fault until it reached the lowest value of zero V dc, which increases rapidly after fault disappearance. However, when the RC circuit protection is added to the contector, the DC voltage is improved during the fault appearance. And its value during fault is acceptable. The Figure 5.45 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u pu which is still acceptable. The gray dotting on the figure shows the previous result of the Torque during 40% dip where the electromechanical was at zero during fault effect of the contactor, however, when the RC circuit protection is added to the contector, the Torque behavior is improved during the fault appearance.

5.2.4.2 Result of DFIG under 20% symmetrical voltage dip with RC contactor coil circuit.

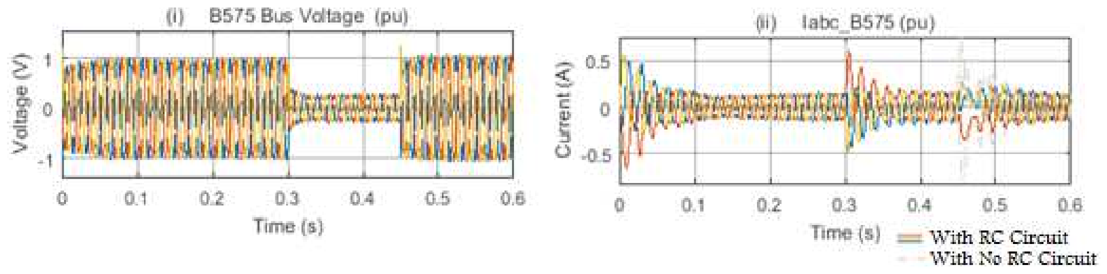

Figure (5.46) simulation results of Bus bar number B575 at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) curve shows the Bus bar voltage, (ii) curve shows Bus bar current. With adding RC circuit to the contactor coil

Figure 5.46 (i) shows that the bus voltage Bus B575 which has constant at 1 p.u until the voltage dip appeared, then voltage suddenly decreased to 0.2 p.u at 0.3 sec of simulation to recovery at 0.45s to reach its normal 1 p.u. again. Figure 5.46 (ii) shows the Bus B575 current, its fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.15p.u until the voltage dip appeared at 0.3sec, then the current fluctuated between fluctuate between 0.6 to 0.2p.u until transient disappeared at 0.45s to stabilized back after that to 0.2p.u. The gray dotting on the figure shows the previous result of the current on the Bus B575at 20% voltage dip without RC circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection.

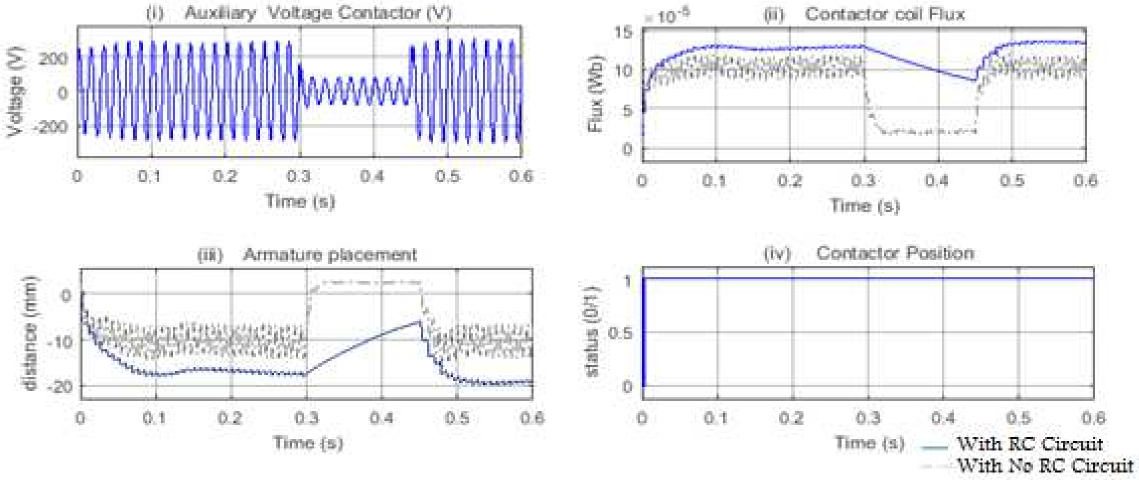

Figure (5.47) simulation results of DFIG Main Contactor statues at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) curve shows the auxiliary contactor voltage, (ii) curve shows contactor coil flux value, (iii) curve describe the contactor armature displacement, and curve (iv), describe the statues of contactor.

The figure 5.47 shows 20% Grid voltage dip is effect the main contactor coil terminals. Figure 5. 47 (i) shows the contactor voltage is decreased at 0.3 sec to 75V, this supposed to cause a sharp drop in the electromagnetic flux of the coils, but as shown in figure 5.47 (ii), the flux decreases linearly as an function in time, which keeps the magnetic force strong enough to magnetize the armature then keep the contactor stay closing its contacts during the fault duration. The gray dotting on the figure 5.47 (ii) shows the previous result of the contactor coil at 40% voltage dip, so with the proposed contactor RC circuit, the coil is recovered upon the fault disappeared. The figure 5.47 (iii) shows that the contactor armature still below zero indicating that the contacts is remained closed during the fault period. This is also shown in figure 5.47 (iv) which describe the opening and closing status of the contector, which in this status indicates 1, The generator is stay connected during the fault.

Figure 5.48 (i) shows the stator voltage, where it was constant at 1 p.u until the voltage dip appeared, and then the stator voltage suddenly decreased to 0.2 p.u at 0.3sec until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.48 (ii) the shows that stator current is fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.8p.u until the voltage dip appeared at 0.3s, after it, the current overshoot to 3 p.u then stabled at 1 p.u until transient disappeared at 0.45s when current a bit fluctuated and then started to recovery to stabilize at 0.8p.u again.

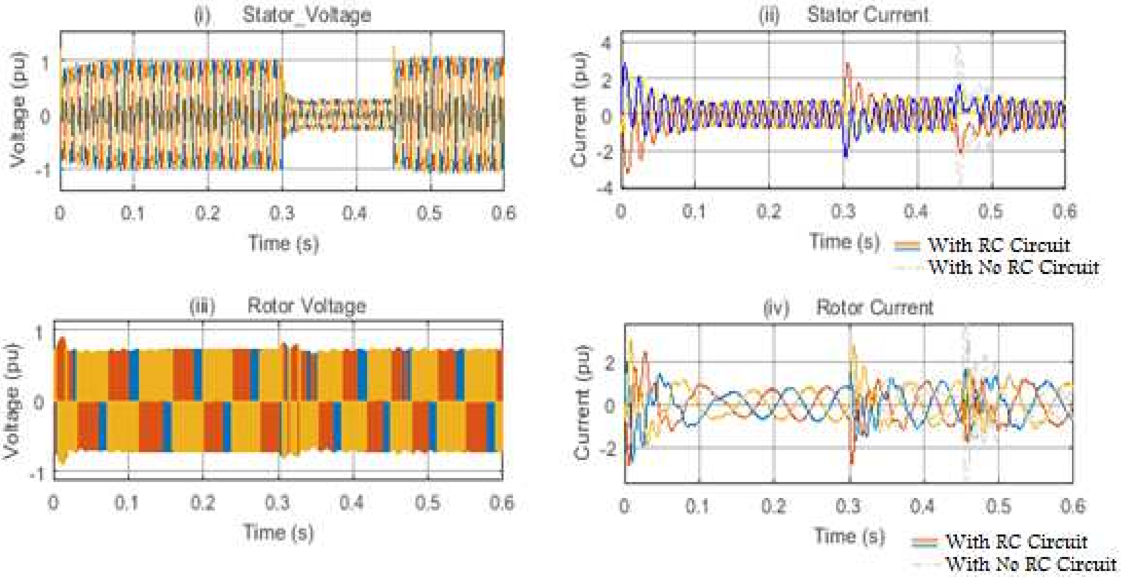

Figure (5.48) the simulation results of DFIG connected to the Grid at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) curve shows the stator voltage, (ii) curve shows the stator current, (iii) curve shows the voltage , curve (iv) shows the current.

The gray dotting on the figure 5.48 (ii) shows the stator current behavior in the result of the stator current during 20% voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared. The figure 5.48 (iii) shows that the voltage is constant at 0.7 p.u until the voltage dip appeared at 0.3 sec, then disturb between 0.7 to 0.72 p.u then disturb between 0.7 to 0.72 p.u, Where the voltage appears in a semi-stable state on the rotor As a result of convertor mechanism, until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. Figure 5.48 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 3 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec when current a bit fluctuated and then started to recovery to stabilize at 1p.u and recovering. The gray dotting on the figure 5. 47 (iv) shows the previous result of the rotor current during voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

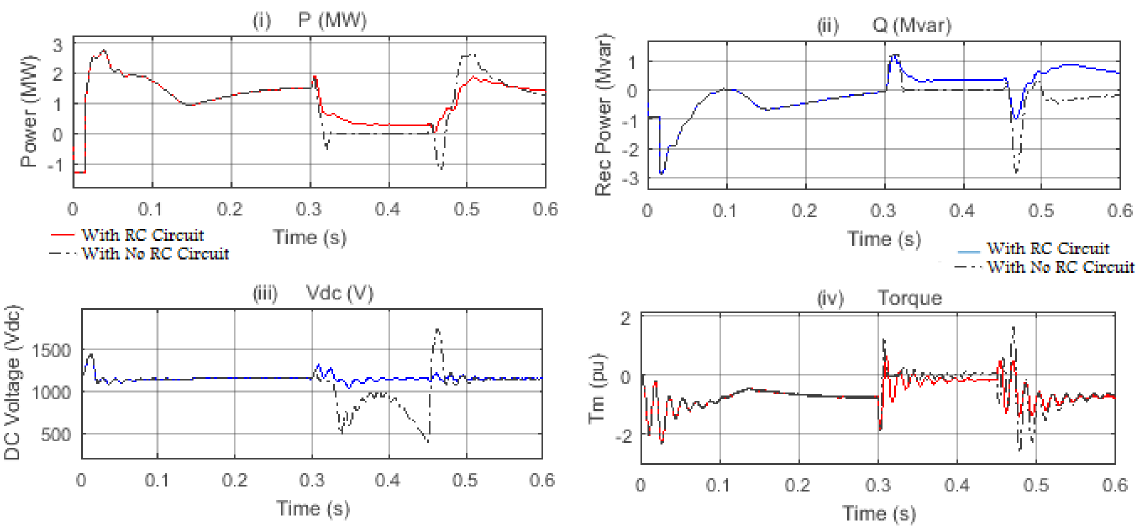

Figure (5.49) the simulation results of DFIG connected to the Grid at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when The curve (i) describe the active power statues, the curve (ii) describe the reactive power statues, curve (iii) shows the Dc voltage and The curve (iv) describe the electrical torque statues.

The simulation results in figure 5.49 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 0.3 MW, then start recovered at 0.45s With time of fault disappearance. The gray dotting on the figure shows the previous result of the active power where it was at zero during fault impact of the contactor, however, when the RC circuit protection is added to the contector, the generator's performance is improved during the fault appearance, but it still showed a decline in power generation due to fault disruption. In Figure 5.49 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the 20% voltage dip appeared at 0.3sec, reactive power sudden disturbed to 1Mvar and then the generator began to intake a reactive power from the grid to reach 0.35 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The gray dotting on the figure shows the previous result of the reactive power during 20% dip where the reactive power was at zero during fault effect of the contactor, however, when the RC circuit protection is added to the contector, the generator's performance is improved during the fault appearance, but the generator still absorbs the reactive power of the grid before voltage dip disappeared, at 0.5 sec the system started recovering. Figure 5.49 (iii) depicts a rise in the voltage of the DC-link up to 1500 Vdc at the beginning to reach the stable 1150 Vdc. At voltage dip, voltage duration of DC-link is described but it is acceptable. The gray dotting on the figure shows the previous result of the DC Voltage during 20% dip where the voltage is suddenly decreased with significantly fluctuated during the fault until it reached the lowest value of zero V dc, which increases rapidly after fault disappearance. However, when the RC circuit protection is added to the contector, the DC voltage is improved during the fault appearance. And its value during fault is acceptable. The Figure 5.49 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u p.u which is still acceptable. The gray dotting on the figure shows the previous result of the Torque during 20% dip where the Torque was at zero during the fault effect the contactor, however, when the RC circuit protection is added to the contector, the Torque behavior is improved during the fault appearance.

5.2.4.3 Result of DFIG under unsymmetrical 2 phase fault with RC Circuit of Contactor Coil

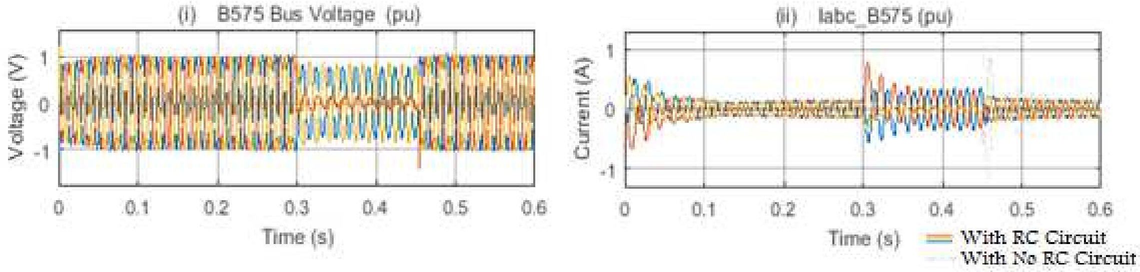

Figure (5.50) simulation results of Bus bar number B575 asymmetrical Grid voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, when (i) shows the Bus bar voltage, (ii) shows Bus bar current. With adding RC circuit to the contactor coil

In this part, the simulated system is applied two phase asymmetrical fault with adding RC circuit to the contactor coil, the fault appeared at 0.3sec for 150 milliseconds then disappeared at 0.45s of simulation time. The results in Figure 5.50 (i) shows that the bus B575 voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared which leads to the bus current transient, as shown in Figure 5.50 (ii), the current on bus B575 Suddenly increased to 0.78 p.u at the beginning of volte transient then settled at 0.3p.u, then the Currents disturbed again at 0.45 sec to reach 0.16 p.u and then start recovery. The gray dotting on the figure 5.50 (ii) shows the previous result of the current on the Bus B575at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection.

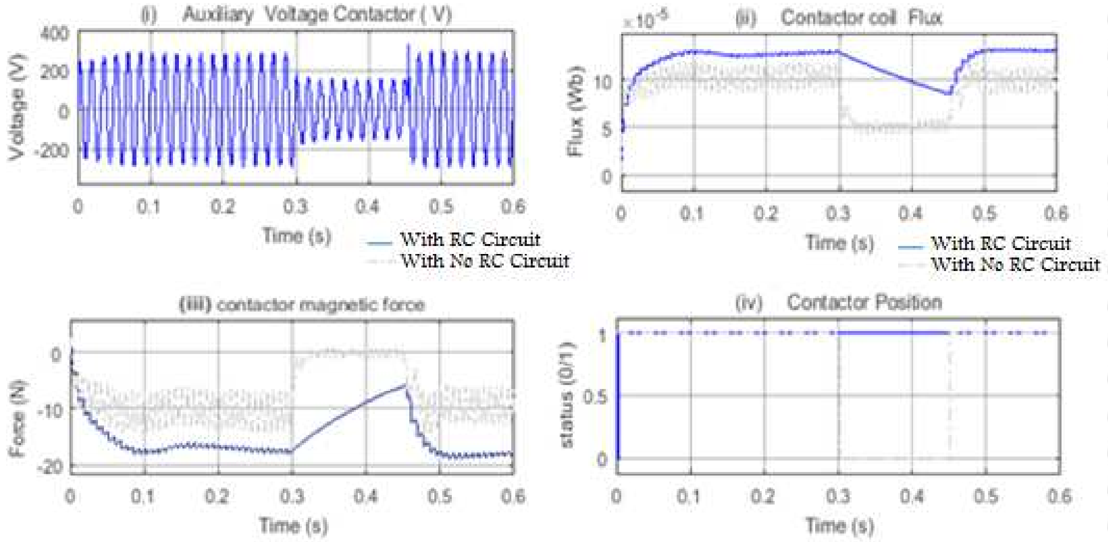

Figure (5.51) simulation results of DFIG Main Contactor statues at asymmetrical Grid voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor armature displacement, and (iv), describe the statues of contactor(on or off).

The figure 5.51 shows the effect of 2 phase grid fault affects the main contactor coil terminals, with adding RC circuit to the contactor coil. Figure 5.51 (i) shows the contactor voltage is decreased at 0.3 sec to 150V, this supposed to cause a sharp drop in the electromagnetic flux of the coils, but as shown in figure 5.51 (ii), the flux decreases linearly as an function in time, which keeps the magnetic force strong enough to magnetize the armature then keep the contactor stay closing its contacts during the fault duration. The gray dotting on the figure 5.51 (ii) shows the previous result of the contactor coil at voltage dip, so with the proposed contactor RC circuit, the coil is recovered upon the fault disappeared. The figure 5.51 (iii) shows that the contactor coil magnetic force still at -3N indicating that the contacts is remained closed during the fault period. This is also shown in figure 5.51 (iv) which describe the opening and closing status of the contector, which in this status indicates 1, The generator is stay connected during the fault.

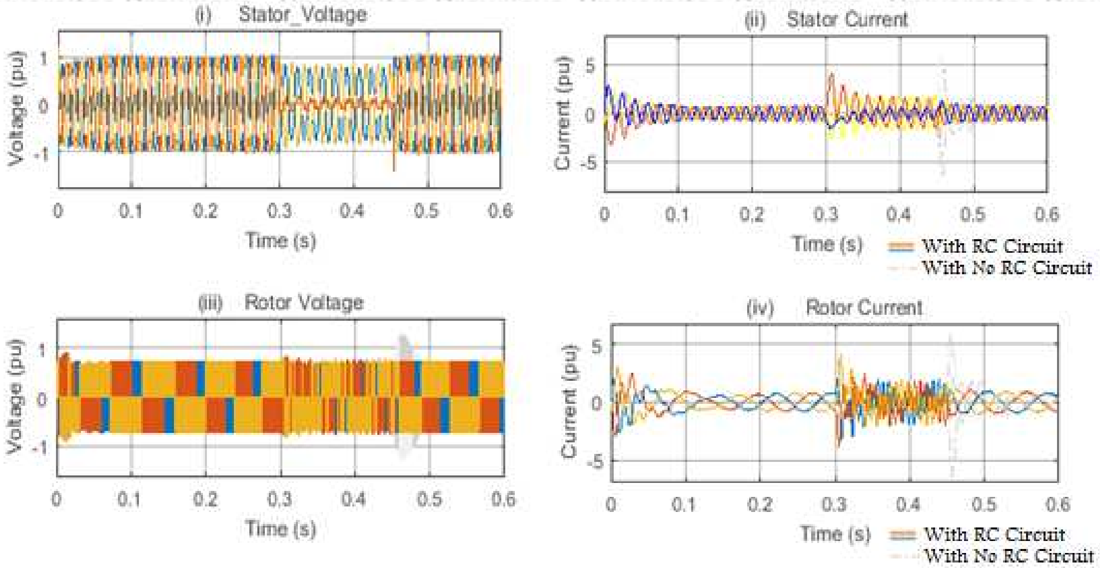

Figure (5.52) the simulation results of DFIG connected to the grid at asymmetrical Grid voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.52 (i) shows that the stator voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared this leads to current transient on the stator current as shown in Figure 5.52 (ii), the current suddenly increased to 4 p.u at the beginning of volte transient, Then stabilized at 2 p.u with an unbalance throughout the period of transient, but the current unbalance did not exceed the allowable range. At 0.45 sec the current stabled at 0.8 p.u and then start recovery. The gray dotting on the figure 5.52 (ii) shows the previous result of the stator current at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. The figure 5.52 (iii) shows that the voltage is constant at 0.7 p.u until the voltage dip appeared at 0.3 sec, then disturb between 0.7 to 0.72 p.u where the voltage appears in a semi-stable state on the rotor As a result of convertor mechanism, Where the voltage appears in a semi-stable state on the rotor As a result of convertor mechanism, until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. The gray dotting on the figure 5.52 (iii) shows the previous result of the stator voltage at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the voltage shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. Figure 5.52 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 3 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec when current a bit fluctuated and started to recovery to stabilize at 1p.. The gray dotting on the figure 5.52 (iv) shows the previous result of the rotor current during voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

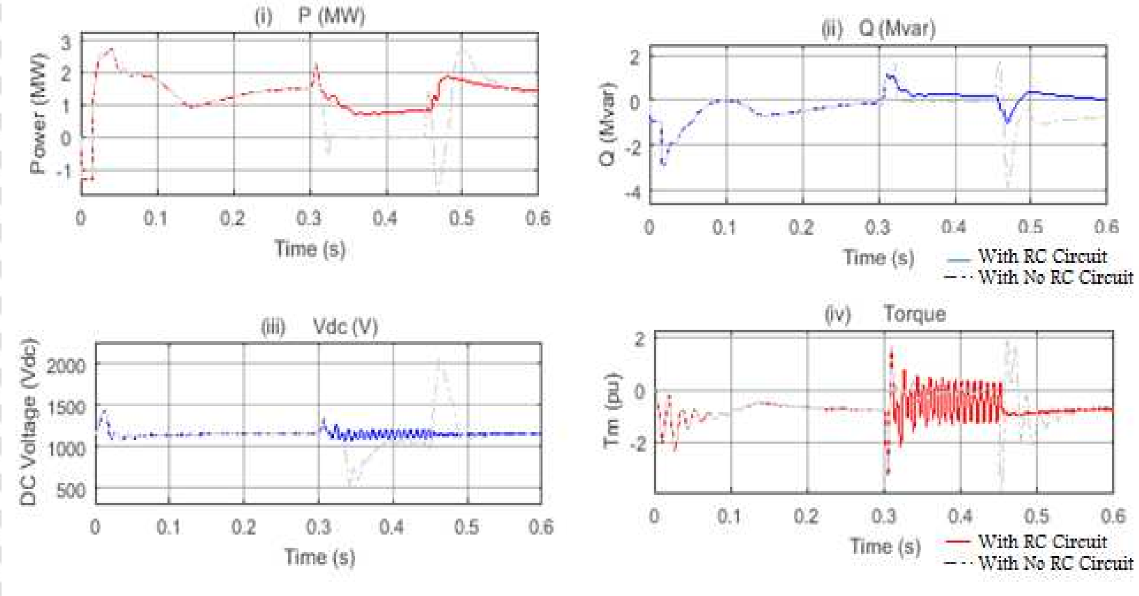

Figure (5.53) the simulation results of DFIG connected to the Grid at asymmetrical Grid voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, when The curve (i) describe the active power statues, the curve (ii) describe the reactive power statues, curve (iii) shows the Dc voltage and The curve (iv) describe the electrical torque statues.

The simulation results in figure 5.53 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared due to grid two phase fault at 0.3sec, Active power drops to 0.8 MW, at 0.45s With fault disappearance start recovered. The gray dotting on the figure shows the previous result of the active power where it was at zero during fault impact of the contactor, however, when the RC circuit protection is added to the contector coil, the generator's performance is improved during the fault appearance, but it still showed a decline in power generation due to fault disruption. In Figure 5.53 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the fault transient appeared at 0.3sec, reactive power sudden disturbed to 1.3 Mvar then the generator began to intake a reactive power from the grid to reach 0.25 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The gray dotting on the figure shows the previous result of the reactive power during fault where the reactive power was at zero during fault has effected the contactor, however, when the RC circuit protection is added to the contector coil, the generator's performance is improved during the fault appearance, but the generator still absorbs the reactive power of the grid before voltage dip disappeared, at 0.5 sec the system started recovering. Figure 5.53 (iii) depicts a rise in the voltage of the DC-link up to 1500 Vdc at the beginning to reach the stable 1150 Vdc. At voltage dip, voltage duration of DC-link is described but that is acceptable. The gray dotting on the figure shows the previous result of the DC Voltage during two phase grid fault duration, where increased rapidly after fault disappearance. However, when the RC circuit protection is added to the contector, the DC voltage is improved during the fault appearance. The Figure 5.53 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u p.u which is still acceptable. The gray dotting on the figure shows the previous result of the Torque during fault where the Torque was at zero during the fault effect the contactor, however, when the RC circuit protection is added to the contector, the Torque behavior is improved during the fault appearance.

5.2.4.4 Result of DFIG under unsymmetrical 2 phase to ground fault with RC circuit of the contactor coil

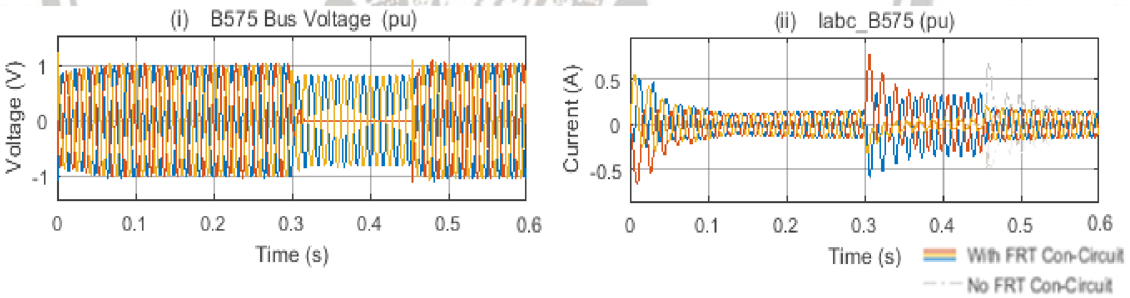

Figure (5.54) simulation results of Bus bar number B575 asymmetrical Grid voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, when (i) shows the Bus bar voltage, (ii) shows Bus bar current. With adding RC circuit to the contactor coil

In this part, the simulated system is applied two phase to ground asymmetrical fault with adding RC circuit to the contactor coil, the fault appeared at 0.3sec for 150 milliseconds then disappeared at 0.45s of simulation time. The results Figure 5.54 (i) shows that the bus B575 voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared which leads to the bus current transient, as shown in Figure 5.54 (ii), the current on bus B575 Suddenly increased to 0.8 p.u at the beginning of transient then settled at 0.35p.u, with phase unbalance, then again at 0.45 sec stabled at its value 0.16 p.u to start recovery.

The gray dotting on the figure 5.54 (ii) shows the previous result of the current on the Bus B575at two phase asymmetrical fault without FRT contactor circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector coil protection.

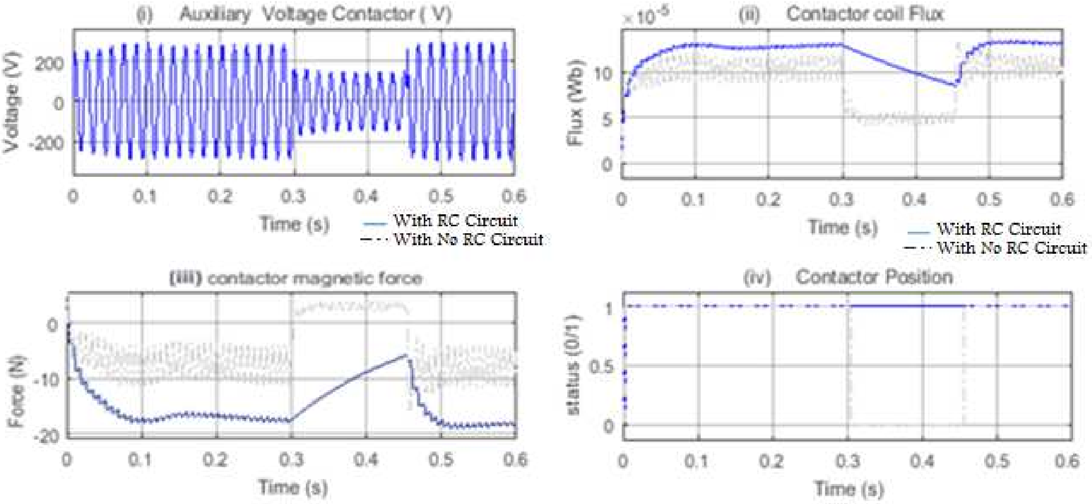

Figure (5.55) simulation results of DFIG Main Contactor statues at asymmetrical Grid voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil force, and (iv), describe the statues of contactor (on or off).

The figure 5.55 shows the effect of two phase to ground grid fault affects the main contactor coil terminals, with adding RC circuit to the contactor coil. Figure 5. 54 (i) shows the contactor voltage is decreased at 0.3 sec to 130V, this supposed to cause a sharp drop in the electromagnetic flux of the coils, but as shown in figure 5.55 (ii), the flux decreases linearly as an function in time, which keeps the magnetic force strong enough to magnetize the armature then keep the contactor stay closing its contacts during the fault duration. The gray dotting on the figure 5.55 (ii) shows the previous result of the contactor at voltage dip, so with the proposed RC circuit, the coil contactor is recovered upon the fault disappeared. Figure 5.55 (iii) shows that the contactor magnetic force still at -3N indicating that the contactor is remained closed its contacts during the fault period. This is also shown in figure 5.55 (iv) which describe the opening and closing status of the contector, which in this status indicates 1, The generator is stay connected during the fault.

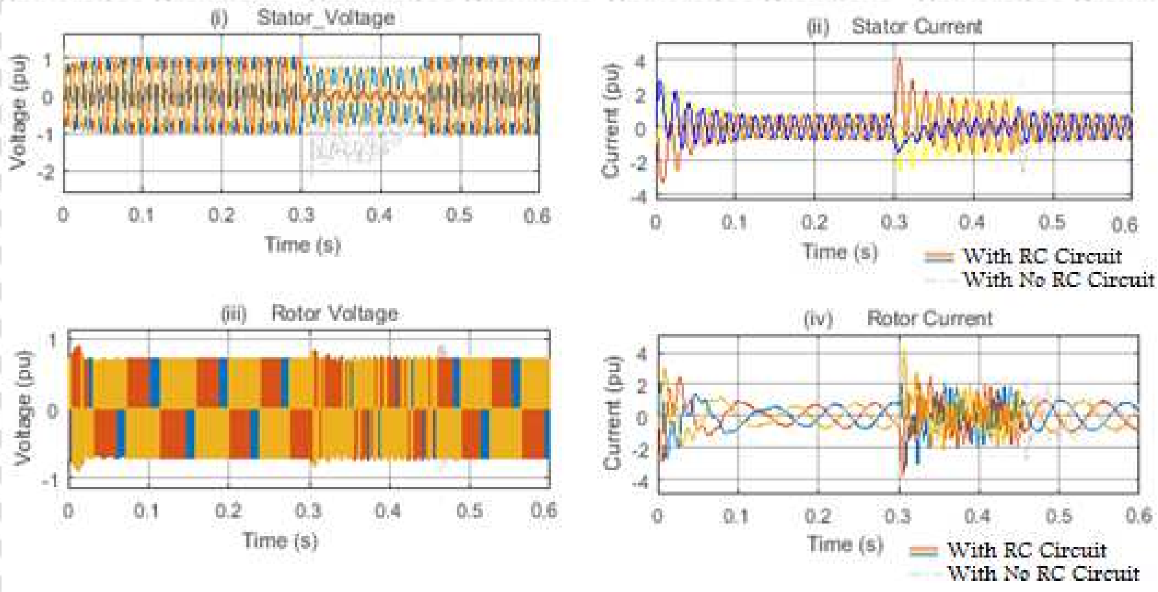

Figure (5.56) the simulation results of DFIG connected to the grid at asymmetrical Grid voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor Voltage , (iv) shows the rotor current.

During two phase to ground asymmetrical grid fault, the results in Figure 5.56 (i) shows that the stator voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared during the fault until the system recovered at 0.45s to reach its normal condition 1 p.u again. The gray dotting on the figure 5.56 (i) shows the previous result of the stator voltage at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the voltage shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. The voltage unbalance on the stator during the fault leads to current transient on the stator as shown in Figure 5.56 (ii), when the current suddenly increased to 4 p.u at the beginning of volte transient, then stabilized at 1.8 p.u with an unbalance during the period of transient, but the current unbalance did not exceed the allowable range. At 0.45 sec the current stabled 1 p.u and then start recovery. The gray dotting on the figure 5.56 (ii) shows the previous result of the stator current at two phase to ground asymmetrical fault without RC circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. Figure 5. 56 (iii) shows that the voltage is constant at 0.7 p.u until the voltage dip appeared at 0.3 sec, then disturb between 0.7 to 0.72 p.u, Where the voltage appears in a semi-stable state on the rotor As a result of convertor mechanism until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. The gray dotting on the figure 5.56 (iii) shows the previous result of the stator voltage at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the voltage shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. Figure 5.56 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 4 p.u then decreased to 1.1 p.u with current unbalance until transient disappeared at 0.45sec when current a bit fluctuated and started to recovery to stabilize at 1p. The gray dotting on the figure 5.56 (iv) shows the previous result of the rotor current during voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

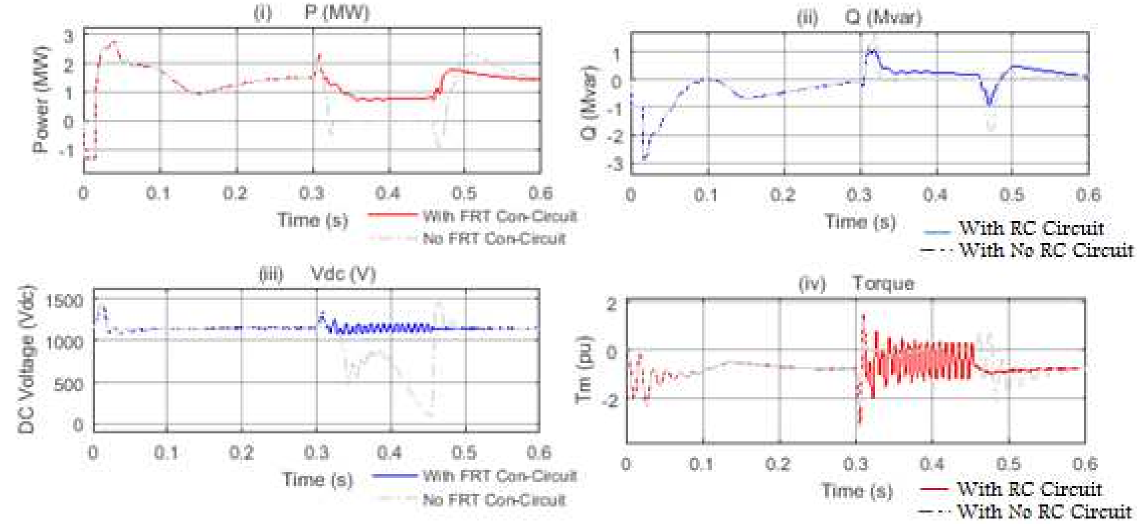

Figure (5.57) the simulation results of DFIG connected to the Grid at asymmetrical by two phase to ground fault, with adding RC circuit to the contactor coil, when (i) describe the active power statues, the (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.57 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared due to grid two phase to ground fault at 0.3sec, Active power drops to 0.75 MW, at 0.45s With fault disappearance start recovered. The gray dotting on the figure shows the previous result of the active power where it was at zero during fault impact of the contactor, however, when the RC circuit protection is added to the contector coil, the generator's performance is improved during the fault appearance, but it still showed a decline in power generation due to fault disruption. In Figure 5.57 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the fault transient appeared at 0.3sec, reactive power sudden disturbed to 1.3 Mvar then the generator start to absorb a reactive power from the grid to reach 0.3 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The gray dotting on the figure shows the previous result of the reactive power during fault where the reactive power was at zero during fault has effected the contactor, however, when the RC circuit protection is added to the contector coil, the generator's performance is improved during the fault appearance, but the generator still absorbs the reactive power of the grid before voltage dip disappeared, at 0.5 sec the system started recovering. Figure 5.57 (iii) shows an increase in the DC-link voltage to reach a value 1500 Vdc at startup to stable to 1150 Vdc. The gray dotting on the figure shows the previous result of the DC Voltage during two phase grid fault duration, where the voltage is suddenly decreased with significantly fluctuated during the fault until it reached the lowest value of zero Vdc, which increases rapidly after fault disappearance. However, when the RC circuit protection is added to the contector, the DC voltage is improved during the fault appearance. And its value during fault is acceptable. The Figure 5.57 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u. The gray dotting on the figure shows the previous result of the Torque during fault where the Torque was at zero during the fault effect the contactor, however, when the RC circuit protection is added to the contector, the Torque behavior is improved during the fault appearance.

5.2.4.5 Result of DFIG under symmetrical three phase fault with RC circuit of the contactor coil

In this part, the simulated system is applied three phase symmetrical fault with adding RC circuit to the contactor coil, the fault appeared at 0.3sec for 150 milliseconds then disappeared at 0.45s of simulation time.

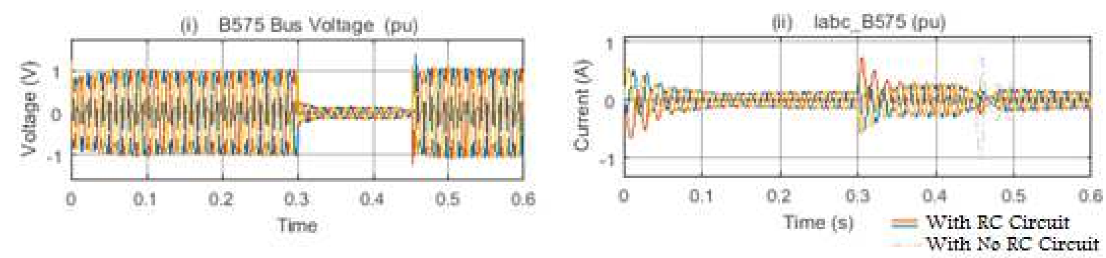

Figure (5.58) simulation results of Bus bar number B575 asymmetrical Grid voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, when (i) curve shows the Bus bar voltage, (ii) curve shows Bus bar current. With adding RC circuit to the contactor coil

The results Figure 5.58 (i) shows that the bus B575 voltage is dipped to 0.15 p.u, then at 0.45s when fault disappeared, voltage reach its normal 1 p.u. again. in Figure 5.58 (ii), the current on bus B575 Suddenly increased to 0.74 p.u at the beginning of volte transient then settled at 0.3p.u, at 0.45 sec while fault disappeared current disturbed then stabled at its value 0.16 p.u to start recovery. The gray dotting on the figure 5.58 (ii) shows the previous result of the current on the Bus B575at three phase symmetrical grid fault without FRT contactor coil circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector coil protection.

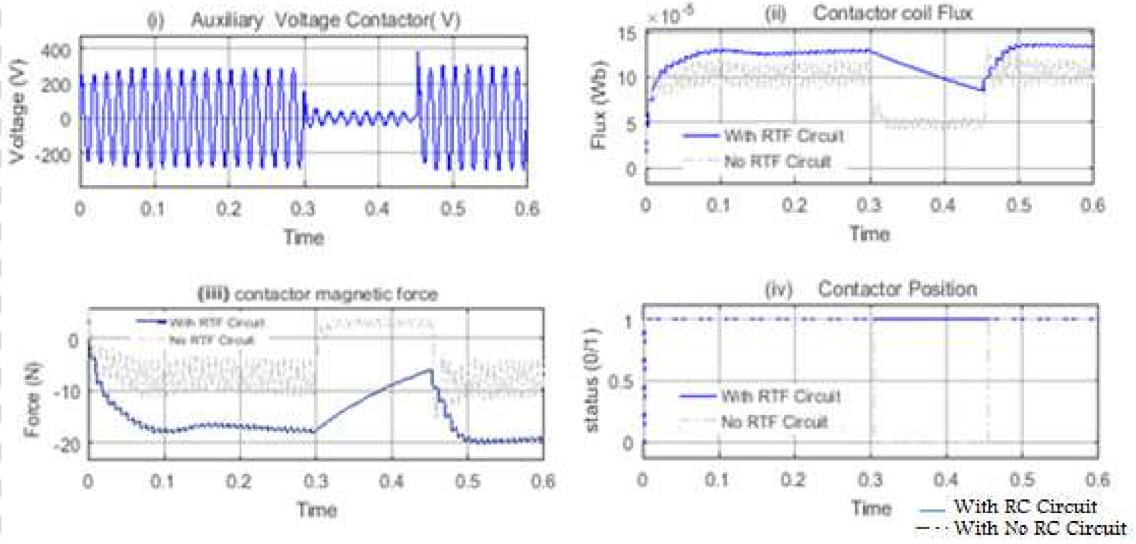

Figure (5.59) simulation results of DFIG Main Contactor statues at asymmetrical Grid voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, when (i) shows the auxiliary contactor voltage, (ii) shows contactor coil flux value, (iii) describe the contactor coil magnetic force, and (iv), describe the statues of contactor (on or off).

The figure 5.59 shows the three phase grid fault affected the main contactor coil terminals, with adding RC circuit to the contactor coil. Figure 5.59 (i) shows the contactor voltage is decreased at 0.3 sec to 40V, this supposed to cause a sharp drop in the electromagnetic flux of the coils, but as shown in figure 5.59 (ii), the flux decreases linearly as an function in time, which keeps the magnetic force strong enough to magnetize the armature then keep the contactor stay closing its contacts during the fault duration. The gray dotting on the figure 5.59 (ii) shows the previous result of the contactor at voltage dip, so with the proposed RC circuit, the contactor coil is recovered upon the fault disappeared. Figure 5.59 (iii) shows that the contactor magnetic force still below -3N indicating that the contactor is remained closed its contacts during the fault period.

This is also shown in figure 5.59 (iv) which describe the opening and closing status of the contector, which in this status indicates 1, The generator is stay connected during the fault.

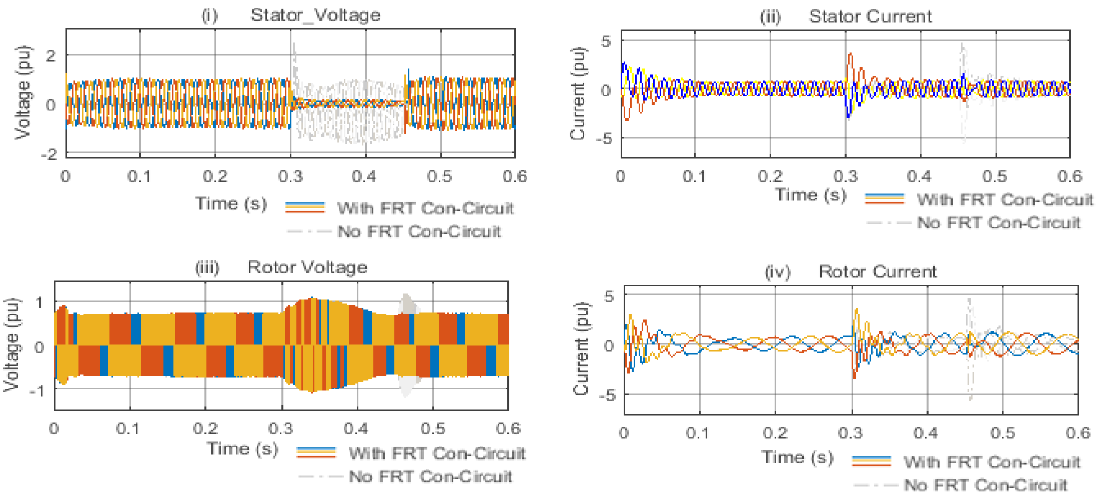

Figure (5.60) the simulation results of DFIG connected to the grid at asymmetrical Grid voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

During three phase symmetrical grid fault, the results in Figure 5.60 (i) shows that the stator voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared during the fault until the system recovered at 0.45s to reach its normal condition 1 p.u again.

The gray dotting on Figure 5.60 (i) shows the previous result of the stator voltage at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the voltage shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. The voltage unbalance on the stator during the fault leads to current transient on the stator as shown in Figure 5.60 (ii), when the current suddenly increased to 4 p.u at the beginning of volte transient, then stabilized at 1.8 p.u with an unbalance during the period of transient. At 0.45 sec the current stabled 1 p.u and then start recovery. The gray dotting on the figure 5.60 (ii) shows the previous result of the stator current at two phase to ground asymmetrical fault without RC circuit, so with the proposed contactor protection, the current shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. The figure 5.60 (iii) shows that the voltage is constant at 0.7 p.u until the voltage dip appeared at 0.3 sec, then increased to 1.2 p.u until the system recovered at 0.45s to reach its normal condition 0.7 p.u again. The gray dotting on the figure 5.60 (iii) shows the previous result of the stator voltage at two phase asymmetrical fault without RC circuit, so with the proposed contactor protection, the voltage shows improvement during the period of fault disappearance compared to its condition with no FRT contector protection. Figure 5.60 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 4 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec when current a bit fluctuated and started to recovery to stabilize at 1p. The gray dotting on the figure 5.60 (iv) shows the previous result of the rotor current during voltage dip, without FRT contactor circuit, so with the proposed contactor protection, the current is recovered upon the fault disappeared.

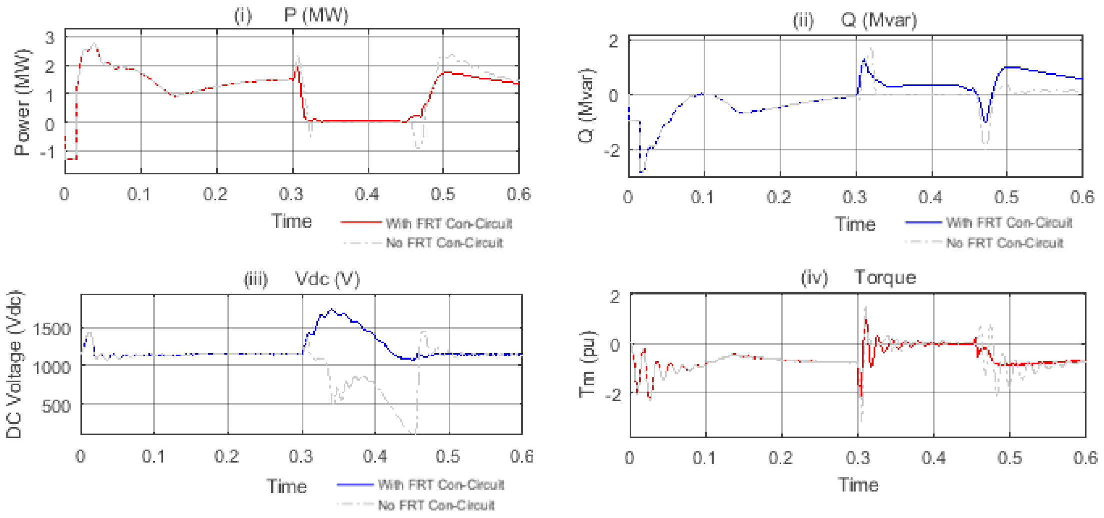

Figure (5.61) the simulation results of DFIG connected to the Grid at asymmetrical Grid voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, when (i) describe the active power statues, (ii) describe the reactive power statues, curve (iii) shows the Dc voltage and (iv) describe the electrical torque statues.

The simulation results in figure 5.61 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared due to grid three phase to ground fault at 0.3sec, Active power drops to zero MW, at 0.45s with fault disappearance start recovered. The gray dotting on the figure shows the previous result of the active power where it was at zero during fault impact of the contactor, however, when the RC circuit protection is added to the contector coil, the generator's performance is improved during the fault appearance, but it still showed a decline in power generation due to fault disruption. In Figure 5.61 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the fault transient appeared at 0.3sec, reactive power sudden disturbed to 1.2 Mvar then the generator start to absorb a reactive power from the grid to reach 0.3 Mvar before voltage dip disappeared, it is showed that the generator observed reactive power from the grid similar to the synchronous motors without any active power productivity. When the grid fault disappeared at 0.5 sec the system started recovering. The gray dotting on the figure shows the previous result of the reactive power during fault where the reactive power was at zero during fault has effected the contactor, however, when the RC circuit protection is added to the contector coil, the generator's performance is improved during the fault appearance, but the generator still absorbs the reactive power of the grid before voltage dip disappeared, at 0.5 sec the system started recovering. Figure 5.61 (iii) shows an increase in the DC-link voltage to reach a value 1500 Vdc at startup to stable to 1150 Vdc, at voltage dip duration, DC-link voltage is steadily increased to reach its highest value 1760 Vdc, This value of the DC voltage represents a danger to the converter. The gray dotting on the figure shows the previous result of the DC Voltage during three phase grid fault duration, where the voltage is suddenly decreased with significantly fluctuated during the fault until it reached the lowest value of zero V dc, which increases rapidly after fault disappearance. However, when the RC circuit protection is added to the contector, High voltage on the converter is a real risk that may cause it to be damaged. The Figure 5.61 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 1 p.u which is still acceptable then dropped to zero during fault. After the grid fault were recede, the torque regularly stabilized. The gray dotting on the figure shows the previous result of the Torque during fault where the Torque was at zero during the fault effect the contactor, however, when the RC circuit protection is added to the contector, the Torque behavior is improved during the fault appearance.

5.2.4.6 The results Summary

Through the simulated voltage dips caused by Grid fault under study in this part 5.4.4 of simulation. The proposed RC circuit was added to the simulated contactor coil. The faults under study are symmetrical 40% and 20% voltage dip and also the asymmetrical two phase and two phase to ground faults and symmetrical three phase fault. Where the simulated contactor coil has showed a significant effect with these type of faults during the simulation in part 5.4.3. The analysis of the results showed that the proposed additional RC circuit of the contactor coil was successful with all the faults that affected the contactor in previous experiments. However, the simulation demonstrated that some of these faults significantly effects the performance of the DFIG wind turbine, where the symmetrical voltage dip up to 20% of the grid voltage showed that, the DFIG generator still provide active power to the Grid with, although there is a reactive power to do so. The electromechanical torque is also disruptive during the faults. Also, the current disturbance on the rotor and the stator of DFIG, as well as the DC-link voltage Shows oscillation but at an acceptable rate during up to 20% symmetrical voltage dip. During asymmetrical voltage dip due to two phase and two phase to ground grid faults. the results indicated a voltage unbalance and fluctuation in the current on both the rotor and stator of the DFIG generator during the fault time. The frequency of the rotor current is also oscillated due to the grid frequency and the increase in the turbine rotation resulting from the fluctuation of torque. The DC link voltage of the converter appears distortion and the active power decreases, and the Generator observes reactive power from the Grid. The of the rotor voltage increases steadily during the voltage drop resulting due symmetrical three-phase Grid faults, also, the DC link voltage is increased.

Thus, the proposed VR crowbar protection will be added to the converter and rotor windings, to continue the study the behavior of the generator during Grid faults. The protection is a variable resistor, which automatically increases according to the DC link voltage during the faults, to protect the converter from increasing current, and chopper resistor also added to limit the DC link voltage. Therefore, the previous faults will be analyzed in the next part of simulation by adding both the proposed protections, the contactor RC circuit and VR crowbar protection to the simulated model and the study of the results, in an attempt to achieve a safe and successful ride through during grid fault.

5.2.5 Simulation Result of DFIG under voltage dip with adding RC contactor circuit and VR crowbar protection

The Simulation is operated protection under voltage dip with adding RC circuit in parallel to the contactor coil and VR crowbar protection which consist of controllable variable Resistance in parallel to DFIG rotor winding and chopper resistor in Parallel converter Bus Link capacitor.

5.2.5.1 Result of DFIG with RC & VR proposed protection under 40% voltage dip

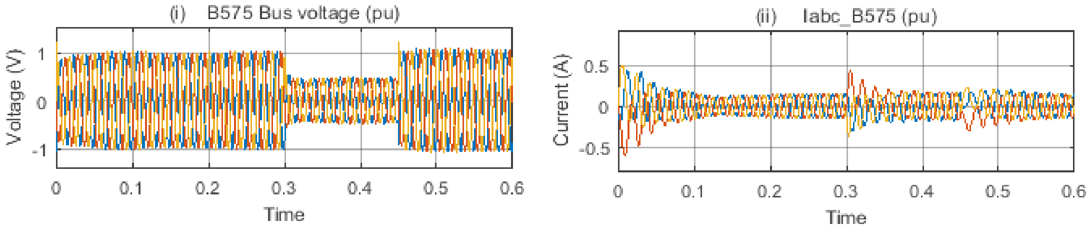

Figure (5.62) simulation results of Bus bar number B575 at 40 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the Bus bar voltage, (ii) shows Bus bar current.

Figure 5.62 (i) shows that the bus voltage Bus B575 which has constant at 1 p.u until the voltage dip appeared, then voltage suddenly decreased to 0.4 p.u at 0.3 sec of simulation to recovery at 0.45s to reach its normal 1 p.u. again. Figure 5.62 (ii) shows the Bus B575 current, its fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.15p.u until the voltage dip appeared at 0.3sec, then the current fluctuated between fluctuate between 0.35 to 0.2p.u until transient disappeared at 0.45s to stabilized back after that to 0.15p.u.

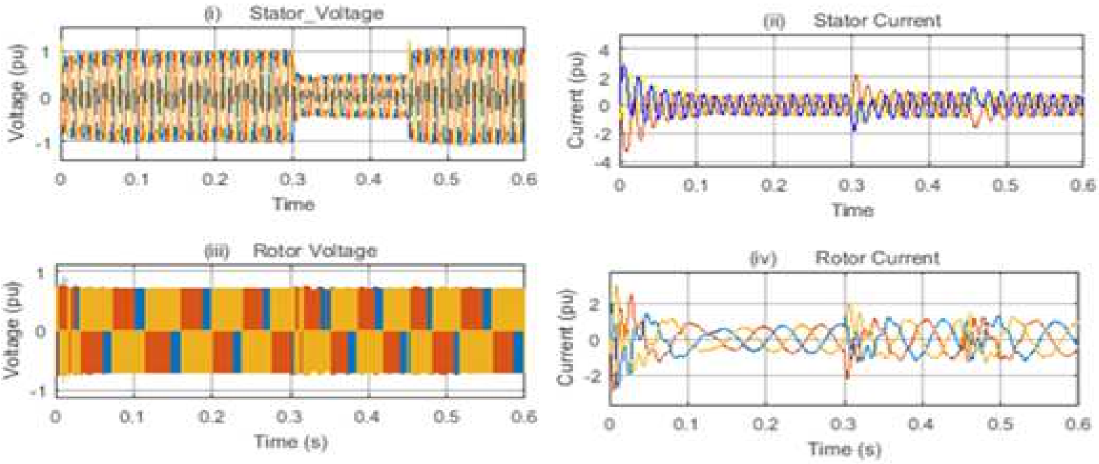

Figure (5.63) the simulation results of DFIG connected to the Grid at 40 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.63 (i) shows the stator voltage, where it was constant at 1 p.u until the voltage dip appeared, and then the stator voltage suddenly decreased to 0.4 p.u at 0.3sec until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.63 (ii) the shows that stator current is fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.8p.u until the voltage dip appeared at 0.3s, after it, the current overshoot to 2 p.u then stabled at 1 p.u until transient disappeared at 0.45s to stabilize at 0.8p.u again.

The figure 5.63 (iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared at 0.3sec, there is a slight disturbance of the rotor voltage, this due to the interaction of proposed protection with the grid fault effects, which contributed to the inhibition of the increase in voltage on the rotor, Which contributed to improving the rotor voltage during this type of faults. Figure 5.63 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 2 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec to stabilized after that at 1p.u and recovering.

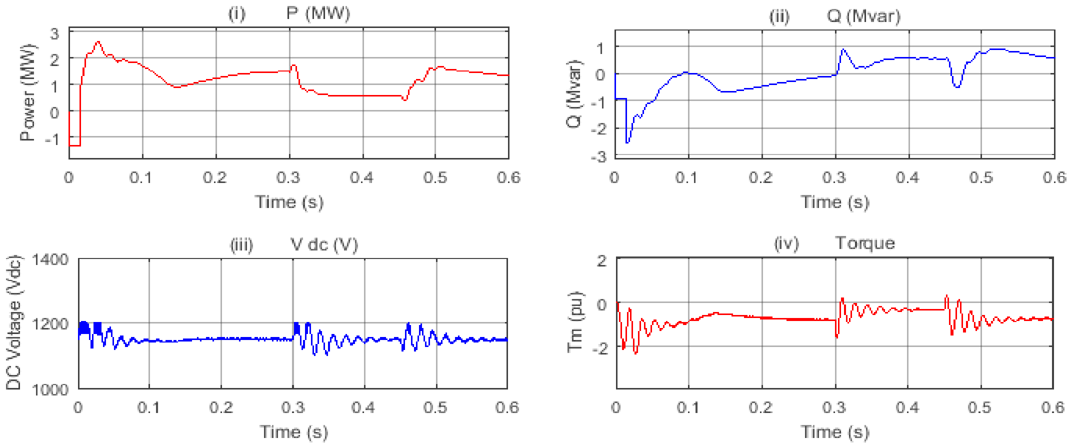

Figure (5.64) the simulation results of DFIG connected to the Grid at 40% symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the active power statues, (ii) describe the reactive power statues, (iii) shows the Dc voltage and (iv), describe the torque statues.

The simulation results in figure 5.64 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 0.8 MW, then start recovered at 0.45s With time of fault disappearance. In Figure 5.64 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the 40% voltage dip appeared at 0.3sec, reactive power sudden disturbed to 1Mvar then the generator start to absorb a reactive power from the grid to reach 0.8 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The Figure 5.64 (iii) shows an increase in the DC-link voltage reached 1200 Vdc during startup to stable to 1150 Vdc, at voltage dip appearance, The proposed RV crowbar worked to damping the value of DC voltage at 1200V dc, which is what the results, where the highest voltage value is 1200 during the simulation period. Figure 5.64 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec to reach a value 0.7p.u pu which is still acceptable.

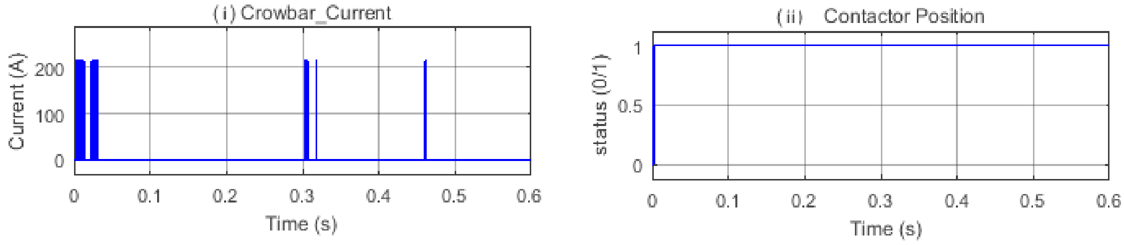

Figure (5.65) the simulation results of DFIG connected to the Grid at 40% symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the crowbar resistor current in ampere, (ii) describe the statues of contactor(on or off) during the fault.

In figure 5.65 (i) the proposed protection shows a response to the changes in the DC link voltages, which contributed to the inactivation of the current on the converter during the startup status of the generator. This protection appeared again during the grid fault, which contributed to the determination of the DC voltage. Figure 5.65 (ii) which describe the opening and closing status of the contector, which in this status indicates 1, the generator is stay connected during the fault.

5.2.5.2 Result of DFIG with RC & VR proposed protection under 20% voltage dip

In this part, 20% voltage dip applied with adding RC circuit to the contactor coil and VR crowbar to the DFIG wind torbin .

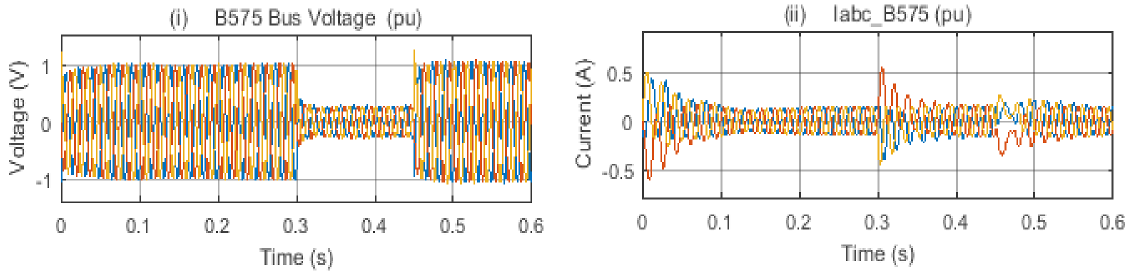

Figure (5.66) simulation results of Bus bar number B575 at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the Bus bar voltage, (ii) shows Bus bar current.

Figure 5.66 (ii) shows the Bus B575 current, its fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.15p.u until the voltage dip appeared at 0.3sec, then the current fluctuated to 0.6 then stabled to 0.2p.u until transient disappeared at 0.45s to stabilized back after that to 0.15p.u.

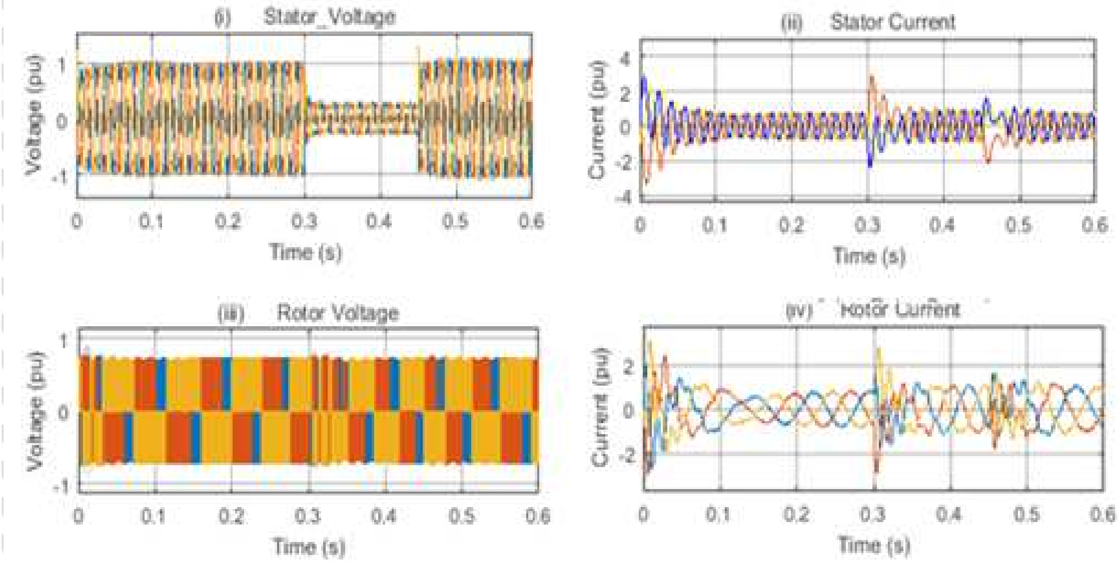

Figure (5.67) the simulation results of DFIG connected to the Grid at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.67 (i) shows the stator voltage, where it was constant at 1 p.u until the voltage dip appeared, and then the stator voltage suddenly decreased to 0.2 p.u at 0.3sec until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.67 (ii) the shows that stator current is fluctuated at startup for an interval time of 0.1sec, then stabilized at 0.8p.u until the voltage dip appeared at 0.3s, after it, the current overshoot to 3 p.u then stabled at 1 p.u until transient disappeared at 0.45s when current a bit fluctuated and then started to recovery to stabilize at 0.8p.u again. Figure 5.67 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 3 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec when current a bit fluctuated and then started to recovery to stabilize at 1p.u and recovering.

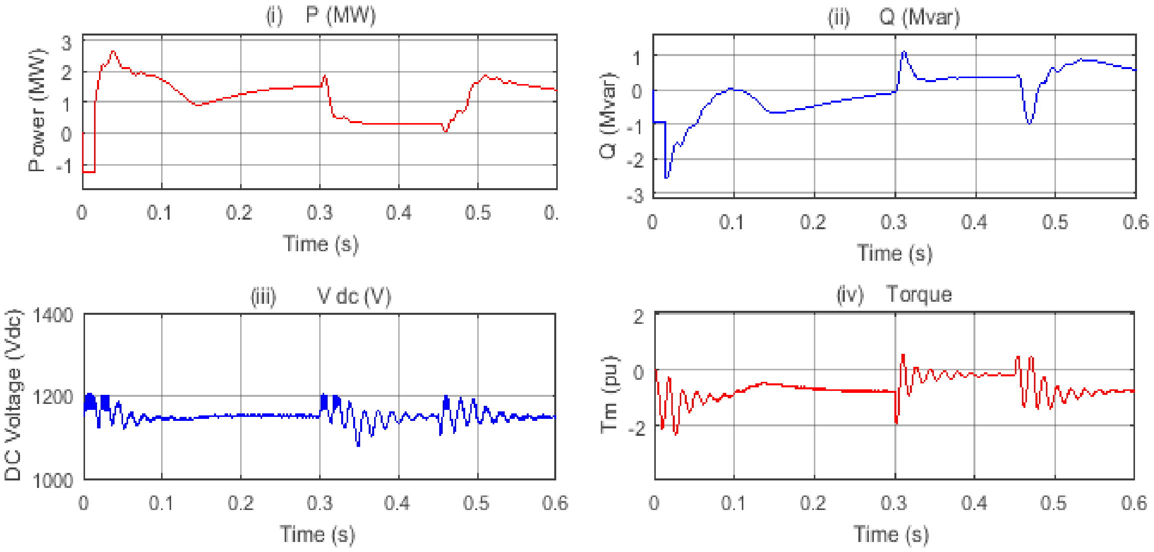

Figure (5.68) the simulation results of DFIG connected to the Grid at 20 % symmetrical Grid voltage dip with adding RC circuit to the contactor coil, when (i) describe the active power statues, (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the electrical torque statues.

The simulation results in figure 5.68 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 0.3 MW, then start recovered at 0.45s With time of fault disappearance. In Figure 5.68 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the 20% voltage dip appeared at 0.3sec, reactive power sudden disturbed to 1Mvar then the generator start to absorb a reactive power from the grid to reach 0.35 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The Figure 5.68 (iii) shows an increase in the DC-link voltage reached 1200 Vdc during startup to stable to 1150 Vdc, at voltage dip appearance, The proposed RV crowbar worked to damping the value of DC voltage at 1200V dc, which is what the results, where the highest voltage value is 1200 during the simulation period. The Figure 5.68 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec is disturbed to reach a value -2 then stabled to 0.7p.u. At 0.45 sec, the torque a bit fluctuated and then started recovery.

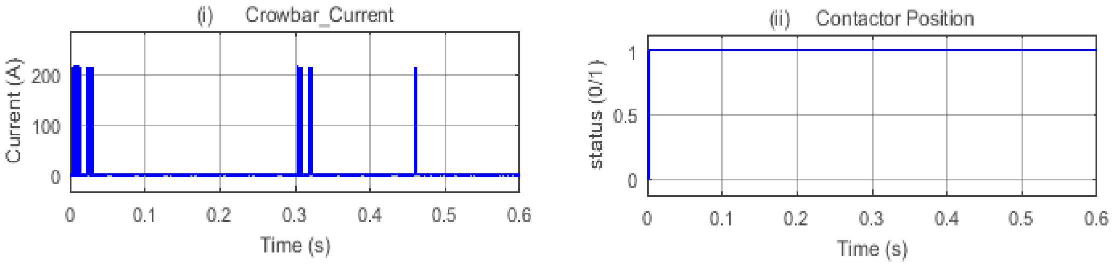

Figure (5.69) the simulation results of DFIG connected to the Grid at 20% symmetrical Grid voltage dip with adding RC circuit to the contactor coil, and VR crowbar to the generator, when The (i) describe the crowbar resistor current in ampere, the (ii) describe the statues of contactor(on or off) during the fault.

In figure 5.69 (i) the proposed protection shows a response to the changes in the DC link voltages, which contributed to the inactivation of the current on the converter during the startup status of the generator. This protection appeared again during the grid fault, which contributed to the determination of the DC voltage. Figure 5.69 (ii) which describe the opening and closing status of the contector, which in this status indicates 1, the generator is stay connected during the fault.

5.2.5.3 Result of DFIG with RC & VR proposed protection under unsymmetrical two phase fault

In this part of simulated system is the results of two phase asymmetrical fault with adding RC circuit to the contactor coil and VR crowbar, the fault appeared at 0.3sec for 150 milliseconds then disappeared at 0.45s of simulation time.

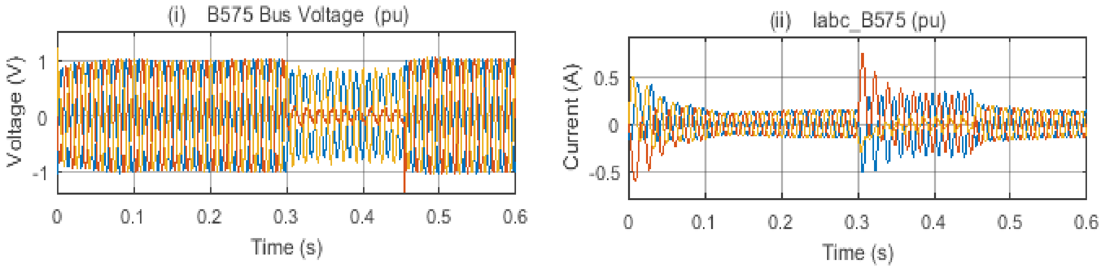

Figure (5.70) simulation results of Bus bar number B575 asymmetrical Grid voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the Bus bar voltage, (ii) shows Bus bar current. With adding RC circuit to the contactor coil

The results Figure 5.70 (i) shows that the bus B575 voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared which leads to the bus current transient, as shown in Figure 5.70 (ii), the current on bus B575 Suddenly increased to 0.78 p.u at the beginning of volte transient then settled at 0.3p.u, then the Currents disturbed again at 0.45 sec to reach 0.16 p.u and then start recovery.

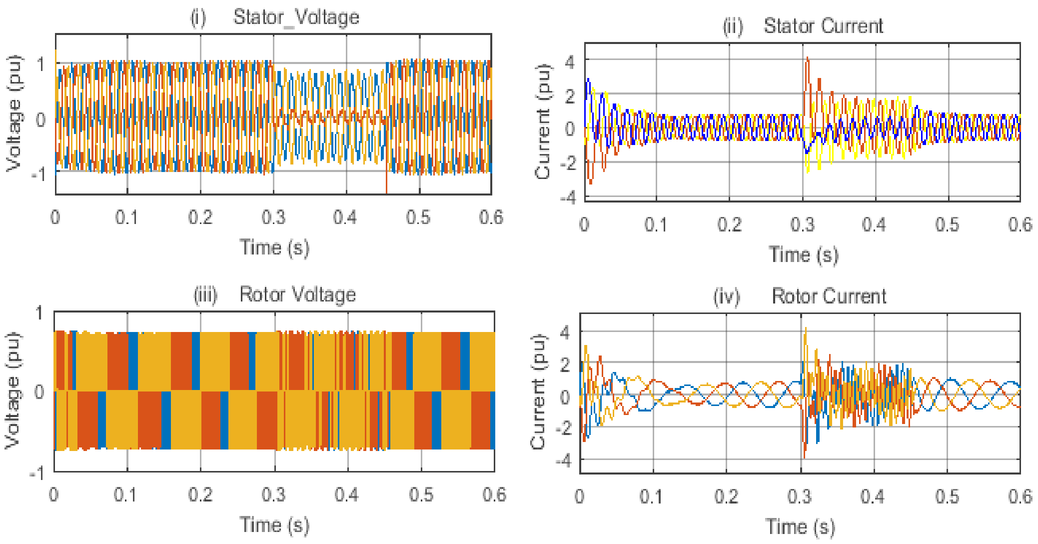

Figure (5.71) the simulation results of DFIG connected to the grid at asymmetrical Grid voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the stator voltage, (ii) curve shows the stator current, (iii) shows the voltage, (iv) shows the current.

Figure 5.71 (i) shows that the stator voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared this leads to current transient on the stator current as shown in Figure 5.71 (ii), the current suddenly increased to 4 p.u at the beginning of volte transient, Then stabilized at 2 p.u with an unbalance throughout the period of transient,. At 0.45 sec the current stabled at 0.8 p.u and then start recovery. The figure 5.71 (iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared at 0.3sec, there is a slight disturbance of the rotor voltage, this due to the interaction of proposed protection with the grid fault effects, which contributed to the inhibition of the increase in voltage on the rotor, Which contributed to improving the rotor voltage during this type of faults. Figure 5.71 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 3 p.u then decreased to 1.1 p.u with unbalance until transient disappeared at 0.45sec when current a bit fluctuated and started to recovery to 1 p.u.

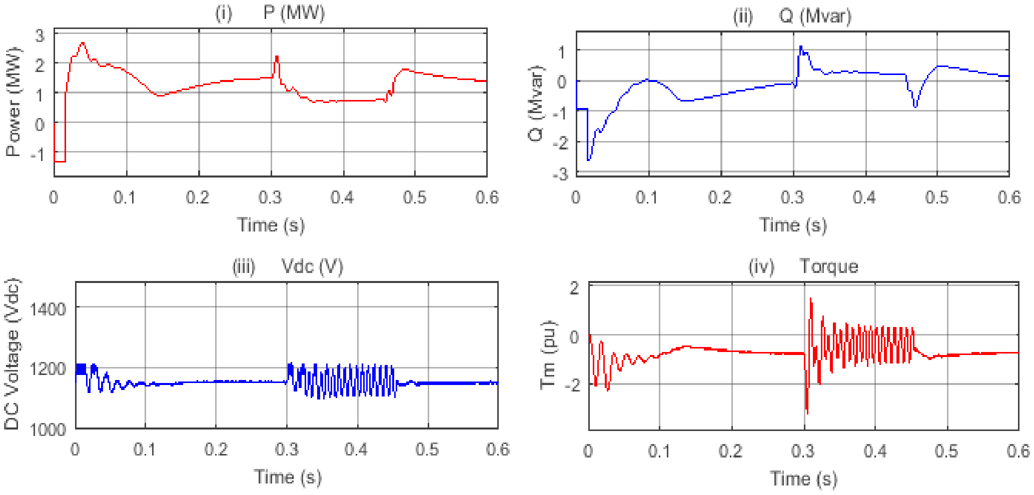

Figure (5.72) the simulation results of DFIG connected to the Grid asymmetrical voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the active power statues, (ii) describe the reactive power statues, (iii) shows the Dc voltage and The (iv) describe the torque statues.

The simulation results in figure 5.72 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 0.8 MW, then start recovered at 0.45s With time of fault disappearance. In Figure 5.72 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the voltage dip appeared at 0.3sec, reactive power sudden disturbed to 1.3 Mvar then the generator start to absorb a reactive power from the grid to reach 0.25 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The Figure 5.72 (iii) shows an increase in the DC-link voltage reached 1200 Vdc during startup to stable to 1150 Vdc, at voltage dip appearance, The proposed RV crowbar worked to damping the value of DC voltage at 1200V dc, which is what the results, where the highest voltage value is 1200 during the simulation period. The Figure 5.72 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec, At 0.45 sec stabled to 0.7 p.u and then started recovery.

In figure 5.73 (i) the proposed protection shows a response to the changes in the DC link voltages, which contributed to the inactivation of the current on the converter during the startup status of the generator. This protection appeared again during the grid fault, which contributed to the determination of the DC voltage. Figure 5.73 (ii) which describe the opening and closing status of the contector, which in this status indicates 1, the generator is stay connected during the fault.

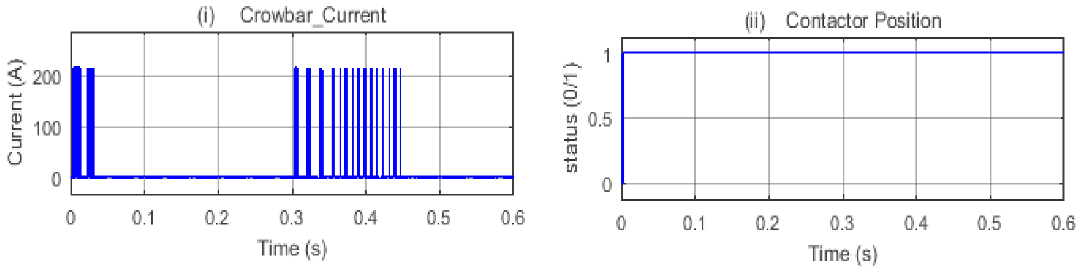

Figure (5.73) the simulation results of DFIG connected to the Grid asymmetrical voltage dip caused by two phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator,, when (i) describe the crowbar resistor current in ampere, (ii) describe the statues of contactor(on or off) during the fault.

5.2.5.4 Result of DFIG with RC & VR proposed protection under unsymmetrical two phase fault to Ground fault

In this part of simulated system is show the results of two phase to ground asymmetrical fault with adding RC circuit to the contactor coil and VR crowbar, the fault appeared at 0.3sec for 150 milliseconds then disappeared at 0.45s of simulation time.

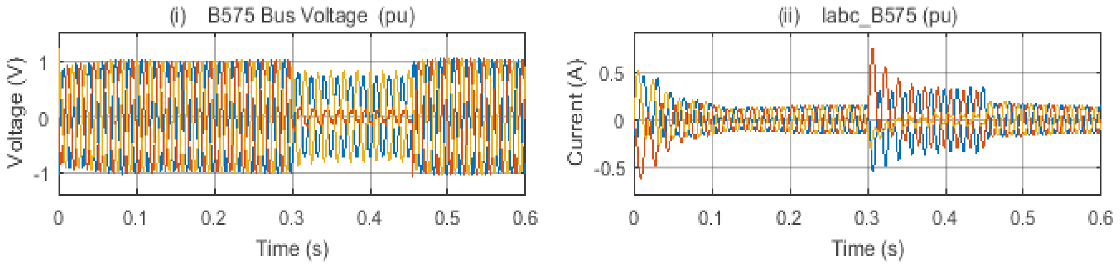

Figure (5.74) simulation results of Bus bar number B575 asymmetrical Grid voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the Bus bar voltage, (ii) shows Bus bar current. With adding RC circuit to the contactor coil

The results Figure 5.74 (i) shows that the bus B575 voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared which leads to the bus current transient, as shown in Figure 5.74 (ii), the current on bus B575 Suddenly increased to 0.78 p.u at the beginning of volte transient then settled at 0.35 p.u with considerable current unbalance , then the fault disturbed at 0.45 sec, then current start recovery.

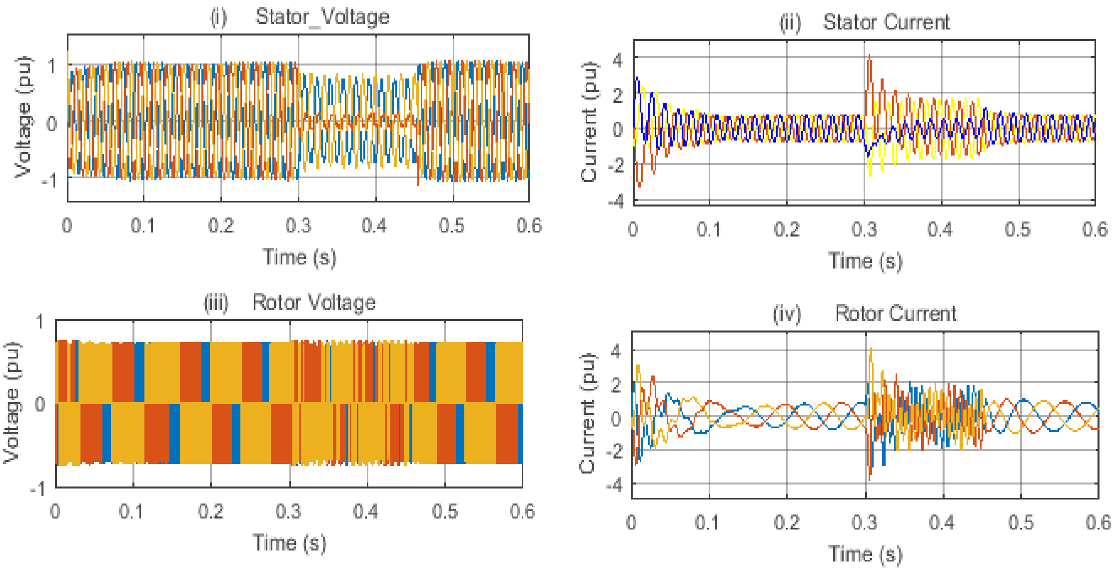

Figure (5.75) the simulation results of DFIG connected to the grid at asymmetrical Grid voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage, (iv) shows the rotor current.

Figure 5.75 (i) shows that the stator voltage is dipped to 0.75 p.u, with Voltage unbalance is appeared, this leads to current transient on the stator current as shown in Figure 5.75 (ii), the current suddenly increased to 4 p.u at the beginning of volte transient, Then stabilized at 2 p.u with an unbalance throughout the period of transient, At 0.45 sec the current stabled at 0.8 p.u and then start recovery. The figure 5.75 (iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared at 0.3sec, there is a slight disturbance of the rotor voltage, this due to the interaction of proposed protection with the grid fault effects, which contributed to the inhibition of the increase in voltage on the rotor, Which contributed to improving the rotor voltage during this type of faults. Figure 5.75 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 4 p.u then decreased to 1.1 p.u with considerable unbalance until transient disappeared at 0.45sec when current a bit fluctuated and then recovery to 1 p.u.

The simulation results in figure 5.76 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared at 0.3sec, Active power drops to 0.8 MW, then start recovered at 0.45s With time of fault disappearance. In Figure 5.76 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the voltage dip appeared at 0.3sec, reactive power sudden disturbed to 1.3 Mvar then the generator start to absorb a reactive power from the grid to reach 0.25 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering.

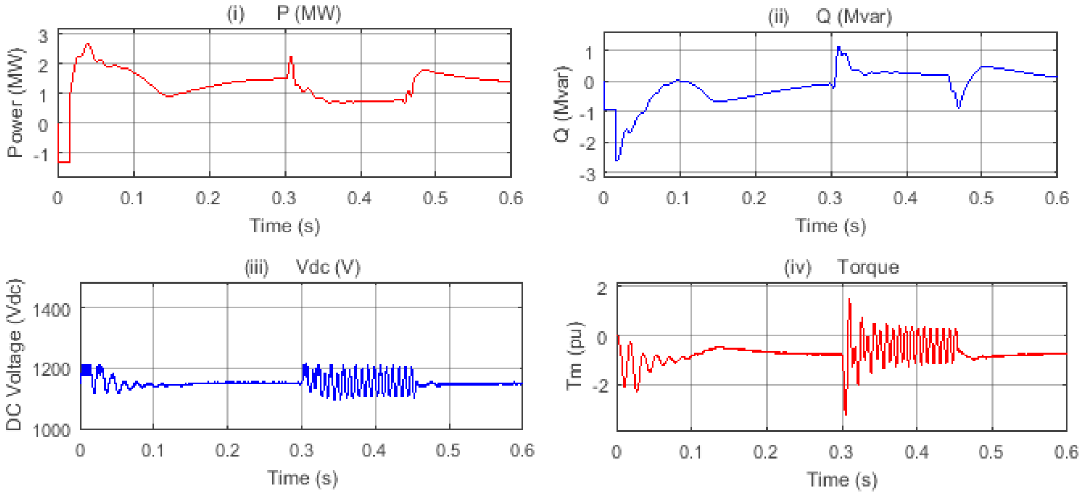

Figure (5.76) the simulation results of DFIG connected to the Grid asymmetrical voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the active power statues, (ii) describe the reactive power statues, (iii) shows the Dc voltage and (iv) describe the torque statues.

The Figure 5.76 (iii) shows an increase in the DC-link voltage reached 1200 Vdc during startup to stable to 1150 Vdc, at voltage dip appearance, The proposed RV crowbar worked to damping the value of DC voltage at 1200V dc, which is what the results, where the highest voltage value is 1200 during the simulation period. The Figure 5.76 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec, At 0.45 sec stabled to 0.7 p.u and then started recovery.

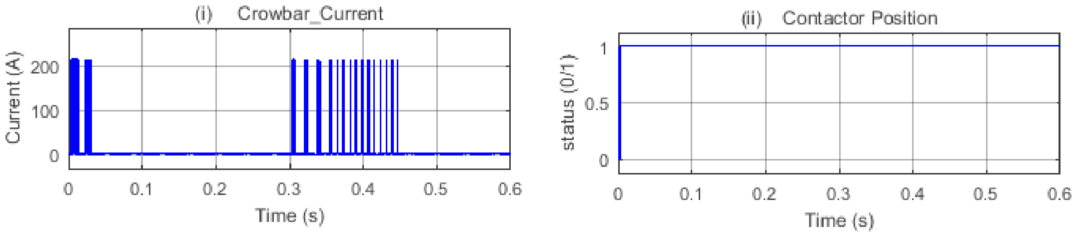

Figure (5.77) the simulation results of DFIG connected to the Grid asymmetrical voltage dip caused by two phase to ground fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the crowbar resistor current in ampere, (ii) describe the statues of contactor (on or off) during the fault.

In figure 5.77 (i) the proposed protection shows a response to the changes in the DC link voltages, which contributed to the inactivation of the current on the converter during the startup status of the generator. This protection appeared again during the grid fault, which contributed to the determination of the DC voltage. Figure 5.77 (ii) which describe the opening and closing status of the contector, which in this status indicates 1, the generator is stay connected during the fault.

5.2.5.5 Result of DFIG with RC & VR proposed protection under symmetrical three phase fault

In this part of simulated system is show the results of three phase symmetrical fault with adding FRT contactor circuit and VR crowbar protection have added to the simulated model , the fault appeared at 0.3sec for 150 milliseconds then disappeared at 0.45s of simulation time.

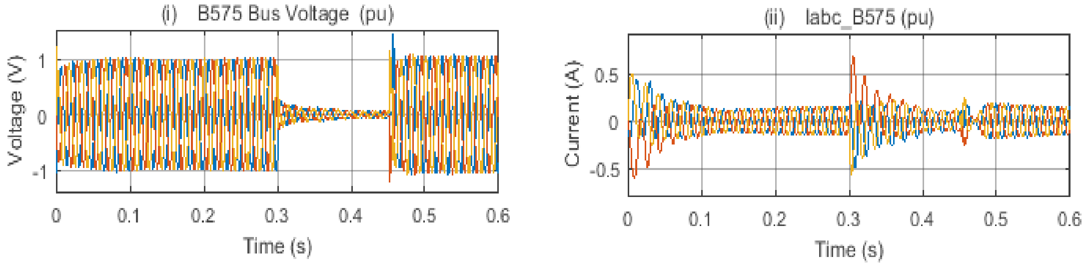

Figure (5.78) simulation results of Bus bar number B575 asymmetrical Grid voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the Bus bar voltage, (ii) shows Bus bar current. With adding RC circuit to the contactor coil

The results Figure 5.78 (i) shows that the bus B575 voltage is dipped to 0.15 p.u, then at 0.45s when fault disappeared, voltage reach its normal 1 p.u. again. In Figure 5.78 (ii), the current on bus B575 Suddenly increased to 0.74 p.u at the beginning of volte transient then settled to 0.3p.u, at 0.45 sec, when fault disappeared, the current disturbed again then stabled at its value 0.16 p.u to start recovery.

During three phase symmetrical grid fault, the results in Figure 5.79 (i) shows that the stator voltage is dipped to 0.8 p.u, and Voltage unbalance is appeared during the fault until the system recovered at 0.45s to reach its normal condition 1 p.u again. Figure 5.79 (ii) shows the current suddenly increased to 4 p.u at the beginning of volte transient, then stabilized at 1.8 p.u during the fault time. At 0.45 sec the current stabled 1 p.u and then start recovery. The figure 5.79 (iii) shows that the voltage which is constant at 0.7 p.u until the voltage dip appeared at 0.3sec, there is a slight disturbance of the rotor voltage, this due to the interaction of proposed protection with the grid fault effects, which contributed to the inhibition of the increase in voltage on the rotor, Which contributed to improving the rotor voltage during this type of faults.

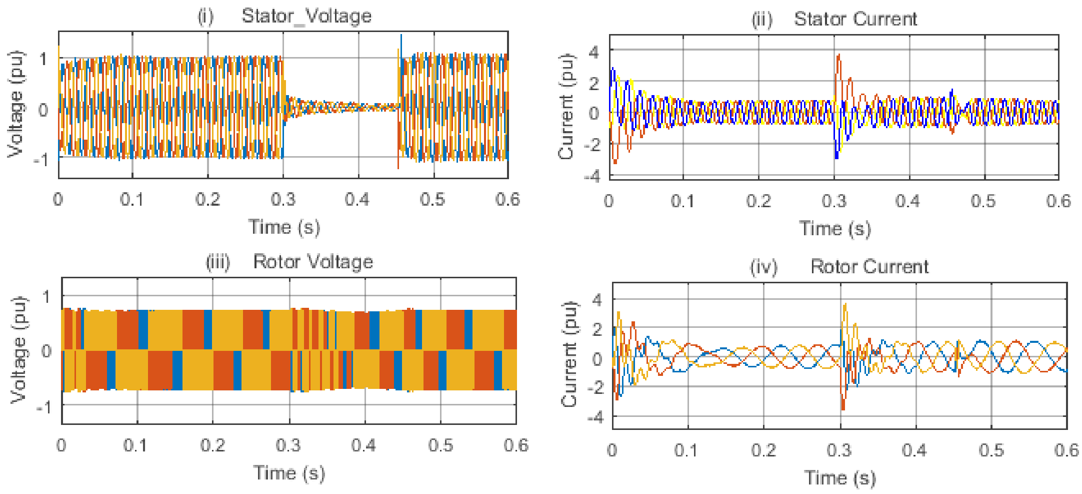

Figure (5.79) the simulation results of DFIG connected to the grid at asymmetrical Grid voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) shows the stator voltage, (ii) shows the stator current, (iii) shows the rotor voltage , (iv) shows the rotor current.

Figure 5.79 (iv) describe the current, where fluctuated at startup for an interval time of 0.1sec, then stabilize at 0.8p.u until the voltage dip appeared at 0.3sec, the current overshoot to 4 p.u then decreased to 1.1 p.u until transient disappeared at 0.45sec when current a bit fluctuated and started to recovery to stabilize at 1p.

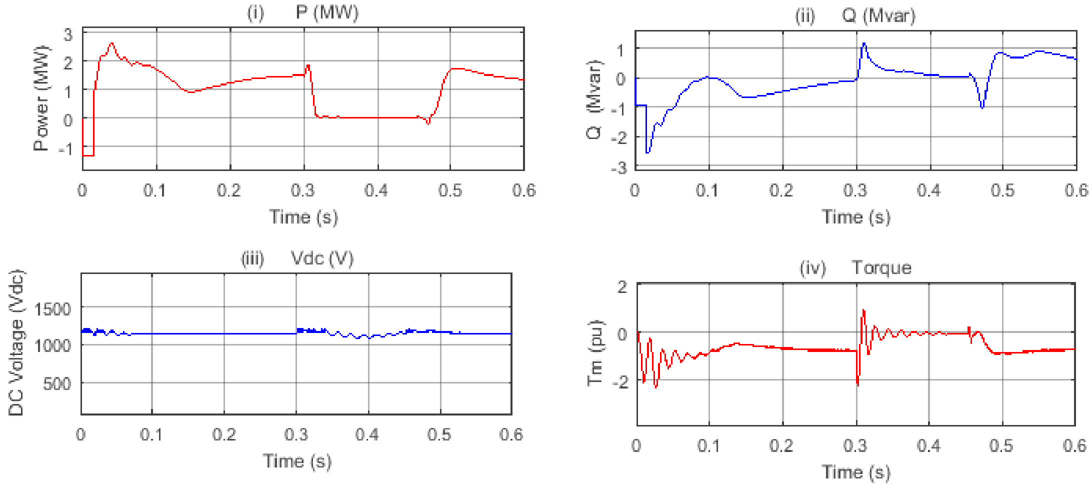

Figure (5.80) the simulation results of DFIG connected to the Grid symmetrical voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the active power statues, (ii) describe the reactive power statues, (iii) shows the Dc voltage and (iv) describe the torque statues.

The simulation results in figure 5.80 (i) shows the active power statues when it sudden raised during the startup to reach 2.8MW then dropped nearly to 1MW to stable to 1.5 MW at 0.28 s. when the voltage dip appeared due to grid three phase to ground fault at 0.3sec, Active power drops to zero MW, at 0.45s With fault disappearance start recovered. In Figure 5.80 (ii) the reactive power is interrupted between -3 to 0 Mvar during startup time until 0.1 sec of simulation time, then stabled to zero at 0.28. When the voltage dip appeared at 0.3sec, reactive power sudden disturbed to 1.3 Mvar then the generator start to absorb a reactive power from the grid to reach 0.25 Mvar before voltage dip disappeared, at 0.5 sec the system started recovering. The Figure 5.80 (iii) shows an increase in the DC-link voltage reached 1200 Vdc during startup to stable to 1150 Vdc, at voltage dip appearance, The proposed RV crowbar worked to damping the value of DC voltage at 1200V dc, which is what the results, where the highest voltage value is 1200 during the operation time. The Figure 5.80 (iv) show the variation in torques during the voltage dip at the instant 0.3 sec when the torque Instantaneous rise to 2 p.u , then at 0.45 sec stabled to 0.7 p.u , then started recovery.

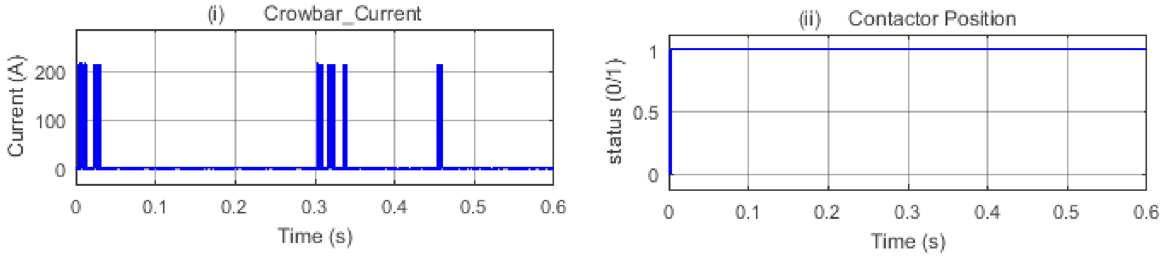

Figure (5.81) the simulation results of DFIG connected to the Grid asymmetrical voltage dip caused by three phase fault, with adding RC circuit to the contactor coil, and VR crowbar to the generator, when (i) describe the crowbar resistor current in ampere and (ii) describe the statues of contactor (on or off) during the fault.

In figure 5.81 (i) the proposed protection shows a response to the changes in the DC link voltages, which contributed to the inactivation of the current on the converter during the startup status of the generator. This protection appeared again during the grid fault, which contributed to the determination of the DC voltage. Figure 5. 81 (ii) which describe the opening and closing status of the contector, which in this status indicates 1, the generator is stay connected during the fault.

5.2.5.6 The results Summary

At the moment of a symmetrical faults, because of the dip grid voltage on the generator, the stator voltage drops as a percentage of the grid voltage drop during the faults, so there is a decrease in active power and the generator absorbs the reactive power of the grid at the moment of the fault time. The DC bus voltage was damped under the proposed VR crowbar so that it did not exceed its highest value 1200 Volt dc, this resulted to regulate the rotor voltage, and this improvement appears even at the startup of the DFIG generator. The torque of the generator shows deterioration during the faults but it recovers remarkably quickly. During asymmetrical grid faults, the results indicated a voltage unbalance and fluctuation in the current on both the rotor and stator of the DFIG generator during the fault time, but the rotor voltage value shows a recovery during the fault. It can also be observed that the voltage unbalance is compensated through the converters during the transient, resulting frequency oscillation on the rotor voltage and current, this is as a result of the grid frequency and the increase in the turbine rotation due to deterioration of torque. The proposed RV crowbar resistors showed good response during all grid transients on the rotor converter and DC Bus, where the results show the changes in the value of the current on the crowbar resistance and the DC voltage controlled In all cases studied.

5.3 The results discussions

In this simulation, DFIG wind turbine with main contactor experiences grid disturbance; such as symmetrical and asymmetric voltage dips, to study the impact of their occurrence on the stability of the DFIG wind turbine generator model modeled during the temporary grid. In the first phase of the simulation, the power system is completely clear from any error when the stable condition of the DFIG wind turbine for all parameters analyzed has been investigated and used as reference case.

In the second phase of the simulation, different types of symmetrical and unsystematic voltage drop have been introduced to the simulated system and results were obtained in each case. Since the simulation results showed the effect of the contactor coil with the voltage drop below 60% of the grid voltage drop which in turn significantly influenced the performance of the DFIG, where The results showed that the main contactor coil is affected by the voltage drop. These result is confirmed by the Shareff, H et,al in their study in this study case. Consequently, the results in this part of simulation showed the effect of the DFIG performance due to the conductor Affected during the grid voltage dips at 40%, 20% symmetrical voltage dips, the results included voltage dip during three phase grid faults, and also asymmetric two phase and two phase to ground grid faults, which necessitated to include the proposed RC circuit to the contactor coil to continue third phase of simulation, Where the results showed the success of the proposed RC protection of the main contector in all the faults that simulated in this part, but the Generator performance still appeared an impact during these types of grid faults , especially when grid voltage got less than 40% voltage dips, Where the results in this segment showed a disturbance in the rotor voltage and current due to the drop of the grid voltage, and there is a deterioration in the DC voltage and oscillation in the torque Where it is clearly shown in faults that cause a voltage dips of less than 20%. In asymmetrical faults unbalance is appeared on the grid voltage, This unbalance causes oscillation in both the voltage and the current of the rotor and the stator of DFIG generator, This voltage unbalance causes also oscillation on the DC voltage and rotor torque. Thus, in order to protect the converter from the disturbances caused by the grid voltage dips, two types of protection were added to the last part of simulation, VR crowbar which including a chopper protection. Therefore, in the this part of simulation, the DFIG was simulated with all the protections proposed in this study, where the main contactor was protected by the RC-circuit and the contactor by RV crowbar, the results showed the proposed protection is contributed in improving the DC voltage on the converter, and also contributed the improvement of the rotor voltage in all cases that were under study. It also showed that the voltage unbalance caused by asymmetric grid faults resulting unbalance in the current and voltage of DFIG and fluctuation in DC voltage, which increases the generated frequency, also it caused a pit disturbance in the rotor torque. This unbalance caused by asymmetrical grid faults may result in a hit dots on generator windings and disturbance on the Mechanical shaft and gearbox. Through these results obtained in this simulation, the proposed RC circuit to make the contactor riding grid though during symmetrical and asymmetrical grid voltage dip under study was satisfactory. Thus, the proposed RC circuit enabled the DFIG generator to stay connected during these faults. As well as The proposed VR protection witch proposed to protect the GFIG wind turbine converter to achieve a safe ride through during the faults under study, which consists of Chopper on the converter link capacitor and variable DC resistors in parallel to the DFIG rotor winding, the results were satisfactory with all symmetrical faults, which enabled the generator to ride the grid faults safely where the DC voltage and the rotor voltage has improved and the current on the rotor has damped during faults as shown on RV crowbar resistors. In asymmetric faults, the results showed an unbalance on the grid voltage where the stator and rotor currents become very unbalanced. As a consequence of the voltage imbalance, this is because the negative sequence rotation causes the voltage imbalance, which leads to oscillation in the rotor frequency and the voltage of the DC bus. The impacts of the unbalanced voltage also occur on the torque of the rotor. Meanwhile, the distortion in this network voltage has a negative impact on the engine, while the proposed protection in turn to protect the converter is done satisfactorily.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This thesis presents the analyzing of DFIG wind turbine and its main contactor being subjected to symmetrical and asymmetrical grid disturbances which lead to voltage dips, to study the impacts of their occorance on the stability of the power generation during the grid transients. To investigate the transient effects on the generator parts subjected under study, accurate simulation of transient grid conditions is required. Using MATLAB/SIMULINK the wind turbine with DFIG and the main contractor mechanism are modelled and simulated to examine and analyze the performance of the AC contactor during normal and grid transient conditions and the influence of its performance on the simulated generator of DFIG. the contactor connect the generator terminals (rotor and stator windings) to the grid through its contacts, which opened and close as a result of the contactor coil electromagnetic force generated by grid voltage source of the contactor. Since the contactor coil, which is responsible for the mechanics of connecting and disconnecting the generator parts to the public network, is affected by changes in the network voltage, The study presented a clear effect of the contactor mechanism at the grid voltage dip below 60%, which results in a sudden discharge of the generator from the grid at the generator synchronous speed, caused a deterioration in the voltage and torque of the generator converter and thus a clear effect on the performance of the generator and the wind turbine. Therefore, when proposed protections added to both the contactor coils and DFIG generator, the results showed a clear improvement in the contactor's performance in all grid failures under study. The results also showed a clear impact of the proposed RV protection on the DFIG and its converter during the studied grid faults, in which the analysis result indicated that there is an increase on the voltage of DC link of the converter and the output voltage on the rotor side of generator during all the cases under study. The proposed protection also led to the rotor side, which dampens the rotor current disturbances, thus protecting the converter from any voltage and current disturbances without the need to disconnect the convertor from the grid during the system voltage dips. However, during asymmetric faults across a grid there is a voltage unbalance, which caused a disturbance in mechanical torque and grid frequency during fault period. The effects of these grid transients are depending on other factors outside the scope of this study, including the speed of disconnect response to the failure grid protections and the distances from the nearest point where wind turbine can be connected to the grid. Therefore, the effect of these unbalance on the DFIG is related to the generator protection relays where the protection works if the voltage unbalance is higher than the allowable settings on the generator terminals.

Thus, it is possible to say that the proposed protection of RC circuit and RV crowbar on both the contector and the converter has worked as expected, and this is what the results of this study showed.

6.2 Recommendation

Based on the results of the simulation, it has been confirmed that the effectively functional system is the system with proposed protection. Nevertheless, the following some recommendations have been made as further works it can be improving the system. The ability to maintain the voltage during asymmetrical voltage dips at nominal steady state level can greatly enhance the generator performance during all types of Grid faults.

Also, any proposed protection to enable the contactor to ride the grid faults according to FRT requirements, should be subject to separation and connection by protection devices of the generator to prevent the delay of time in the equipment separation time from the network during the faults.

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