Arab Academy for Science, Technology and Maritime Transport
College of Engineering and Technology

Protection of Doubly Fed Induction Generator (DFIG)

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A Thesis
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Statement

This thesis is submitted to Arab Academy for Science, Technology and Maritime Transport in partial fulfillment of the requirements for the Master of Science Degree in Electrical and Control Engineering.

The work included in this thesis is carried out by the author at Electrical and Control Engineering Department, Arab Academy for Science, Technology and Maritime Transport. No part of this thesis has been submitted for a degree or a qualification at any other university or institute.

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Abstract

Recently, wind energy is considered as one of the most important energy resources. The growing share of the wind energy in the electrical grids made many countries introduced new grid codes to identify the responsibilities and rights of the wind farms during all grid conditions.

Nowadays, The Doubly Fed Induction Generator (DFIG) becomes one of the most popular generators in variable wind turbine systems. The DFIG has the advantages of; low cost, low weight, and high efficiency. However, one of its main disadvantages is its sensitivity to the voltage dips. Therefore, there are various techniques were developed to protect the DFIG and enhance its performance during the faults so as to meet the grid codes requirements.

In this thesis, various protection techniques of the DFIG were discussed and simulated under different conditions using the Matlab/Simulink.

Acknowledgment

I must first thank Allah for his prosperity in completion this thesis despite of some hard times.

I would like also to thank my beloved parents, who gave me a great help and support to accomplish this work, also my brother and my sister.

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List of Symbols

A	Whole cross sectional area of wind turbine rotor blades
C_p	Power performance coefficient
E	Kinetic energy
Is	Stator current
Ir	Rotor Current
m	Mass
P	Active power
P_r	Rotor power
P_{rcl}	Rotor cupper losses
P	Air stream power
P_{ag}	Air gap power
P_m	Mechanical power delivered to the generator
P_s	Stator power
P_{scl}	Stator cupper losses
Q	Reactive power
s	Slip
Tem	Electromagnetic torque
T	Temperature
t	Time
T	Torque
υ	Air stream volume
V	Velocity
V	Voltage
Vs	Stator voltage
Wr	Rotor speed
ω_r	Rotor speed

ω_s	Synchronous speed
x	Air stream Thickness
Z	Elevation
β	Blade pitch angle
ρ	Air stream density
Ψ_r	Rotor Flux
λ	Tip speed ratio

List of Abbreviations

DBR	Dynamic braking resistor
DFIG	Doubly fed induction generator
DPC	Direct power control
DSO	Distribution system operators
DTC	Direct torque control
GSC	Grid side converter
GTO	Gate turn-off thyristor
IGBT	Insulated gate bipolar transistor
LVRT	Low voltage ride through
P-DTC	Predictive direct torque control
P-DPC	Predictive direct power control
PGSC	Parallel grid side converter
PMSG	Permanent magnet synchronous generator
RSC	Rotor side converter
SCIG	Squirrel cage induction generator
SCR	Silicon controlled rectifier
SGSC	Series grid side converter
STI	Short time interruption
TSO	Transmission system operators
VSC	Voltage Source Converter
WRIG	Wound rotor induction generator
WRSG	Wound rotor synchronous generator

Chapter 1

Introduction

1.1 Thesis Objective

Nowadays, the utilization of renewable energy in electrical power generation field is rapidly growing in many countries all over the world, not only because this type of energy is free, clean & infinite but also the traditional energy sources (e.g. Gas , Petrol , …) will be so limited in the near future. The Wind energy has a great concern of many countries in the last two decades. As the share of wind energy in the electrical networks is increasing, the disconnection of wind farms during abnormal conditions became not acceptable anymore. As a result, many countries began to introduce new grid codes so as to control the interconnection of the wind farms with its networks to ensure the stability of its network in both steady state and transient conditions.

Doubly Fed Induction Generator (DFIG) is one of the most commonly used generators in wind farms nowadays. It has many advantages like; its low converter rating (The converter rating of the DFIG is 25-30% from the machine rating) consequently its relatively high efficiency, lighter in weight, its low cost and its capability of decoupling the control of both active and reactive power. On the other hand, DFIG's main disadvantage is its sensitivity to grid faults.

The objective of this thesis is to discuss :

1. The DFIG operation theory.
2. Different control techniques of the DFIG.
3. The performance of the DFIG during transient conditions (symmetrical & asymmetrical faults).
4. Different protection techniques of the DFIG.
5. Conduct a comparison study between the most efficient techniques.

1.2 Thesis Outlines

The thesis is divided into four parts, Chapter 1 is an introduction to the wind energy & its usage in the field of the power electrical generation.

Chapter 2 focuses on & discusses the wind energy system components (wind energy, wind turbine & generators coupled with the wind turbines).

Chapter 3 discusses the Doubly Fed Induction Generator (DFIG), its theory behind the operation, power flow, modes of operation, control topologies and the protection techniques usually used in DIFG protection.

Chapter 4 is the case study, in this chapter the performance of the DFIG studied under symmetrical and asymmetrical faults with different protection techniques applied in order to compare their effect on the DFIG behavior during different types of faults.

Chapter 5 is the conclusion of the thesis and also suggestions for future research work.

Chapter 2

Wind Energy Systems, Background and Literature Survey

2.1 <u>Introduction</u>

The Wind energy is one of the main types of renewable energy which have a remarkable concern of many countries and researchers in the last two decades. While wind energy usage spread is increasing some problems began to raise concerning the effect of the wind farms on its neighbors like its sound and shadow flicker. On the other hand there is also some technical problems concerning the interconnection of the wind farms with the networks and the behavior of the wind turbines during both the steady state and the transient conditions. Fig. 2.1 classifies the electricity production in 2011 according to the power plants type.

Consequently, many countries began to introduce a new grid codes that contain the rules which regulate the rights and responsibilities of the wind farms connected to the grid. The grid code considers both steady state and transient condition to ensure the stability of the network. Therefore the wind generators manufactures must take into their account those codes.

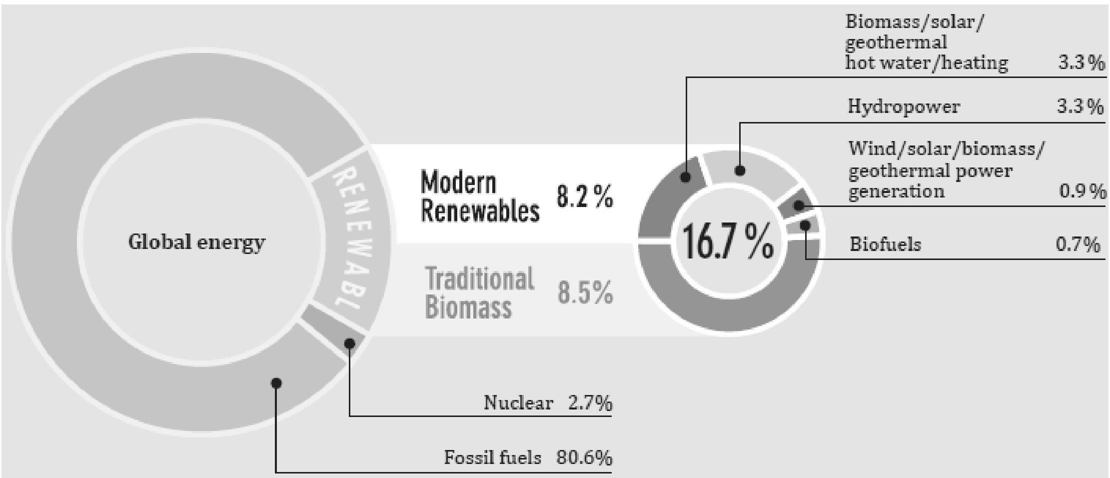

Fig. 2.1 Renewable energy share of global electricity production 2011 [1]

2.2 Wind Energy Status and Challenges

The global wind power capacity at the end of 2011 is 238 GW, which represents a cumulative market growth of more than 20%. However this growth is lower than the last 10 years average, which is about 28% as shown in fig. 2.2 which summarizes the global annual installed wind capacity from 1996 till 2011 [1].

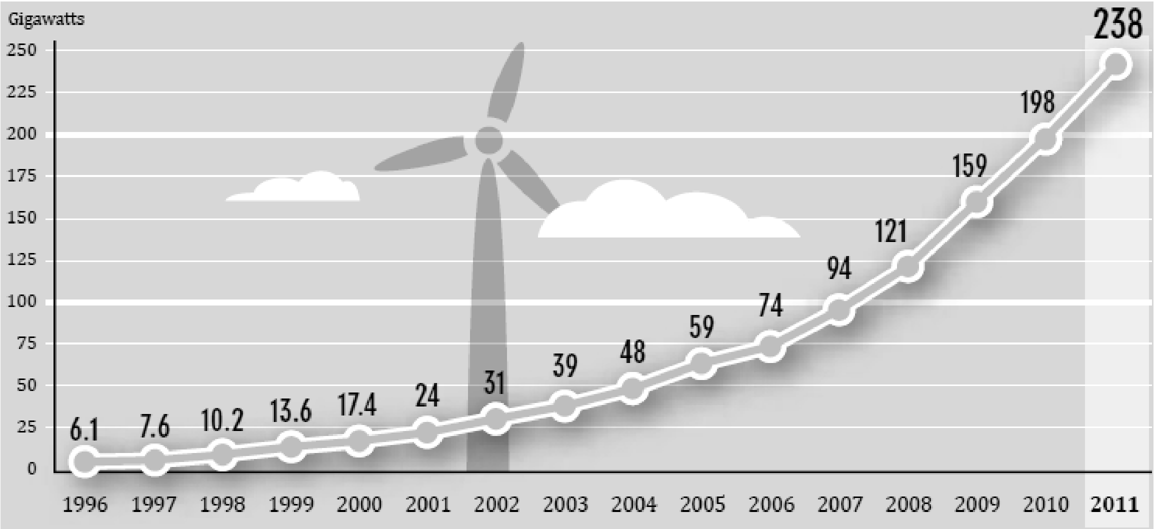

Fig.2.2 Global Annual Installed Wind Capacity 1996-2011 [1]

The main drivers of growth in the global market, as they have been for the past several years, are the Asian powerhouses of China and India. The US market made a respectable recovery while Canada had a record year, and Europe remained on track to meet its 2020 targets. Offshore installations in Europe decreased slightly last year, but strong growth figures were posted in Romania, Poland and Turkey. A strong year in Germany reflects a renewed and even stronger commitment to renewable in the wake of the nuclear phase-out decision [2]. Fig. 2.3 shows the top 10 countries in cumulative capacity until Dec 2011.

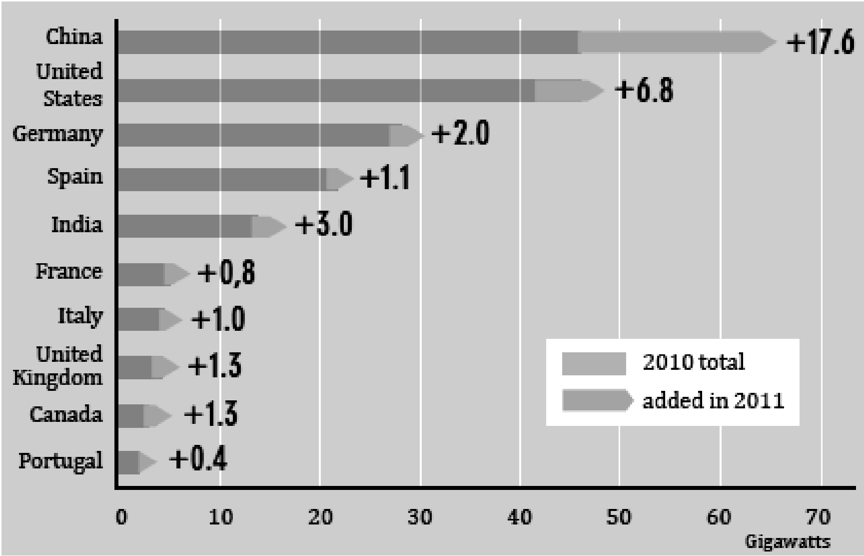

Fig. 2.3 Top 10 countries in cumulative capacity Dec 2011 [1].

The challenges which the wind energy faces can be divided into two sectors; Civil and Technical challenges

1) **The civil challenges sector which is concerned by non specialized people contain [3] :**
   a) The wind turbine sound which is are heard by its close neighbors however nowadays wind turbine manufacturers have made significant strides since the early days of the industry in reducing turbine noise.
   b) The local and migrated birds which is killed by wind turbine blades and habitat removal or alteration of birds due to wind farms spread. However these problems can be minimized by making a whole study on the selected location of the new wind farms projects.
   c) Shadow flicker occurrence by wind turbine blades which is observed by close neighbors of wind farm.

2) **The technical challenges Sector which is concerned by specialized people interested in the filed of electrical power generation and transmission contain :**
   a) Interconnection of the wind farms with the networks of the conventional power stations. The wind power isn't constant and then the output power, while the conventional power stations have constant output power.
   b) Reactive power which is needed by wind farms (Which use induction generators) during steady state and transient conditions.
   c) Fault ride through requirements during the faults for a specified period.

2.3 Basic Theory of Wind Power Conversion :

Basically it should be noted that the energy utilized in the wind is the kinetic energy of the large air masses moving over the earth surface. When these masses hit the wind turbine blades, the kinetic energy transfers to the blades and make it turn. This rotary movement can be used in many mechanical or electrical applications [4].

In this part, some fundamentals relations involved in the wind power conversion system is discussed [4 , 5]

The kinetic energy of a stream of air with mass m and moving with a velocity V is given by :

$$E = 1/2 \; m \; V^2 \qquad (2.1)$$

Considering a wind turbine rotor blades with a whole cross sectional area A expose to a stream of air with density ρ , volume υ and thickness x as shown in Fig. 2.4. The kinetic energy contained in this air mass and available for the turbine blades can be expressed as :

$$E = 1/2 \; (\rho \; \upsilon) \; V^2 \qquad (2.2)$$

$$E = 1/2 \; (\rho \; A \; x) \; V^2 \qquad (2.3)$$

The power of this air mass is the time derivative of the kinetic energy E

$$P = \frac{dE}{dt} = 1/2 \; \rho \; A \; V^2 \frac{dx}{dt} = 1/2 \; \rho \; A \; V^3 \qquad (2.4)$$

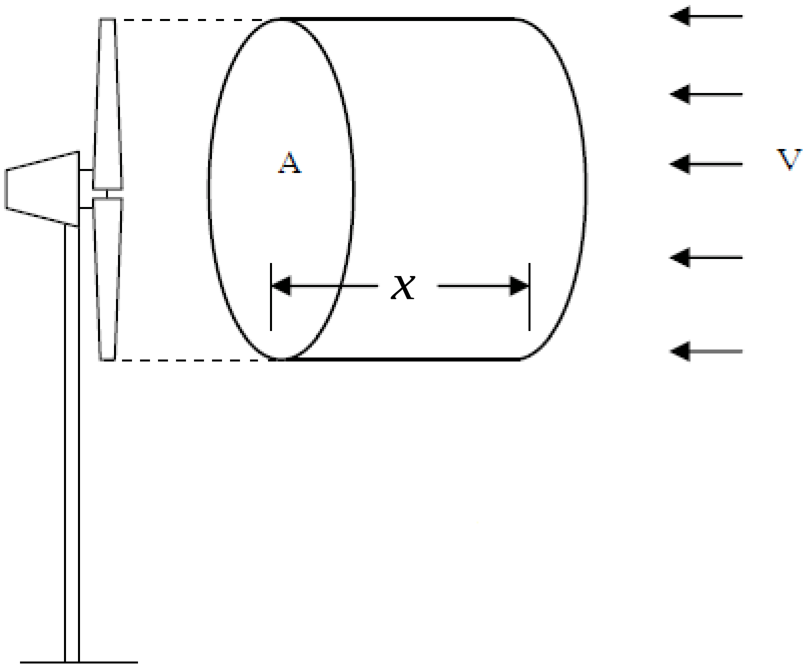

Fig. 2.4 An air mass moving toward wind turbine [4]

Eq. (2.4) shows that the factors which affect the power available in the wind are :

1) The air density.
2) The cross sectional area of the rotor blades.
3) The wind speed is the most effecting factor because it is cubic.

If the elevation Z and temperature T of a site is known then the air density in this site can be expressed as :

$$\rho \;=\; \frac{353.049}{T}\, e^{(-0.034\, Z/T)} \qquad (2.5)$$

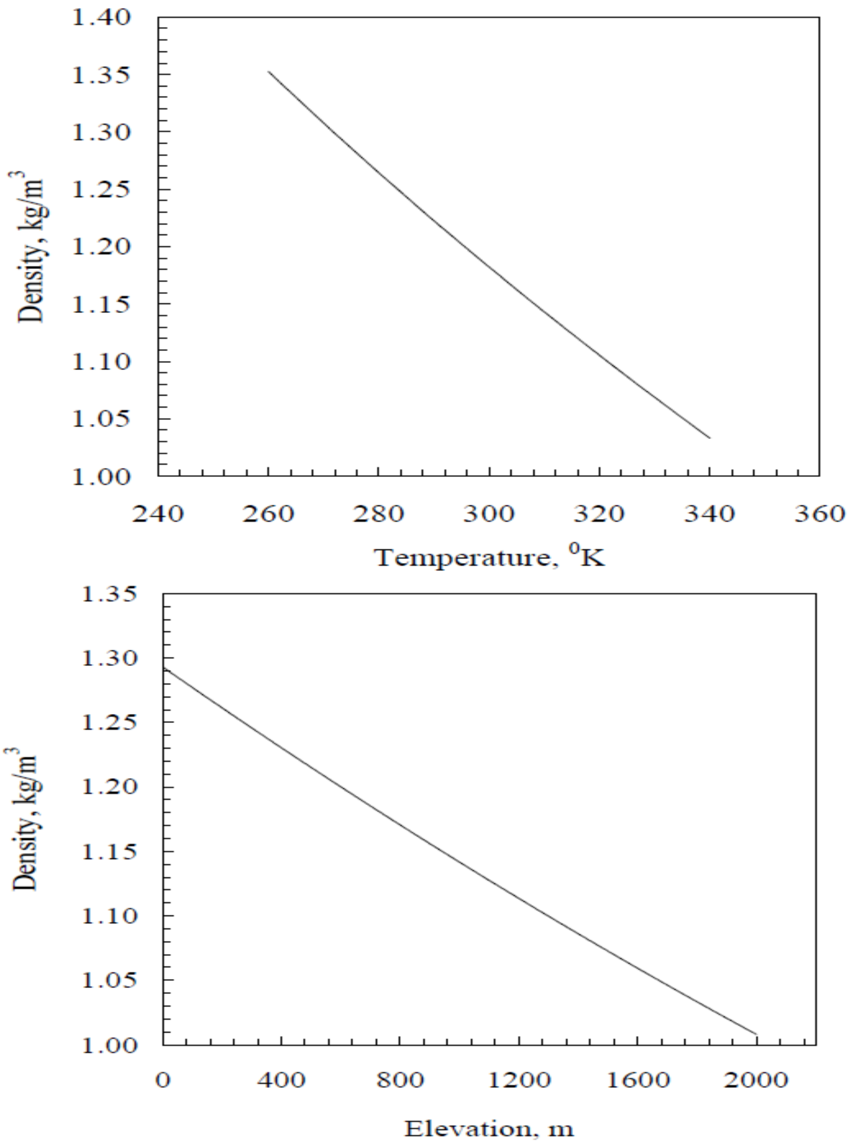

Fig. 2.5 Effect of elevation and temperature on air density [4]

The elevation and the temperature of the air in a place affect the wind power. However, the wind speed still the most effective and the main factor which affect the wind power available in a place. From eq.

2.4 it can be noted that, if the wind speed is doubled then the wind power available will increased by 8 times. Therefore a precise study on the site climate - all over the year - which will be selected to host a wind farm is very important.

It can be noticed that the density of air decreases with the increase in site elevation and temperature as illustrated in fig. 2.5. For most of the practical cases the air density may be taken as 1.225 kg/m^3. Due to this relatively low density large sized systems are often required for substantial power production [4].

Although the power equation mentioned above eq. 2.4 gives the power in the wind, the actual power that can be extracted from the wind is significantly less than this value. The actual power will depend on several factors like the machine type, the blade design and the friction losses [6]. In order to account for this, the power equation 2.4 is multiplied by C_p (power performance coefficient) yielding the following equation:

$$P = 1/2 \ \rho \ A \ V^3 C_p \qquad (2.6)$$

Based on eq. 2.6, the only parameter that can be controlled to maximize the energy output at a given wind speed is C_p as it depends on the specific design of the wind converter and its orientation to the wind direction. For a horizontal axis wind turbine with given blades the power coefficient C_p basically depends only on the tip speed ratio λ and the blade pitch angle β [7]. The tip speed ratio λ is defined as the ratio of the blade tip speed (blade rotational speed times rotor radius) to the wind speed. The pitch angle is defined as the angle between the chord line of the blade and the plane of rotation of the blade as shown in fig. 2.6 [7].

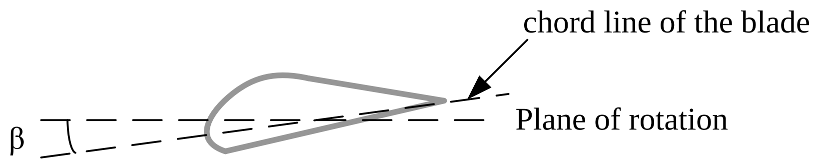

Fig. 2.6 Definition of the pitch angle β

For a given blade pitch angle and rotation speed, C_p a non linear function of the wind speed and will reaches its peak value at a given tip speed ratio and drop off again to zero at higher tip speed ratios. As an example, fig. 2.7 shows the dependency of the power coefficient C_p on the tip speed ratio λ and the blade pitch angle β for a specific blade [7].

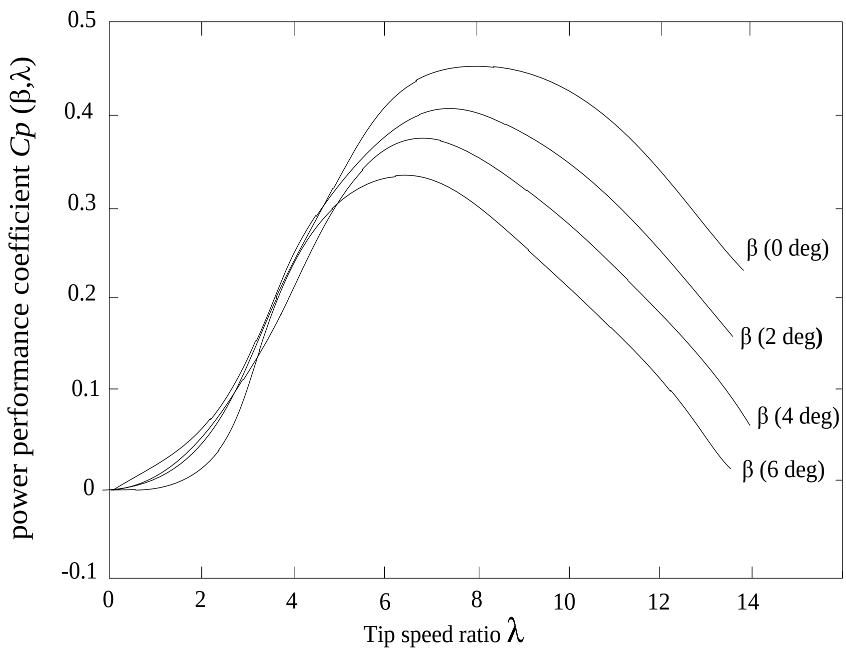

Fig. 2.7 The power coefficient C_p as a function of the tip speed ratio λ and pitch angle β for a specific blade [7]

When the wind turbine runs at a fixed speed, the tip speed ratio cannot be actively controlled, as the rotor speed and thus the blade tip speed is fixed. Nevertheless, the tip speed ratio varies with wind speed, and thus reaches the optimum value at one wind speed only in case of fixed speed designs. On the other hand, if the wind turbine runs at variable speed, the tip speed ratio can be varied. For maximum output power, the tip speed ratio must be maintained at the value which corresponds to the optimum power coefficient at all times. For a given wind turbine, this is achieved by controlling the rotor speed according to its tracking characteristic.

2.4 <u>Wind Turbine Main Components</u>:

As shown in fig. 2.8 the main components of a wind turbine are [8]:

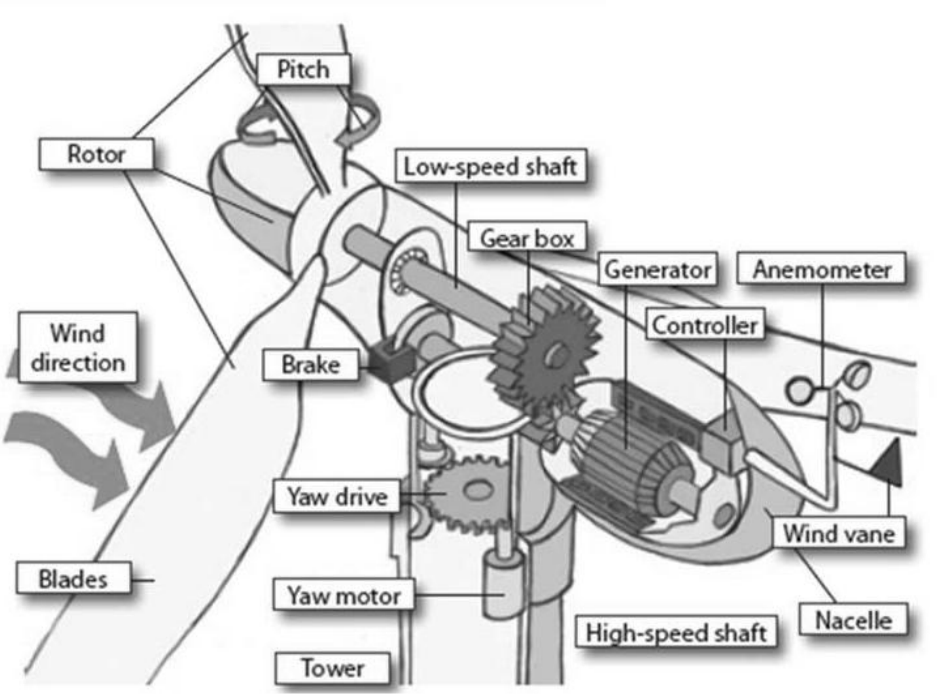

Fig. 2.8 Typical wind turbine system

<u>Anemometer:</u> Measures and transmits wind speed data to the controller.

<u>Blades:</u> Most turbines have either two or three blades.

<u>Brake:</u> A disc brake, which can be applied electrically, mechanically, or hydraulically to stop the rotor in emergencies.

Controller: The controller starts up and shut down the machine according to a pre-designed wind speed range.

Gear box: Gears connect the low-speed shaft which connected to the blade to the high-speed shaft which connected to the generator , Generators which run with "direct-drive" technology don't need gear boxes.

Generator: Usually be an induction generator.

High-speed shaft: Drives the generator.

Low-speed shaft: Driven by the blades.

Nacelle: The nacelle sits at the top of the tower and contains low- and high-speed shafts, gear box, brake, generator and controller. Some nacelles are large enough for a helicopter to land on.

Pitch: Blades are turned, or pitched, out of or face to the wind to control the rotor speed.

Rotor: The blades and the hub together are called the rotor.

Tower: Towers are made from tubular steel (shown here), concrete, or steel lattice.

Wind direction: This is an "upwind" turbine, so-called because it operates facing into the wind. Other turbines are designed to run "downwind," facing away from the wind.

Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Yaw drive: The yaw drive is used to keep the rotor facing into the wind as the wind direction changes.

Yaw motor: Powers the yaw drive .

2.5 Basic Operational Characteristics of Wind Turbine :

As mentioned before, the mean wind speed in a specific site is a significant factor affecting the electrical power generating from the wind turbines placed in that site. Fig 2.9 shows the representation of a wind turbine's electric power output as a function of incident wind speed and it is known as the wind turbine's power curve. Important parameters included are the cut-in speed, the rated speed and the cut-out speed.

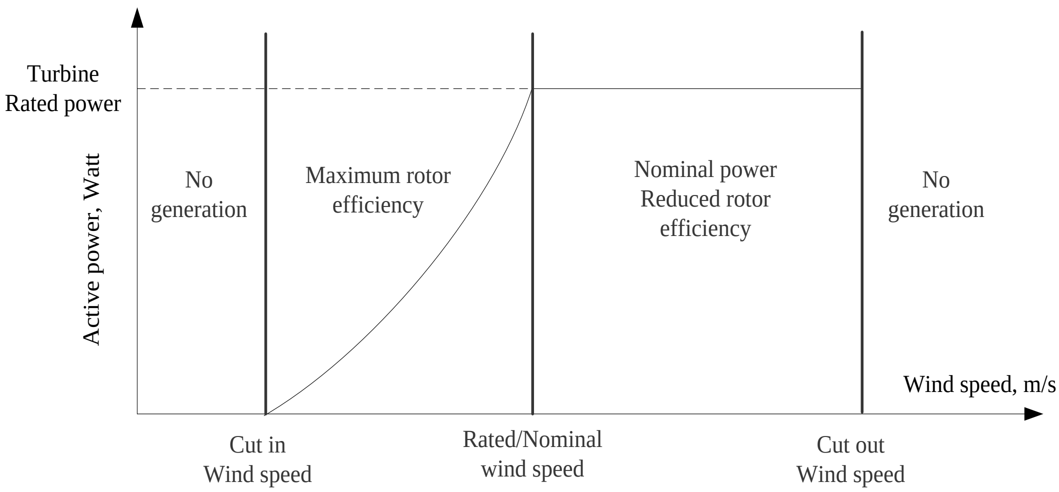

Fig. 2.9 A typicality power curve of a wind turbine [7]

In general, as seen in fig. 2.9 a wind turbine starts operation above a particular wind speed known as the cut-in speed while below the cut-in speed a very little energy available so the operation of the wind turbine unavailable or impossible. While increasing the wind speed the power production increases rapidly until reaching the rated speed as the same time the turbine has reached its maximum electric power production capability at that wind speed. The turbine power production continues at its maximum level with further increases in wind speed until the reaching of the cut-out speed. Beyond the cut-out speed, the wind energy is so high that it can cause mechanical damage to major turbine components [7].

Typically, a site for good wind energy production may have a mean wind speeds between 7m/s and 10 m/s. Therefore, the general approach is to design wind turbines to capture the maximum amount of wind energy available at wind speeds between 10 m/s and 15 m/s and at wind speeds above 15 m/s it start to spill away some of the power until they shut down at relatively high speed. This high speed is typically in excess of 25 m/s as the very high wind speeds are so rare and also put a significant stresses on the turbine components [7].

2.6 Power and Speed Control Methods of Wind Turbines :

As mentioned before, there is a direct relation between the wind turbine output power and its speed which related to the wind speed , In order to control the output power of the wind turbine, turbine speed is controlled. However today large wind turbines being installed tends to be of variable speed design (incorporating pitch control and power electronics). On the other hand, small machines must have simple construction, low-cost power and speed control methods. The speed control methods fall into the following categories which is summarized in fig. 2.10 [9]:

2.6.1 No Speed Control

With this type, the turbine, mechanical system and the electrical generator are designed to withstand the extreme speed.

2.6.2 Yaw/tilt Control

Yaw and tilt control always orient the rotor toward wind direction in normal wind speed to capture more power or it orient the rotor out of the wind direction in the case of high wind speed to protect the turbine components. The yaw technique change the direction of the rotor horizontally while the tilt technique change it vertically. However, rotating blades with large moments of inertia often resulting in loud noise [9].

2.6.3 Pitch Control

In this type, the turbine’s electronic controller checks the power output of the turbine several times per second. When the wind speed exceeds turbine's rated value, it sends an order to the blade pitch mechanism, which pitches (turns) the rotor blades slightly out of the wind. On the other hand, when the wind drops again the blades are turned back into the wind. Large-scale power generation is moving towards variable speed turbines with power electronics incorporating with a pitch control. This control requires a smart design in order to make sure that the rotor blades were pitched exactly to match the required power variation [9 , [10]].

2.6.4 Stall Control

Basically there are two types of stall control; passive-stall control and active stall control.

2.6.4.1 <u>Passive Stall Control</u>

One of the simplest form of power control is passive stall control. In this type, when the wind speed exceeds a certain point, the aerodynamic design of the blade increases the angle of attack (at which the relative wind strikes the blades) with the wind flow and reducing the drag which associated with lifting the blade, and then the wind flow help in the rotor stalling. This not only protects the blades from mechanical overstress, but also protects the electrical generator from overloading and overheating. The Design and manufacturing are so sophisticated for such blades. However this control type avoids the mechanical moving parts and complexities associated with pitch control. On the other hand, besides the blade's high complicated design, the sudden changes in wind speed (such as a gust) make a sudden changes in generator output, therefore if such units are used with weak grids, it may result in voltage flicker. Also this type doesn't behave effectively with low wind speeds [4 , 7 , 9 , 10].

2.6.4.2 <u>Active Stall Control</u>

In this type, the advantages of both the pitch and the passive stall control options are utilized. In this method, the blades are pitched to attain its best performance in lower wind speeds (often they use only a few fixed steps depending on the wind speed.). However, once the wind exceeds the rated velocity, the blades are turned in the opposite direction to increase the angle of attack and thus forcing the blades into a stall region. The active stall control allows more effective power control and the turbine can be run nearly at its rated capacity at high winds [4 , 10].

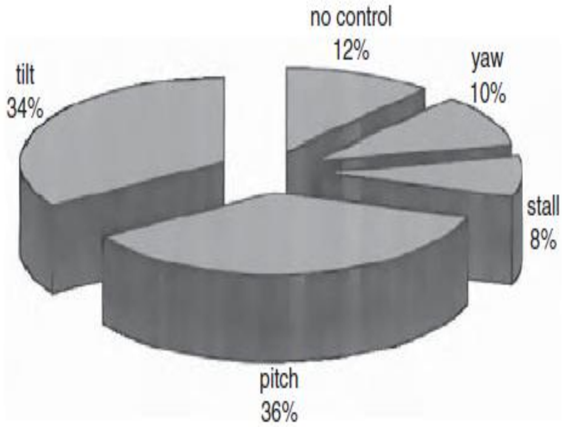

Fig. 2.10 Speed control methods used in small to medium turbines [9]

Fig. 2.10 shows the distribution of the control methods used in small and medium wind turbine designs however large machines generally use the power electronic speed control.

2.6.5 Safety Brake

In some emergency cases, the turbine should be fully stopped, such as when the generator is suddenly disconnected from the load the turbine will accelerate rapidly and this may damage the turbine and its component. Usually there are two types of the brake systems are commonly used; aerodynamic brake and mechanical brake. For safety the wind turbines usually have the two brake systems, one is the primary and the other one is the backup. Usually, the aerodynamic brake is the primary [4].

2.7 Wind Turbine Systems:

Wind turbines can be classified to :

1. Fixed speed wind turbine
2. Variable speed wind turbine

2.7.1 <u>Fixed Speed Wind Turbine</u> :

In the fixed speed type the wind turbine is coupled with an induction generator via speed increasing – torque decreasing gear box which transmit the rotational movement of the turbine shaft to the generator.

As shown in fig. 2.11, the stator of the induction generator (in this fig. Squirrel Cage induction Generator (SCIG)) normally connected directly to the grid. Sometimes a softstarter is used to eliminate the high starting current at the starting of the generator. In this configuration, a shunt capacitor bank is connected in parallel to compensate the reactive power required for the excitation of the induction generator instead of be taken from the grid.

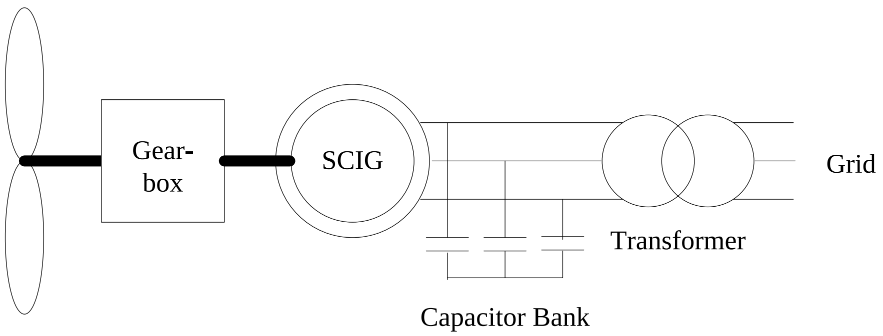

Fig. 2.11 Fixed speed wind turbine

In this type any fluctuation in the wind speed results in power fluctuation as it is designed to achieve maximum efficiency at one particular wind speed [11]. In order to increase power production, some fixed-speed wind turbines are coupled with generators with two winding sets: one is used at low wind speeds (typically 8 poles) and the other at medium and high wind speeds (typically 4–6 poles) [11].

The fixed speed wind turbines have the advantages of being simple in construction and consequently cheaper than the variable speed wind turbine, robust and then reliable [4]. On the other hand, fixed speed wind turbines have the disadvantages of consuming uncontrollable reactive power. Moreover in the case of sudden speed change its gear box is subjected to mechanical stress. Fixed speed wind turbine have limited power quality control and any fluctuation in the wind speed results in output power fluctuation [11].

2.7.2 Variable speed wind turbine :

Recently, the size of wind turbines has become larger and the technology has been changed from fixed-speed to variable-speed [12]. The ability to comply with the serious grid connection requirements was the driver to these development also the reduction in the mechanical loads which has been achieved with the variable speed system.

Variable speed wind turbines are designed to achieve maximum aerodynamic efficiency over a wide range of wind speeds. With a variable speed operation it becomes possible to continuously adapt (accelerate or decelerate) the rotational speed of the wind turbine to the wind speed. In this way, the tip speed ratio is kept constant at a predefined value that corresponds to the maximum power coefficient [11]. On the contrary of the fixed speed system the variable speed system keeps the generator torque fairly constant and absorb the variation in the wind speed by changes the speed of the generator.

As shown in fig. 2.12 the variable speed wind turbine typically coupled with induction or synchronous generator and connected to the grid via power converter, This power converter controls the output frequency and voltage so as to be synchronized with the grid.

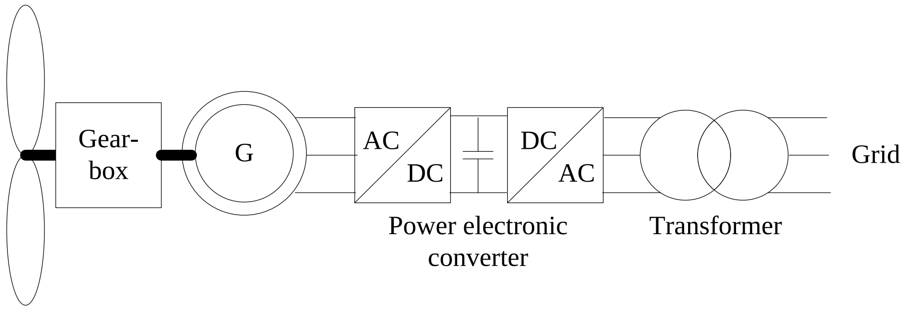

Fig. 2.12 Variable speed wind turbine

<u>Where the generator can be</u> :

PMSG - Permanent magnet synchronous generator

WRSG - Wound rotor synchronous generator

WRIG - Wound rotor induction generator

The advantages of variable speed wind turbines are; increasing energy capture, improving power quality and reducing mechanical stress on the wind turbine. Also when variable speed system is introduced it made an increasing in the number of applicable generator types and also introduces several degrees of freedom in the combination of generator types and power converter type [11].

However, variable speed wind turbines have some disadvantages like; the losses in power electronic switches (as the frequency converter is rated the same as the generator), its control become more complicated and more expensive than the fixed speed system.

2.7.3 <u>Variable Speed Wind Turbine With (DFIG)</u> :

Nowadays DFIG is an interesting option with the growing market. As shown in fig. 2.13 the DFIG consists of a WRIG with stator windings directly connected to the constant frequency grid and with the rotor windings connected also to the grid via a bidirectional back-to-back voltage source converter.

This system allows a variable-speed operation over a large but restricted range. The converter compensates the difference between the turbine speed and the electrical frequency by injecting a rotor current with a variable frequency [11]. Both during faults and normal operation the behavior of the generator is thus governed by the power converter through its controllers.

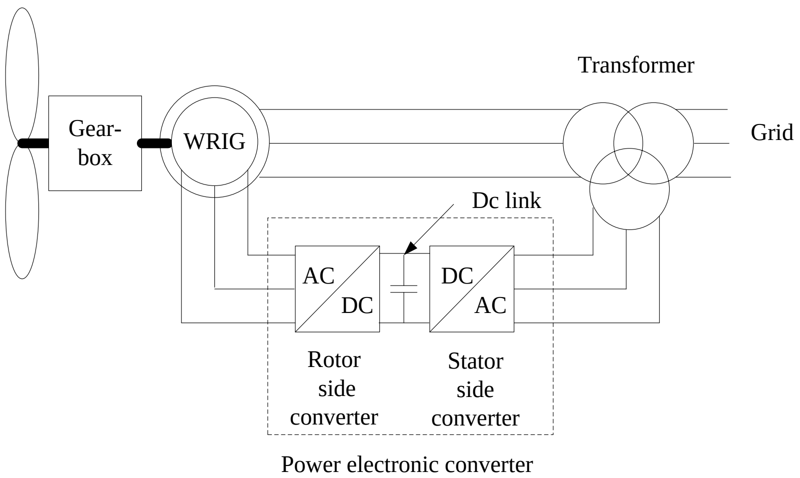

Fig. 2.13 Variable speed wind turbine

This power converter consists of two converters, the rotor side converter (RSC) and grid side converter (GSC), which are controlled independently, The main function of the RSC is to control the active and reactive power by controlling the rotor current components [11], while the main function of the GSC is to maintain the DC-link voltage constant and to ensure a unity power factor operation of the generator (i.e. zero reactive power).

The DFIG has several advantages; it has the ability to control active and reactive power separately, it has partial scale converter (25-30

% of the generator rating) consequently it will be more cheap, it can control the reactive power in case of voltage dips, it can be magnetized from the rotor circuit. It is also capable of generating reactive power that can be delivered to the stator via the GSC [11]. On the other hand, The major disadvantage of the DFIG is its behavior during grid faults. Voltage dips can cause high induced voltage in the rotor winding, resulting in large rotor current in the DFIG. The high rotor current can destroy the DFIG's converters if nothing is done to protect them, and can cause a large increase in the DC-link voltage.

2.8 Grid Code Requirements Of Wind Turbines :

As the share of wind energy generation to electrical grids increases world wide, the disconnection of wind farms during faults isn't accepted anymore (e.g. the European outage on November 4, 2006, caused the disconnection of 2800 MW of wind-origin power in Spain) [13], Therefore many Transmission System Operators (TSO) and Distribution System Operators (DSO) in many countries introduce new grid codes. These grid codes contain a rules that regulate the rights and responsibilities of the power plants which connected to that grid not only in the steady state operation but also in the transient operation. The grid code requirements vary in different parts of the world, but they have common aims such as to permit the development maintenance and operation of a coordinated, reliable and economical transmission and distribution system [7]. Worldwide, the new grid connection requirements have identified three areas to be considered in the operation of wind farms:

1. **Voltage and reactive power control:**

   The grid codes requirements obligate the wind farms to guarantee the continuity of the power injection (especially the reactive power to control the voltage stability) into the grid during the faults for a certain time according to the value and the duration of the faults.

2. **Frequency range of operation:**

   The design of generator plant and apparatus must enable operation according to a certain frequency range specified in the grid code of each country and hence the wind farms are required to be capable of operating continuously between that range [7].

3. **Low Voltage Ride Through (LVRT) Capability:**

   The LVRT requirements in a grid code identify the voltage level and the duration of the fault at which the wind turbine must be still connected to the grid.

   Fig. 2.14 shows an example of a LVRT graph, in which the voltage level at the point of connection is demonstrated also the fault existence time. Concerning the no trip area in which the wind generator should still connected to the grid within the specified voltage limits and fault duration, some grid codes may permits to the wind generator to make a Short Time Interruption (STI) in that area but with a specified conditions. On the other hand, as shown in fig. 2.14 below V_{min} or after exceeding t_{max} wind generator tripping by system protection is accepted [7 , 14 , 15].

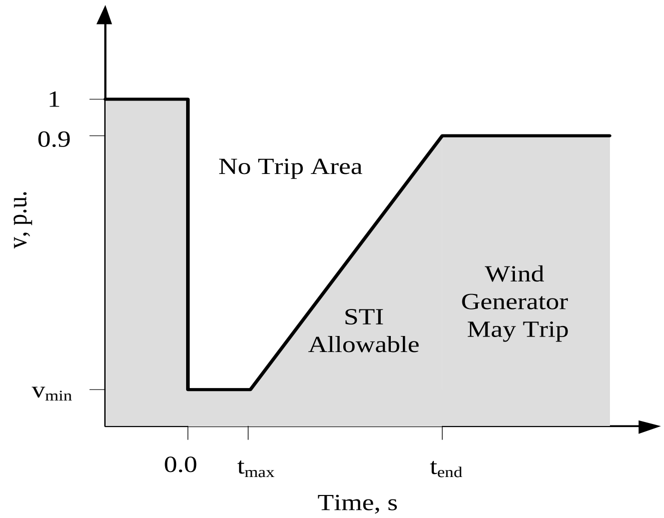

Fig. 2.14 Fault ride through requirement of wind farms

2.9 Conclusions

Wind energy is one of the infinite and clean energy sources on the earth. The applications of the wind energy in electrical power generation increased in the last two decades and will still increasing worldwide as the statistics and predictions indicates. On the other hand there is some technical and civil challenges facing the wind energy growing.

In a typical site there are some factors that enable it to be used as a wind farm like, the mean wind speed - all over the year - , its elevation and its temperature. However, the wind speed is the most important factor nevertheless there is another factors concerning the design of the wind turbine which accounted for by using the power coefficient.

The wind turbines are designed to run at fixed speed or at variable speed. The fixed speed wind turbines are simple in construction, cheap, robust and reliable comparing to the high cost and more complicated variable speed systems. On the other hand, the variable speed wind turbines have several advantages such as; increasing the energy capture, improving the power quality and reducing the mechanical stresses on the wind turbine.

DFIG is one of the most common used generators with the variable speed system because of its ability to control active and reactive power separately, its partial scale converter and hence its low cost, its low weight and its high efficiency. However, one of its main disadvantages is its sensitivity to the voltage dips. However, there are various techniques to protect the DFIG and enhance its performance during the faults so as to meet the new grid codes requirements.

Chapter 3

Doubly Fed Induction Generator (DFIG)

3.1 Introduction

Variable speed wind turbines are more popular than fixed speed one, due to its ability to capture more energy from wind, improved power quality and reduced mechanical stress on the wind turbine. One of the most frequently used generators with variable speed wind turbines is the DFIG which is an interesting alternative with a growing market. It can run at variable speed but produce a voltage at the frequency of the grid. In contrast to a conventional simple induction generator the electrical power generated by a DFIG is independent of the speed. Therefore it is possible to realize a variable speed operation which require to adjust the mechanical speed of the rotor to the wind speed so that the wind turbine operates at the aerodynamically optimal point over a certain wind speed range. DFIG has various advantages like its low converter rating (The converter rating of the DFIG is 25-30% from the machine rating) consequently its relatively high efficiency, lighter in weight, its low cost and its capability of decoupling the control of both active and reactive power. Therefore, the DFIG has its distinguished place among many variable speed wind turbine generators [7].

The theory behind the operation of the DFIG is presented in this chapter also its power flow , modes of operation , control topologies and protection techniques.

3.2 DFIG Theory of operation

As shown in fig. 3.1, DFIG consists of a wound rotor induction generator (WRIG) and bidirectional back-to-back voltage source converters. In this arrangement the stator is directly connected to the grid through a transformer while the rotor winding is connected via slip rings to the stator or the grid through the two back-to-back converters. The back-to-back converter consists of two converters, i.e., rotor side converter (RSC) and grid side converter (GSC) (two AC/DC insulated gate bipolar transistor (IGBT) based Voltage Source Converters (VSCs)). A DC link capacitor is located between the two converters as energy storage, in order to maintain the variations (or ripple) in the DC link voltage small. The main function of the RSC is to control the torque or the speed of the DFIG and also the power factor at the stator terminals. On the other hand the function of the GSC is to keep the DC link voltage constant also in some cases it may inject reactive power into the grid. The variable speed operation of the wind turbine generator or the decoupling of the network electrical frequency from the rotor mechanical frequency is obtained by the power converters by injecting a controllable voltage into the rotor circuit at slip frequency [12].

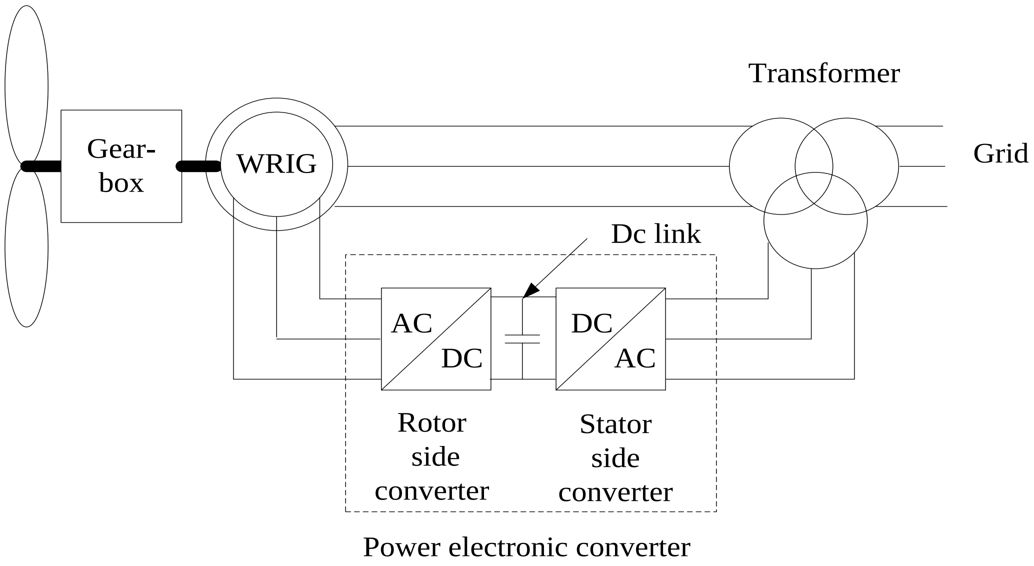

Fig. 3.1 DFIG Scheme

3.3 DFIG Modes of operation

The DFIG system can inject power into the grid through both the stator and rotor, while the rotor can also absorb power. This depends upon the generator rotational speed or in other words, its mode of operation. If the generator operates in super-synchronous mode, power will be delivered from the rotor through the converters to the network, but if the generator operates in sub-synchronous mode then the rotor will absorb power from the network through the converters [12].

These two modes of operation are illustrated in fig. 3.2 where ω_s is the synchronous speed and ω_r is the rotor speed.

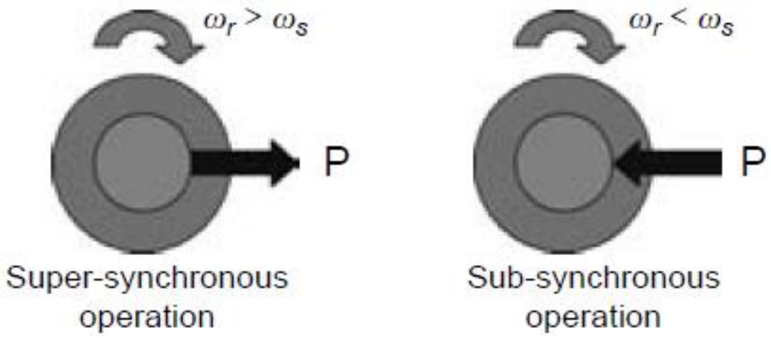

Fig. 3.2 DFIG Modes of operation [12]

Therefore, depending on the sign of the slip, it is possible to distinguish two different operating modes for the machine:

$(\omega_r > \omega_s) \rightarrow (s < 0)$ Super-synchronous operation

$(\omega_r < \omega_s) \rightarrow (s > 0)$ Sub-synchronous operation

Assuming, P_m is the mechanical power delivered to the generator, P_{ag} is the power at the generator air gap, P_r is the power delivered by the rotor and P_s is the power delivered by the stator. P_g is the total power generated and delivered to the grid.

If the stator losses are neglected then [12]:

$P_{ag} = P_s$ (3.1)

and if we neglect the rotor losses then:

$P_{ag} = P_m - P_r$ (3.2)

From eq. (3.1) and eq. (3.2), the stator power P_s is expressed by

$P_s = P_m - P_r$ (3.3)

Eq. (3.3) can be written in terms of the generator torque, T, as:

$T\omega_s = T\omega_r - P_r$ (3.4)

where $P_s = T\omega_s$ and $P_m = T\omega_r$. Rearranging terms in eq. (3.4),

$P_r = -T(\omega_s - \omega_r)$ (3.5)

where s is given in terms of ω_s and ω_r as

$s = (\omega_s - \omega_r)/ \omega_s$ (3.6)

The stator and rotor powers can then be related through the slip s as

$P_r = -sT\omega_s = -sP_s$ (3.7)

Combining eq. (3.3) and eq. (3.7) the mechanical power, P_m can be expressed as,

$P_m = P_s + P_r$

$= P_s - sP_s$ (3.8)

$= (1 - s)P_s$ (3.9)

From eq. 3.1

$P_m = (1 - s)P_{ag}$ (3.10)

The total power delivered to the grid, P_g is then given by

$P_g = P_s + P_r$ (3.11)

3.3.1 Super-Synchronous Mode :

In this mode of operation, the slip, the air gap power, and the mechanical power are negative. In addition, as can be deduced from eq. 3.10, the magnitude of the air gap power $|P_{ag}|$ is less than the magnitude of the mechanical power $|P_m|$. Consequently the rotor power have to be positive. Therefore, the remaining surpluses power sP_{ag} is absorbed by the grid after providing for the rotor cupper losses P_{rcl}. As seen in fig. 3.3 which represent the power flow diagram for this mode of operation, the total generated power in this situation is equal to ($P_s + P_r$) [7].

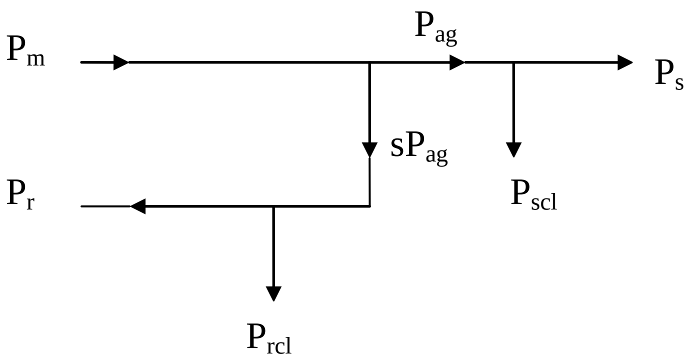

Fig. 3.3 The power flow diagram of the DFIM in super-synchronous mode

3.3.2 <u>Sub-Synchronous Mode</u> :

In this mode of operation, the air gap power, and the mechanical power are negative and because the rotor speed is less than the synchronous speed the slip will be ($0<s<1$). From eq. 3.10, it can be concluded that $|P_{ag}| > |P_m|$. Consequently the rotor electrical power sP_{ag} should be negative. As seen in fig. 3.4 which represent the power flow diagram for this mode of operation, the resultant generated power is equal to ($P_s - P_r$) [7].

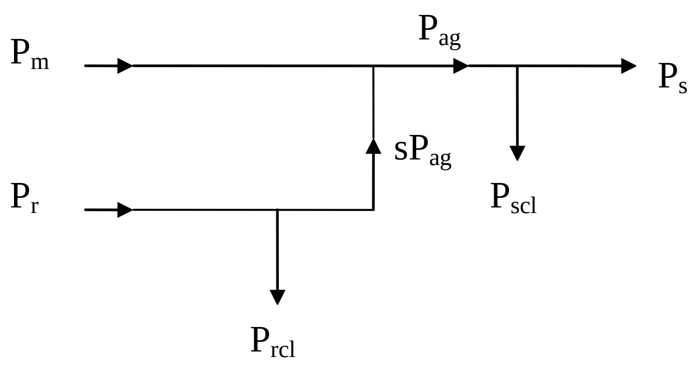

Fig. 3.4 The power flow diagram of the DFIM in sub-synchronous mode

3.4 <u>Control of DFIG</u>

The major task of the DFIG controller is to manage the bidirectional power flow between the rotor and the stator circuit which is achieved by means of controlling the two converters, with an intermediate DC link [7 , 10 , 16].

The control of the DFIG wind turbine consists of three parts [16]:

1) Speed control by controlling the electrical power provided to the converter as well as by the pitch angle,
2) The control of active and reactive power on the stator side which is achieved by the RSC, and
3) GSC control that keeps the DC link voltage constant and provides the additional opportunity to supply reactive power into the grid.

However the DFIG converters are usually controlled using vector control techniques (also known as field oriented control), which allow decoupled control of both active and reactive power or between torque and power factor, Direct control techniques is also used to control the DFIG.

DFIG with vector control is attractive for high performance, variable speed drives and generating applications. The most common control method is to control the rotor currents with stator flux orientation or with Stator voltage orientation [7].

As mentioned above, the control of a DFIG is carried out through controlling the RSC and the GSC. In vector control the RSC is used to control the torque and the power factor through controlling the two components of the rotor current, while, the GSC is used to control the DC link voltage, and the net power factor. Control strategies for both the GSC and the RSC are discussed in the following section.

3.4.1 Vector Control

In general, vector control of a grid connected DFIM is very similar to the widespread classical vector control of a squirrel cage machine. As shown in fig. 3.5, this machine is controlled in a synchronously rotating dq reference frame, with the d axis oriented along the rotor flux space vector position. The direct current is thus proportional to the rotor flux Ψ_r while the quadrature current is proportional to the electromagnetic torque T_{em}. By controlling independently the two components of the current, a decoupled control between the torque and the rotor excitation current is obtained. In a similar way, in vector control of a DFIM, the components of the d and the q axis of the rotor current are regulated. As will be shown, if a reference frame orientated with the stator flux is used, the active and reactive power flows of the stator can be controlled independently by means of the quadrature and the direct current [10].

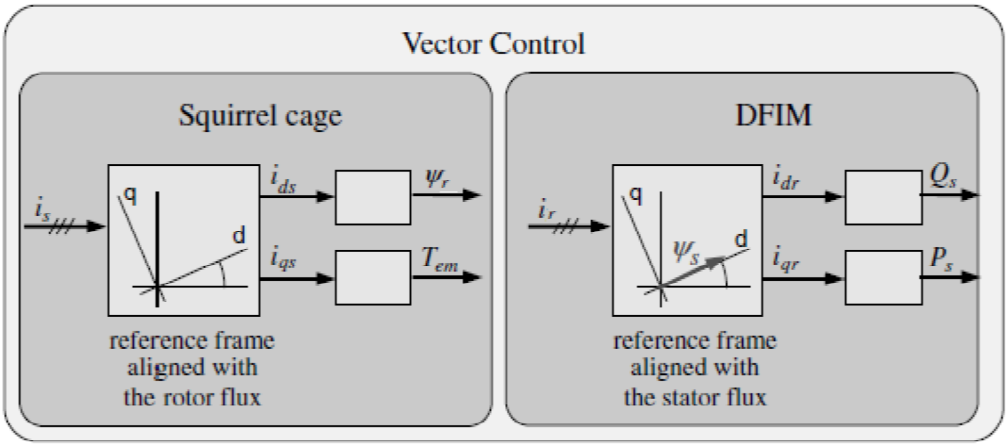

Fig. 3.5 Comparison between the Vector Control of the squirrel cage machine and the DFIM [10]

3.4.1.1 <u>Vector Control of the RSC</u>

The control strategy of the RSC is far more complicated than that of the GSC. This is because, the RSC has to control the machine in both sub-synchronous and super-synchronous modes as well as tracking the maximum power output characteristic of the wind turbine. It is also used to control the power factor. Mainly, the control of a DFIG is obtained through controlling the rotor current using the RSC. Thus the control strategy that describes the DFIG control usually illustrates the control scheme of the RSC. Several vector control schemes have been proposed to control the DFIG consequently the RSC. The RSC is conventionally controlled using either stator flux orientation or stator voltage (grid-flux) orientation [7] .

3.4.1.2 <u>Vector Control of the GSC</u>

The GSC is used to keep the DC link voltage constant regardless of the magnitude and the direction of the rotor power. It may also be responsible for controlling the reactive power to fulfill a desired power factor at the wind turbine terminal.

Usually the GSC is controlled using a vector control approach, with the reference frame oriented along the stator (or the supply) voltage position, enabling independent control of the active and reactive power flowing between the ac system and the GSC [7].

3.4.2 <u>Direct Control of DFIG</u>

Direct control techniques are alternative control solution for AC drives in general. It present control principles and performance features different from vector control techniques. It have two main control types, Direct Torque Control (DTC) and Direct Power Control (DPC). Both methods share a common basic structure and philosophy also they directly control the RSC switches, however each one is oriented to directly control different magnitudes of the machine which leads to slight differences between them. DTC seeks to control the torque and rotor flux amplitude of the machine, while DPC controls the stator active and reactive powers. [10]

Direct control may have an advantage of being have a very high dynamic response more than the vector control which enables it to deal with the grid variations rapidly. On the other hand, one of the most important drawbacks of direct control techniques is the non-constant switching frequency behavior. Consequently, for total harmonic distortion THD sensitive application, vector control appears as the most wise control option because of its low harmonic generation. However an improved version of direct control techniques were designed to avoid that drawback in both DTC & DPC which is known as, predictive direct control techniques (Predictive Direct Torque control (P-DTC) and Predictive Direct Power control (P-DPC)). Based on the same principles as direct control techniques, achieve operation at constant switching frequency on account of the control complexity [10 , 17].

3.5 Protection Systems Of DFIG During Voltage Dips

3.5.1 DFIG During Voltage Dips

The voltage dip is a sudden reduction (within 10% and 90 %) of the voltage at a point of connection with the grid, which continues for half cycle to 1 minute [18]. As mentioned before the DFIG is very sensitive to voltage dips due to its converter rating which is about (25-30%) of its rating.

The voltage dip may results from symmetrical fault (3 phase to ground fault) or asymmetrical fault (phase to ground fault , phase to phase fault and 2 phase to ground fault). In the two cases (symmetrical and asymmetrical faults) there are different types of flux components arising in the stator which depends on the fault type. A large voltage will be induced in the rotor windings and it will depends on the magnitude and the speed of these stator flux components. This high voltage may results in a RSC saturation which means that the RSC became uncontrollable. The uncontrolled current can exceed the semiconductor device rating and results in damage the RSC. In addition, this commonly results in high transient stator currents and transient torque spikes [19].

Concerning the symmetrical fault, the flux in the stator at the fault time can be divided into two components. First, the forced flux which comes from the stator voltage and it rotates at the synchronous speed so its speed with respect to the rotor depends on the slip. Nevertheless as the grid voltage reduces, the magnitude of the forced flux also reduces, so the voltage induced in the rotor during the dips from the forced flux isn't high. The other component is the natural flux which results from the sudden reduction in the voltage. Unlike the forced flux, this natural flux does not rotate so its speed with respect to the rotor is the rotor speed, therefore the voltage induces in the rotor from the natural flux is high. The amplitude of the natural flux decreases exponentially to zero according to the time constant of the stator so its continuity isn't related to the dips interval. Also during the symmetrical fault an important reduction in the electromagnetic torque of the DFIG takes place. [20]

Concerning the asymmetrical fault, the forced flux will be divided into two components positive sequence (rotates at the synchronous speed) and negative sequence (rotates at the synchronous speed reversely) besides the above mentioned natural flux. In this case the natural flux doesn't only depend on the reduction in the voltage level but also on the instant at which the fault appears because the sum of the direction of the positive and negative sequence flux components at an instant (coincide or opposition) affects the magnitude of the stator flux and then the amplitude of the natural flux. Each flux induces a voltage in the rotor according to its amplitude and its relative speed with respect to the rotor windings. Then the harmfulness of the negative sequence flux as its speed is around twice the synchronous speed (with respect to the rotor) is much higher. Also during the asymmetrical dip torque ripples take place due to the negative sequence voltage, which will reflects on the output active power [13 , 21].

Consequently, there are numerous techniques that have been designed to protect the rotor windings , the converters and the DC link. In the following part an overview on the most commonly used protection techniques of the DFIG will take place.

3.5.2 DFIG Protection Techniques

3.5.2.1 Braking Chopper Technique

A braking chopper is a power electronics circuit connected to the DC link bus of the back-to-back converters to prevent an uncontrolled increase of their voltage (see fig. 3.6). It is usually used in electrical streetcars, where the electrical machine may act as a generator when the drive is braking. In such case, the machine feeds energy back to the DC link bus. As very frequently the bus cannot evacuate this energy to the power supply, this energy is accumulated in the DC link and may cause overvoltages in the DC link if it is not dissipated [10].

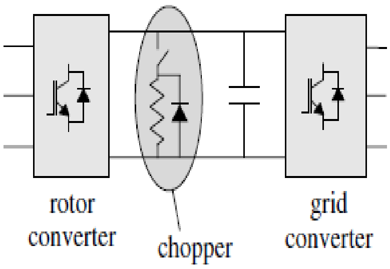

Fig.3.6 DC Chopper system [10].

The braking chopper is made up of a resistor that can be connected or disconnected by means of a switch. A freewheeling diode is also necessary to prevent overvoltages in the switch when it is turned off. Control of the switch is often made by an ON–OFF controller. When the actual DC bus voltage exceeds a specified level, e.g. 1.2 pu, the resistor is connected and the surplus energy is dissipated. The resistor is kept connected until the voltage drops below a minimum specified level, e.g. 1.1 pu, then the resistor is disconnected [10 , 22 , 23].

The installation of a braking chopper in modern commercial turbines to protect the converters from overvoltages in the DC link is more and more common. But because of the disability of the braking chopper to solve the rotor overcurrent problem so it should be used with another technique that can damp the rotor current during faults [10].

3.5.2.2 <u>Changing of Control Strategy Technique</u>

The authors of [24] introduce a topology for limiting the DC link voltage fluctuation by only using improved control strategies for the GSC in the steady state and another one during faults condition. However, that presented technique keeps the DC link voltage nearly constant in steady state conditions and a non-serious voltage dip but on the other hand, that method doesn't have remarkable results concerning the stator voltage and power.

3.5.2.3 <u>Crowbar Technique</u>

The crowbar technique is a traditional protection method of the DFIG during grid faults, as shown in fig. 3.7. Its theory is based on short circuit the rotor windings by a 3 phase resistors to protect the RSC and limit the rotor current during the dips and this can be done by two topologies; passive crowbar and active crowbar [25 , 26].

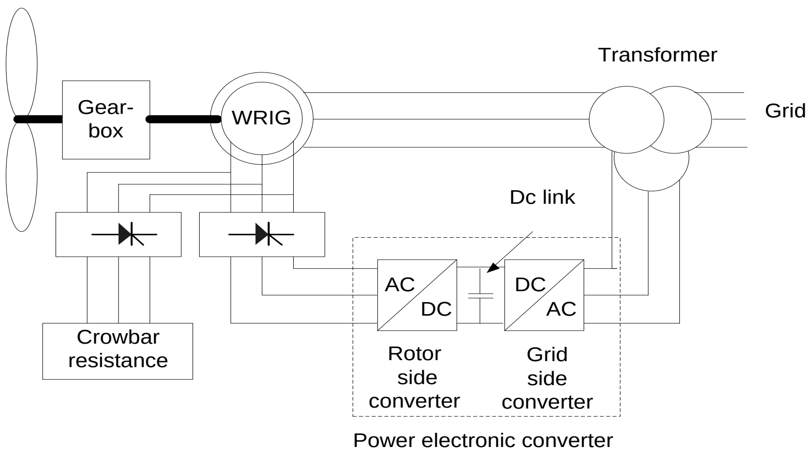

Fig. 3.7 DFIG with crowbar protection

Earlier versions of the crowbar which named "Passive Crowbar" used thyristors (SCR) as switches. However, the problem with thyristors was that their cut-off is not controlled. Once the crowbar is triggered, it remains connected until the circuit breaker of the generator stops the short-circuit current. As a result, the wind turbine is disconnected from the grid and stops generating electric power even if the grid recovers its normal operation. So the passive crowbar is used with small wind farms and when LVRT capability isn't required. In order to provide the LVRT capability, the crowbar activation has to be eliminated before disconnecting the turbine from the grid.

Today most manufacturers use the "Active Crowbar" in which the activation and also the deactivation can be actively controlled. Modern versions of active crowbar is shown in fig. 3.8. It includes at least one switch with cut-off capability, such as GTO or IGBT. This design allows direct disconnection of the crowbar and instant rotor converter reactivation, enabling the continuation of normal operation in the turbine [10].

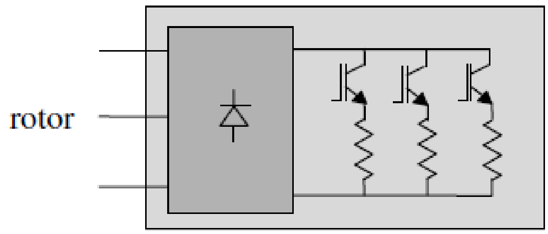

Fig. 3.8 Active crowbar with a set of various resistors [10]

For active crowbar, the control signals are triggered according to the RSC devices which usually have voltage and current limits that should not be exceed. The DC link capacitor voltage is also a monitored variable for crowbar activation [25]. When the crowbar is triggered the rotor windings is short circuited by the crowbar resistors. Therefore the

RSC is disabled and the DFIG behaves as a conventional squirrel cage induction generator (SCIG) with a higher rotor resistance.

While the crowbar is activated the independent controllability of active and reactive power gets thus unfortunately lost. But since the GSC is not directly coupled to the generator windings, there is no need to disable this converter too. The GSC can therefore be used as a STATCOM to produce reactive power - limited however by its rating - during faults [26]. According to [27] a probable range for crowbar resistance is 0.49-1.24pu.

Its should be noted that, The crowbar technique may be effective and may agree with the LVRT requirements in case of symmetrical faults because of the transitory characteristic of the natural flux component. On the other hand, in case of the asymmetrical faults the crowbar can't be connected all the fault time because of the characteristic of the negative sequence component which appears during all the asymmetrical faults period so as to be agreed with the LVRT requirements.

3.5.2.4 <u>Dynamic Braking Resistor (DBR) Techniques</u>

1) <u>DBR Connected to Rotor Windings</u>

This technique was proposed by Jin et al. In this scheme the RSC is protected without disconnecting it from the rotor circuit. A dynamic breaking resistor is connected in series with the rotor in order to limit the current in the rotor circuit [25 , 28 , 29].

In this topology, the DBR is inserted in series between RSC and rotor windings (see fig. 3.9) during voltage dip periods instead of disconnecting the RSC and make the rotor winding short circuited. The DBR resistor limits the rotor current and keeps the RSC connected to the rotor circuit which enables continuous controlling of active and reactive power through the RSC during voltage dip period. Concerning the DBR value, the authors of [28] investigate the value of DBR in terms of stator voltage magnitude changes, slip and rotor speed.

Also the DBR can be variable resistance; Changing its value according to the level of voltage dip so as to maximize the reactive power injected to the grid during different levels of voltage dips [25].

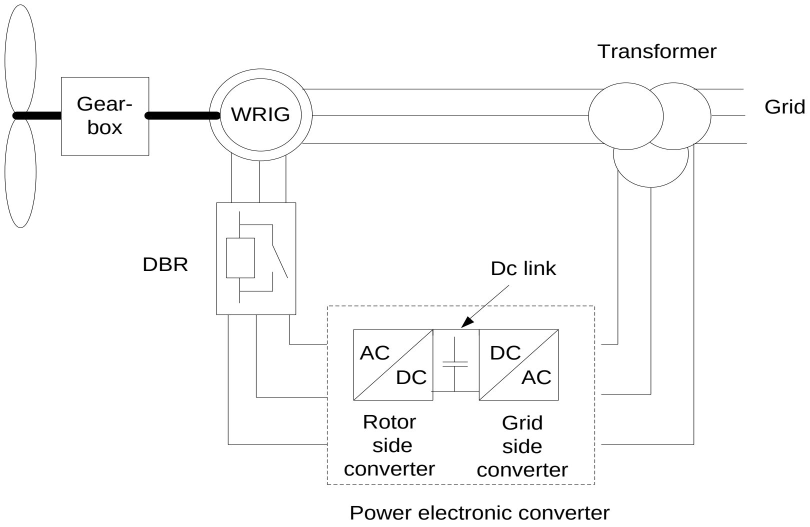

Fig. 3.9 DFIG with DBR connected to rotor

The main advantage of this method over the crowbar method is that the RSC wasn't disconnected from the rotor circuit so the DFIG is still connected to the grid and hence it can control the reactive power injection during voltage dip. On the other hand, if the DBR value wasn't selected carefully it may result in a high voltage in the rotor circuit during the faults which may lead to RSC damage.

2) <u>DBR Connected to Stator Windings</u>

In this topology, a DBR is inserted in series with the stator windings during voltage dip periods (see fig. 3.10). Concerning the effect of the magnitude and the switching time of DBR, the authors of [30] have investigated these issues, A DBR with 0.05pu resistance gives better performances for the DFIG rotor speed and reactive power of the GSC. However, in cases of high DBR resistance (0.1pu and 0.15pu), a high peak in the responses of the active and reactive power of the DFIG appears, while smaller DBR gives a better response. On the other hand, the shorter insertion time from fault initiation and duration of operation of the DBR the better the stability of the DFIG. These investigations in [30] have been done upon the simulation results of three values of both insertion time (after fault initiation) (20 , 50 , 80 ms) and duration of operation time (80 , 100 , 120 ms) respectively.

Also the DBR can be variable; Changing its value according to the level of voltage dip so as to maximize the performance of the DFIG during different levels of voltage dips. Furthermore, it should be selected carefully so as not to effect badly on the generator performance during faults.

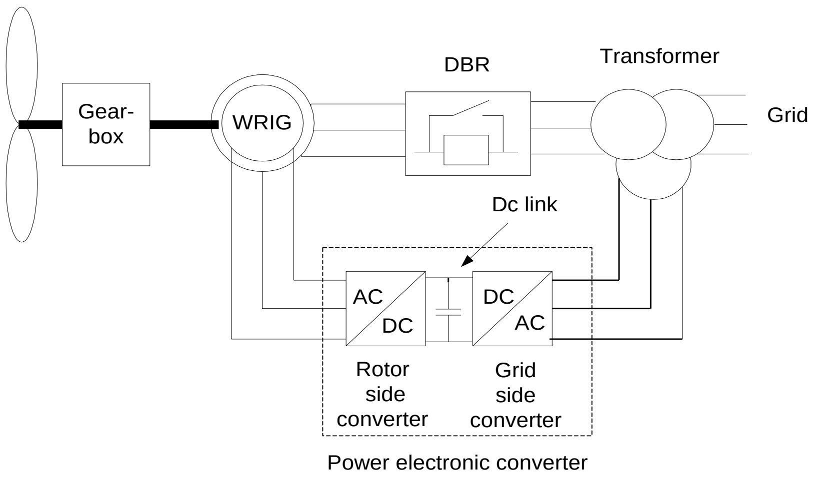

Fig. 3.10 DFIG with DBR connected to stator

This topology have many advantages like, These resistors increase the stator resistance which will lead to stator time constant reduction and hence fast natural flux evolution [31]. The DBR not only control the rotor overvoltage which could cause the RSC to lose control, but also limits high rotor current more significantly. In addition, the rotor current limitation can also avoid DC link overvoltage which could damage the DFIG power converter as it reduces the charging current to the DC link capacitor, The DBR can also balance the active power of the DFIG, and thus improve the DFIG wind generator stability during a fault. Moreover, the DBR will increases the generator output and therefore control the rotor speed acceleration during the grid fault, this effect would improve the post fault recovery of the DFIG system [30 , 32].

3.5.2.5 <u>Rotor Bypass Resistors Technique</u>

Another DBR technique (Shown in fig. 3.11) was presented in [33]. The key of this protection technique is to limit the high currents and to provide a bypass for it in the rotor circuit via a set of resistors that are connected to the rotor windings. This should be done without disconnecting the converter from the rotor or from the grid. Electronic switches can be used to connect the resistors to the rotor circuit. Because the generator and converter stay connected, the synchronism condition remains established during and after the fault.

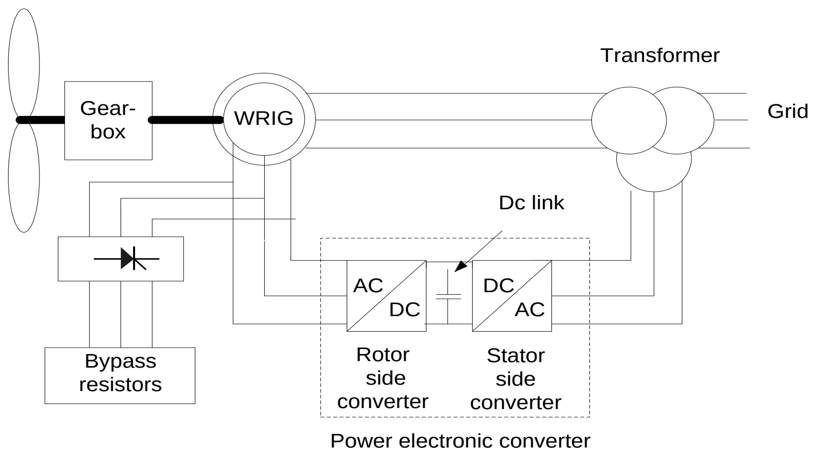

Fig. 3.11 DFIG with bypass resistors

The impedance of the bypass resistors is important but not critical. They should be high enough to limit the current. On the other hand, they should be sufficiently low to avoid too large voltage on the converter terminals. A range of values can be found that satisfies both conditions. According to [33] , a value of 0.86 pu was applied. When the fault in the grid is cleared, the wind turbine is still connected to the grid. The resistors can be disconnected by inhibiting the gating signals and the generator resumes its normal operation. The author of [33] has developed a control strategy that takes care in the transition to normal operation to avoid large transients occurrence.

3.5.2.6 Demagnetizing Current Injection Technique

As mentioned before during the voltage dips there are flux components depending on the nature and the depth of the voltage dips. In some cases these components may be high enough to produce high voltage problems in the rotor not only because of the flux amplitude but also its speed with respect to the rotor. A well-known technique mostly applied to brushless electrical drives is the injection of a current opposite to the magnetic flux to reduce the voltage. Xiang et al. proposed in [34] to inject a current opposite to the undesired components in the stator flux linkage in order to weaken its effect on the rotor. However the rotor flux results from the sum of a term derived from the stator flux and a second term corresponding to the rotor current. If the rotor current opposes the stator flux, the rotor flux decreases. Accordingly, this current may be referred as a demagnetizing current. But according to [34] the required demagnetizing current will exceeds 2 times of the rated current of the converter if the voltage sag is lower than 0.3 pu, which is normally not acceptable. Doubling the capacity of the converter rating makes the DFIG loosing one of its most important advantage [31].

While LÓPEZ et al. in [35] proposed a solution combining crowbar and demagnetizing current injection techniques which enables the DFIG to ride though the symmetrical voltage dips with the same converter capacity and also with reduced crowbar activation time. Such that, the injection of the demagnetizing current in the rotor starts after 50 ms of crowbar activation because during that first 50 ms the demagnetizing solution isn't applicable since it would require a too high current from the converter to oppose the effect of the natural flux at the beginning of the fault. Subsequently, when the machine has been partially demagnetized and the natural flux is decreased, the crowbar is deactivated and the RSC is activated again and then starts to inject a demagnetizing current and produces a reactive power, Thus the turbine could start generating reactive power in about 50 to 60 ms from the beginning of the fault [35]. On the other hand, this technique needs more complicated control strategies to watch the rotor current in order to control the activation and deactivation of the crowbar and also to control the RSC which will direct the injection of the demagnetizing current.

3.5.2.7 <u>Series Grid Side Converter (SGSC) Technique</u>

This configuration was firstly presented by Petersson . In contrast to the traditional configuration of wind turbines based on the DFIG, a SGSC and a three phase injection transformer are added in this configuration. Also, an RL filter is connected between the SGSC and the transformer to limit harmonic losses of the injection transformer [36]. The SGSC, which shares the common dc link voltage with the rotor-side converter and the parallel grid side converter (PGSC), is connected via a three phase injection transformer in series with the main stator windings of the DFIG system as shown in fig. 3.12.

According to this topology the generator's stator terminal voltage becomes now the sum of the grid voltage vector and SGSC voltage vector and hence the generator's stator terminal voltage can be changed by the SGSC. So the transition of the generator stator flux imposed by the stator terminal voltage during the grid faults can be changed through the output voltage of SGSC. i.e. if the SGSC can generate a voltage to counteract the negative sequence and the transient DC flux (natural flux) components in the stator side, the rotor overcurrent caused by these two components can be eliminated.

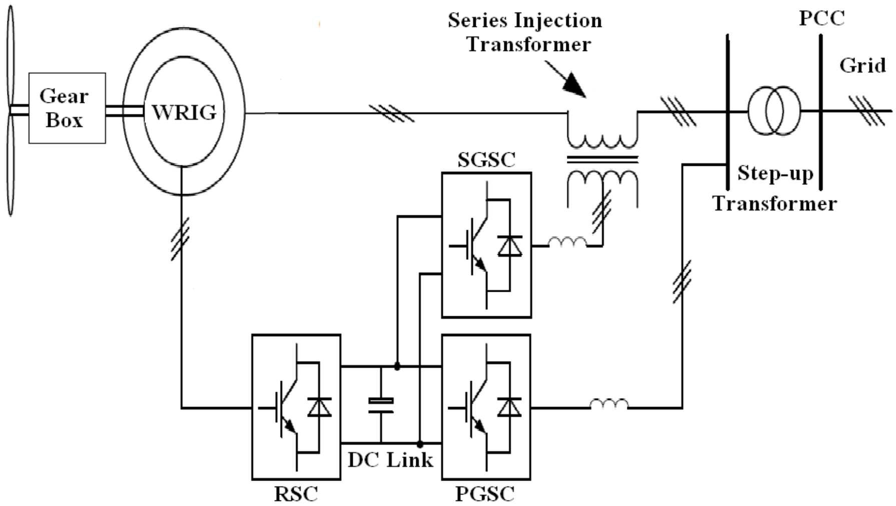

Fig. 3.12 DFIG with SGSC [36]

Thus the transition of DFIG system during grid faults can be changed by controlling the output voltage of the SGSC [36]. But whether the DFIG system demonstrates a good LVRT performance depends on the control scheme of SGSC. On the other hand, this technique has an additional cost of the injection transformer and series converter and complicated control scheme.

3.5.2.8 Replacement Loads Technique

In this technique the DFIG is provided with a standby load, as Figure 3.13 shows. The DFIG is disconnected from the grid and is connected to the standby load in case of the fault. After the fault clearance, the standby load is disconnected and the DFIG is reconnected to the grid.

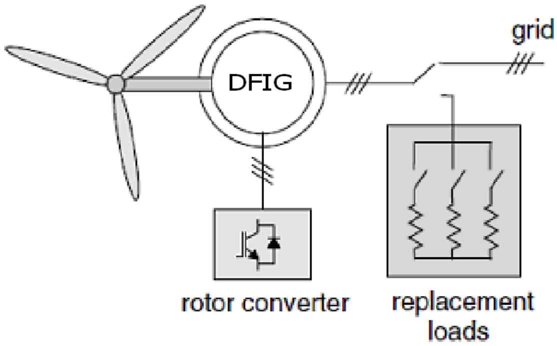

Fig. 3.13 Replacement loads tech.[10]

In this solution, the standby load is selected so that it can dissipate all the rated power of the turbine. The load is controlled in such away to keep the generator voltage at the same level prior to the fault. The wind turbine can therefore continue to generate power, hence avoiding the speed overshoots [10].

Another possibility is to use a reduced load designed to dissipate only a part of the generated power. In this case, the goal is to maintain a certain magnetization in the DFIG. In any case, the replacement load limits the stator and rotor currents during the fault. Besides, since the generator is maintained magnetized during the fault, it can quickly be reconnected to the grid when the fault is removed without performing a time-consuming resynchronization process.

The main drawback of this solution is that during the fault the DFIG is disconnected from the grid hence no active or reactive power injection into the grid except the reactive power which may be injected by the GSC which limited by its power rated. So this solution doesn’t provide LVRT requirements and therefore can't be used with the new grid codes. It may be used with a standalone generator or with small grids which doesn't have grid codes require LVRT capability [10].

3.6 Conclusion

DFIG is one of the most common used generators that are used with the variable speed wind turbine. The DFIG has many advantages like; the independent control of active and reactive power, its partial rated power converters (25 – 30 % of machine rated power) which lead to low cost, more lighter weigh and high efficiency. On the other hand, the DFIG is very sensitive to voltage dips due to its partial rated power of the converters (RSC and GSC).

The control of the DFIG is mainly obtained through the control of the RSC and GSC. Although vector control is usually used to control the DFIG as it allows decoupling control of both active and reactive power and low THD, the direct control techniques have a high dynamics response but with high THD.

During the voltage dips a very high voltage may be induced in the rotor circuit which depends on the level of the voltage dip and also the type of the fault (Symmetrical or Asymmetrical). This high voltage may damage the RSC and also the DC link capacitor, therefore it should be protected during the voltage dips. In this chapter, many protection techniques of the DFIG were discussed and also its advantages and disadvantages.

Chapter 4

Case Study

4.1 Introduction

In this chapter, the performance of the DFIG is studied under symmetrical and asymmetrical faults with different protection techniques applied in order to compare their effects on the DFIG behavior.

In order to conduct this comparison the network shown in Fig. 4.1 is considered. The network consist a 9 Mw wind farm (six 1.5 Mw wind turbines) connected to a 25 kv distribution system exports power to a 120 kv grid through a 30 km, 25 kv feeder. The 9 Mw wind farm is modeled as a one lumped machine. The system shown is Fig. 4.1 is modeled and simulated using the SimPowerSystem toolbox under the Matlab/simulink (Appendix A). The DFIG model used in this study is a modified version of the DFIG detailed model in the MATLAB/Simulink. The detailed model includes complete representation of power electronic converters. This model has to be discretized at a relatively small time step in order to achieve an acceptable accuracy with the operating switching frequencies (1620 HZ and 2700 HZ). In this model a vector control technique based on the stator flux orientation technique is used to control the DFIG's converters. The parameter of the 1.5 Mw DFIG is shown in table 4.1 [37].

The protection techniques applied in this chapter are the DC chopper, Crowbar (CB), rotor connected DBR and stator connected DBR. These techniques were selected because of their remarkable results besides their simplicity and cost effectiveness. In this chapter the DC chopper was combined with all studied techniques because it is an auxiliary technique (as mentioned in chapter 3, it protects the DC link from overvoltage). Furthermore, all the protection techniques were applied after the fault happen by 10 ms so as to be applicable as possible.

Also each technique was applied 3 times with 3 different resistance values in order to show the behavior of the DFIG with the change in the resistance value.

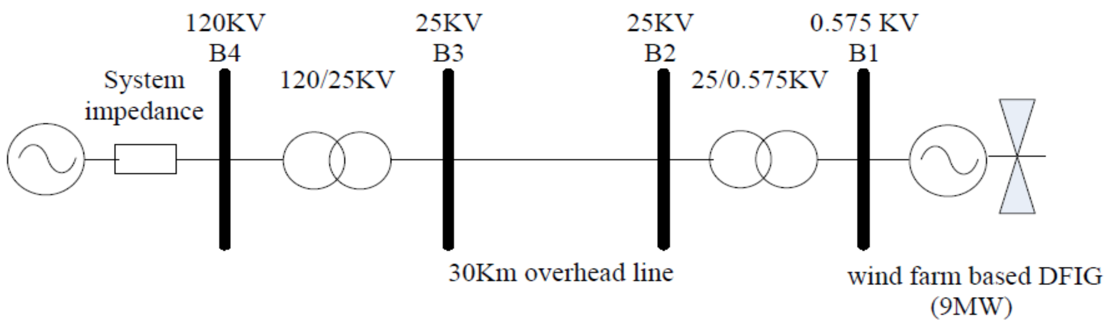

Fig. 4.1 The simulated system

Rating	1.5 Mw
Stator voltage (L-L. RMS)	575 V
Number of pair pole	3
Stator resistance	0.00706 pu
Stator inductance	0.171 pu
Mutual inductance	2.9 pu
Rotor resistance	0.005 pu
Rotor inductance	0.156 pu
Combined inertia constant of the generator and the turbine	5.04 s

Table 4.1. The 1.5 Mw DFIG parameters

The study conducted in this chapter is obtained with the following sequence:

First, in case of asymmetrical fault (single phase to ground fault) is considered. The fault is applied at bus (B1) (particularly on phase B).

Second, in case of symmetrical fault (three line to ground fault) is applied at bus (B4).

All the protection techniques were applied and removed in a predefined time irrespective of the DFIG readings. The duration of the applied faults in the two cases (symmetrical and asymmetrical faults) is

140 ms as mentioned in the most of the new grid codes [38]. The following sections show the simulation results and its discussions.

4.2 <u>The DFIG Behavior Without Protection Applied</u>:

In this section the DFIG is studies under both fault types mentioned above without any protection techniques.

4.2.1 <u>Asymmetrical Fault With No Protection Applied</u> :

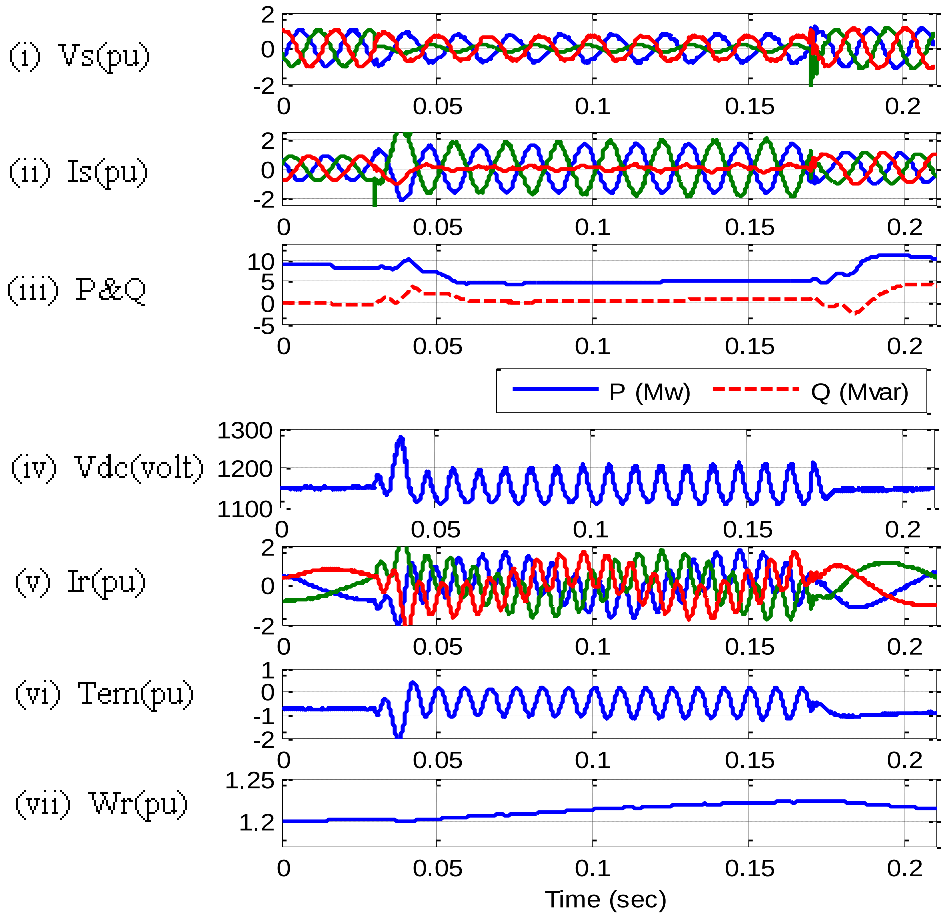

Fig. 4.2 Asymmetrical fault with no protection applied

As shown in Fig. 4.2 , when the DFIG was subjected to the pre-mentioned asymmetrical fault (single line to ground fault of phase B at bus (B1)) the stator voltage Vs reduced to 0.8 pu, the stator current Is increased up to 2 pu and the rotor currents Ir increased up to 1.7 pu asymmetrically. On the other hand the active power P reduced to 5 Mw and the reactive power Q reaches 0.8 Mvar. While the wind turbine speed Wr peaks to 1.224 pu. As results show and as mentioned before in chapter 3, due to this asymmetrical fault noticeable ripples appeared in the DC link voltage and in the electromagnetic torque Tem.

4.2.2 Symmetrical Fault With No Protection Applied :

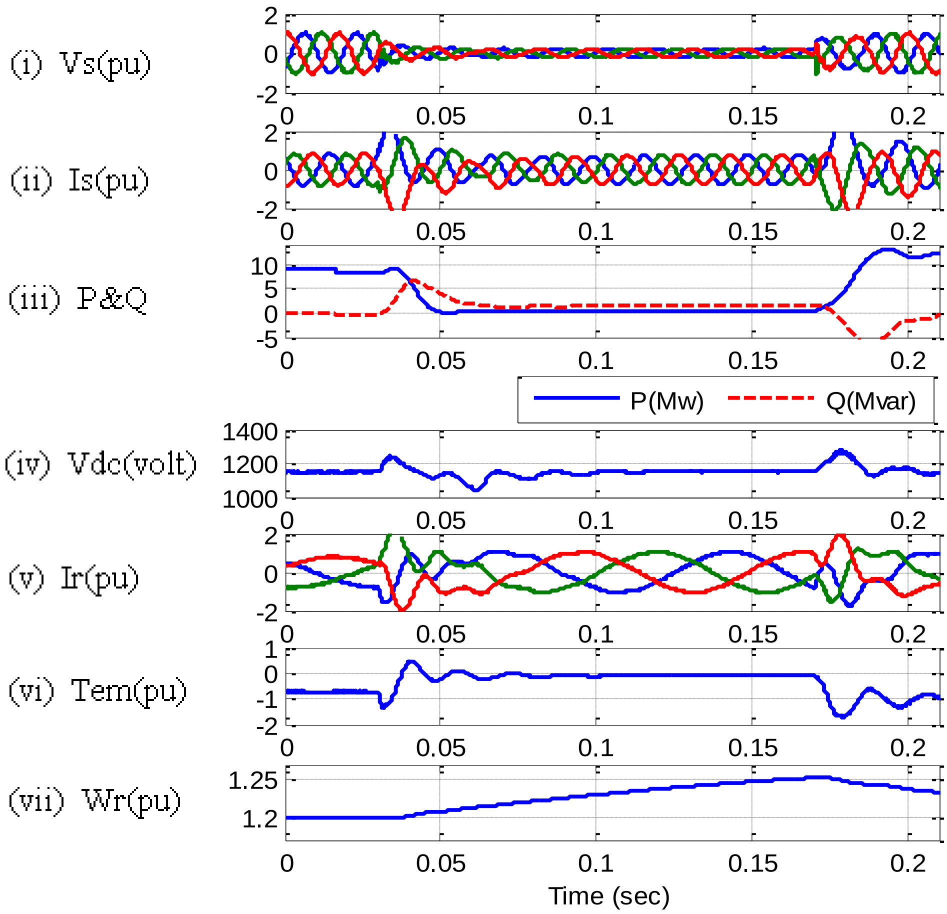

Fig. 4.3 Symmetrical fault with no protection applied

As shown in Fig. 4.3 when the DFIG was subjected to an asymmetrical fault at bus (B4) the stator voltage Vs reduced to 0.24 pu, the stator current Is reduced to 0.79 pu and the rotor current Ir increased up to 1.05 pu. On the other hand the active power P reduced to 0.35 Mw and the reactive power Q reach 1.65 Mvar while the wind turbine speed Wr peaks to 1.253 pu.

4.3 <u>The DFIG Behavior with Only DC Chopper Technique</u>:

As mentioned before, The DC chopper is a power electronics circuit connected to the DC link bus of the DFIG's converters to prevent the uncontrolled increase of the DC bus voltage. Its effect only appears on the DC link voltage. Therefore this technique cannot protect the DFIG's converters. Consequently the DC chopper shouldn't be used alone.

4.3.1 <u>Asymmetrical Fault With Only DC Chopper Technique</u> :

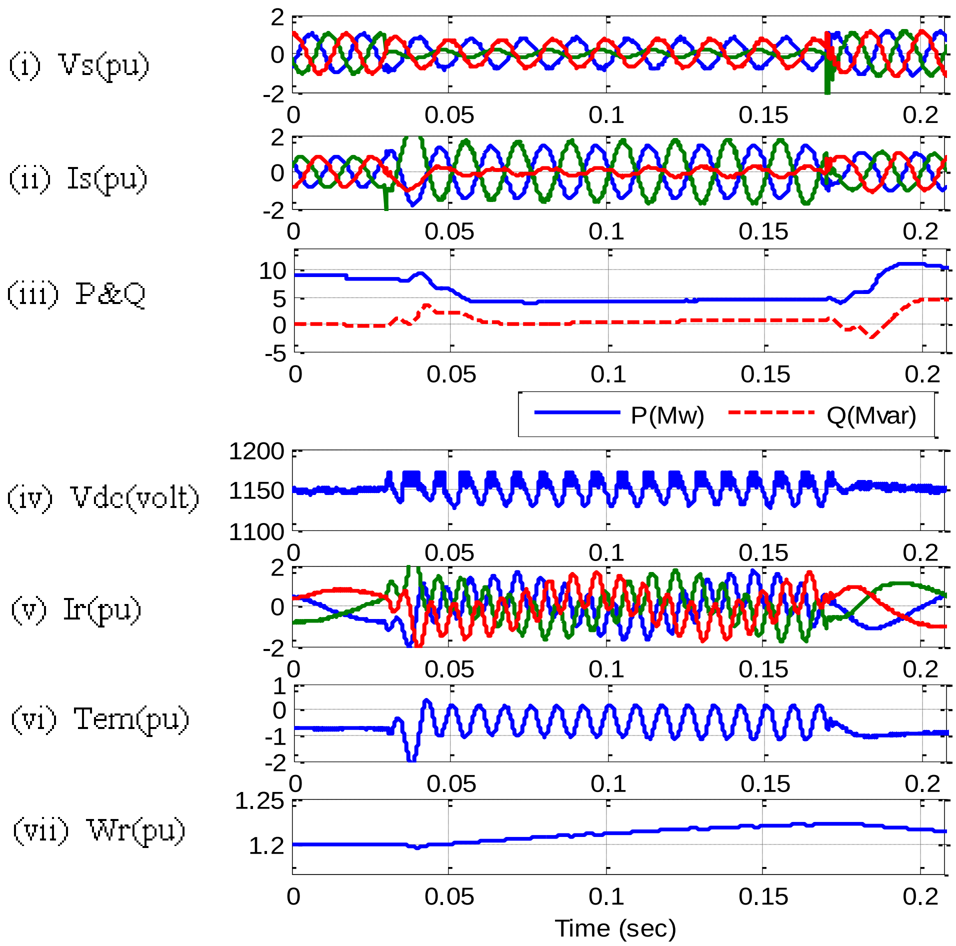

Fig. 4.4 Asymmetrical fault with only DC chopper technique

4.3.2 Symmetrical Fault With Only DC Chopper Technique:

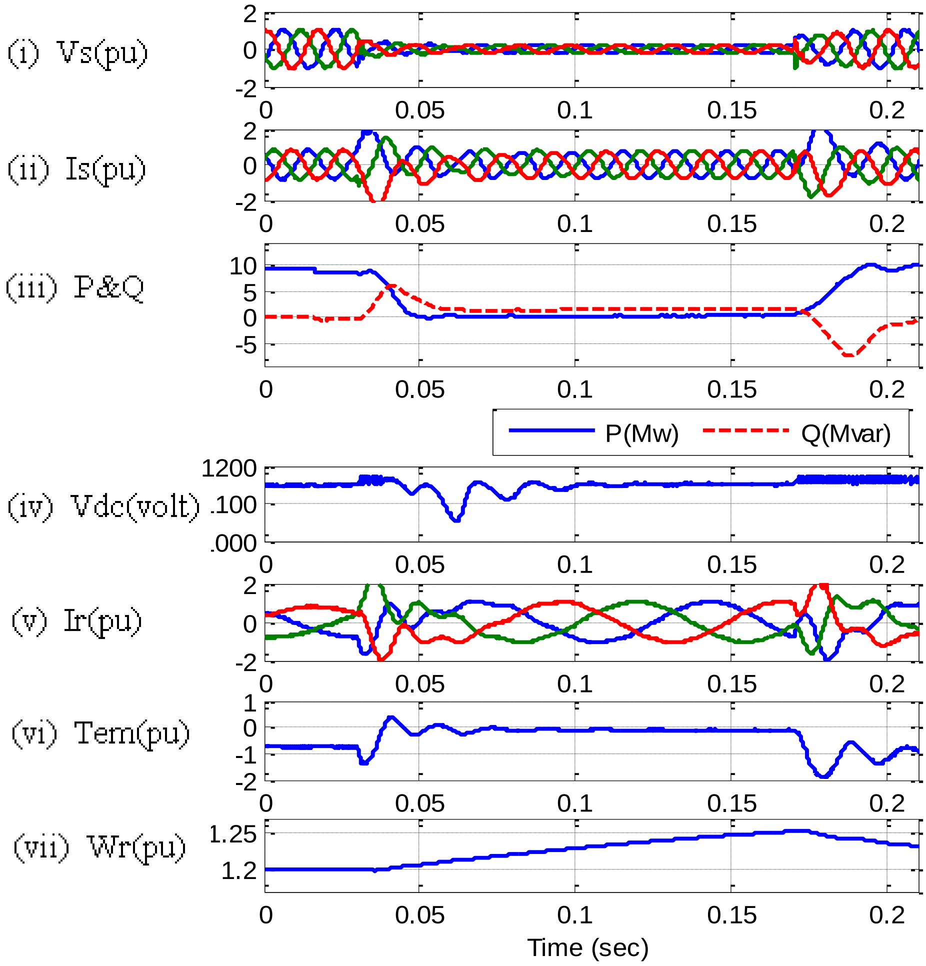

Fig. 4.5 Symmetrical fault with only DC chopper technique applied

As fig. 4.4 and 4.5 show, when the DC chopper technique is applied there is no remarkable effect on the stator and rotor voltage and current and the active and reactive power. The effect of the DC chopper only appears in the DC link voltage. Fig. 4.4 and 4.5 show that the DC link voltage is limited to 1170 V compared to 1280 V. This will lead to the protection of the DC link capacitor and limit the GSC current. Therefore, this technique can't be used alone as a protection method for the DFIG and it should be combined with one of the other techniques.

4.4 The DFIG Behavior with the Crowbar protection Technique:

In this technique the rotor windings are shorted by a 3 phase resistors to protect the RSC and limit the rotor current during the grid faults. According to [27], a probable range for crowbar resistance is 0.49-1.24 pu. Therefore, the selected resistances values are 0.0045 , 0.009 and 0.0108 Ω which equals 0.5 , 1 , 1.2 pu.

4.4.1 Asymmetrical Fault With Crowbar Technique :

4.4.1.1 CB Resistance of (0.0045 Ω) :

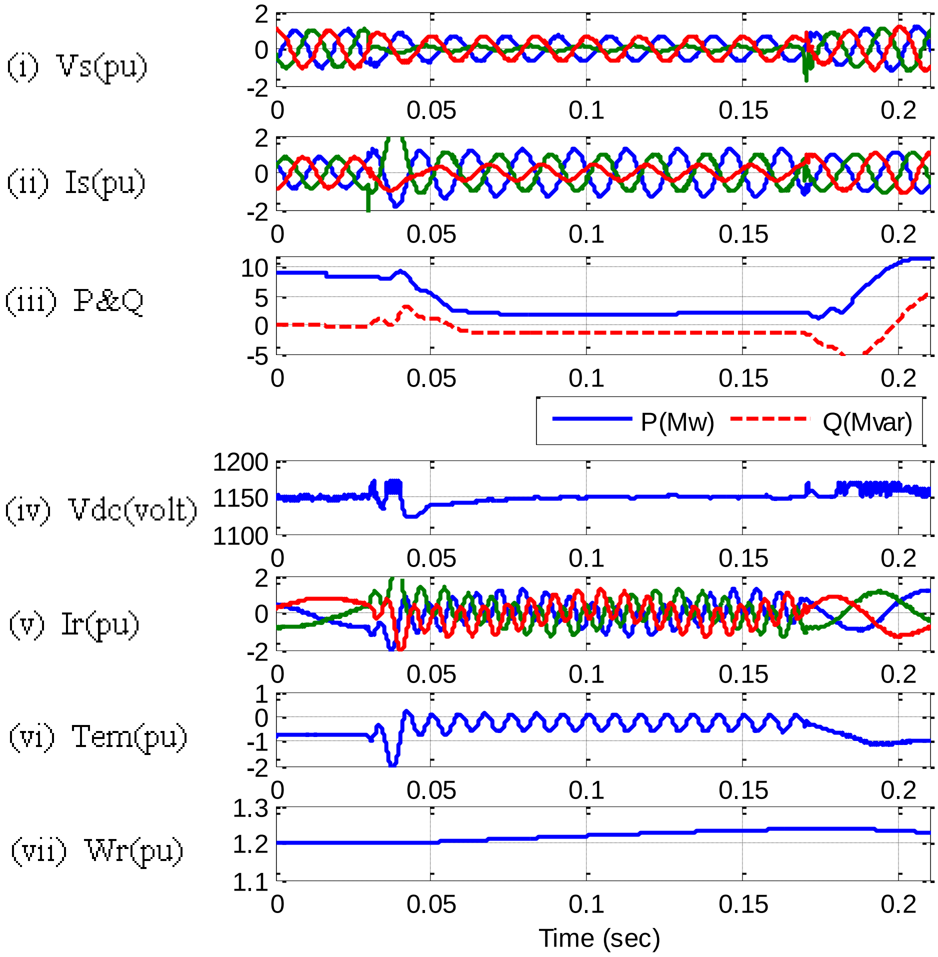

Fig. 4.6 Asymmetrical fault at CB resistance (0.0045 Ω)

Fig. 4.6 shows that when a CB of 0.0045Ω resistance is activated during the fault, the stator voltage reduced to 0.7 pu, the stator current increased to 1.3 pu and the rotor current increased to 1.25 pu asymmetrically. While the active power reduced to 1.9 Mw and the reactive power was -1.5 Mvar. The rotor speed peaks to 1.239 pu.

4.4.1.2 <u>Crowbar Resistance of (0.009 Ω)</u> :

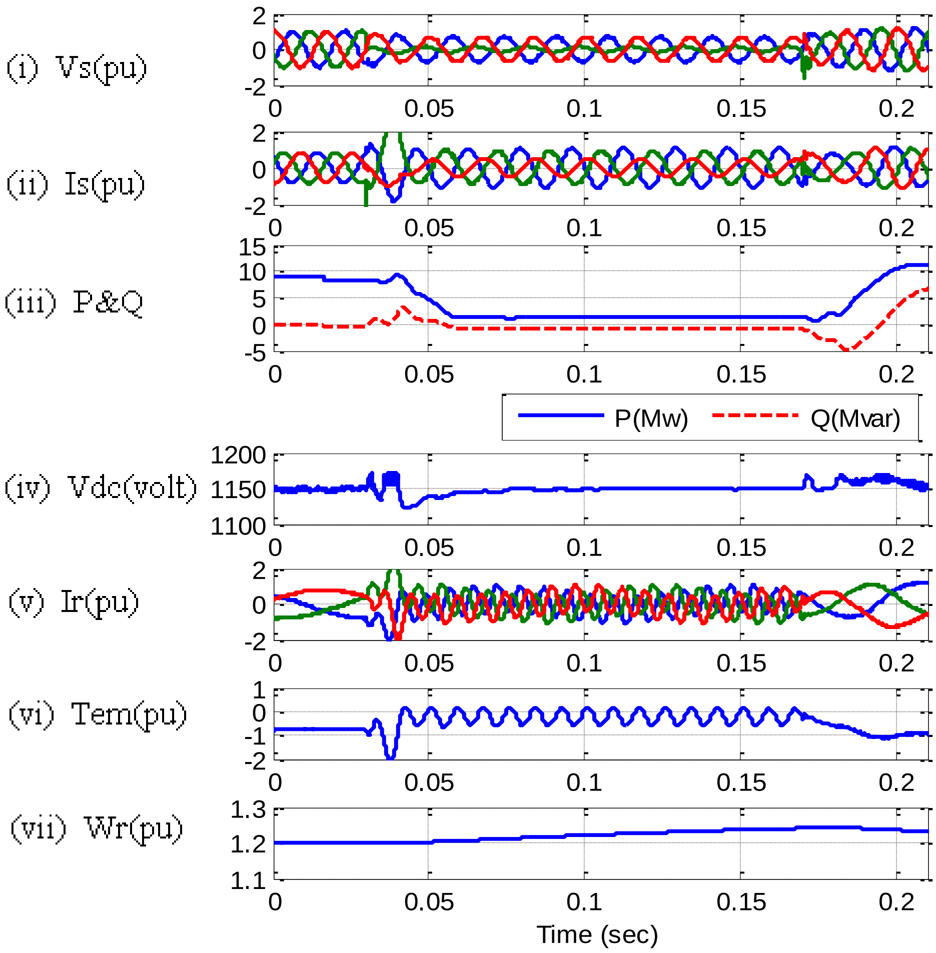

Fig. 4.7 Asymmetrical fault at CB resistance (0.009 Ω)

Fig. 4.7 shows that when a CB of 0.009Ω resistance is activated during the fault, the stator voltage reduced to 0.7 pu, the stator current increased up to 1.09 pu and the rotor current increased up to 1.08 pu asymmetrically, while the active power reduced to 1.4 Mw and the reactive power was -1 Mvar. The rotor speed peaks to 1.242 pu.

4.4.1.3 CB Resistance of (0.0108 Ω) :

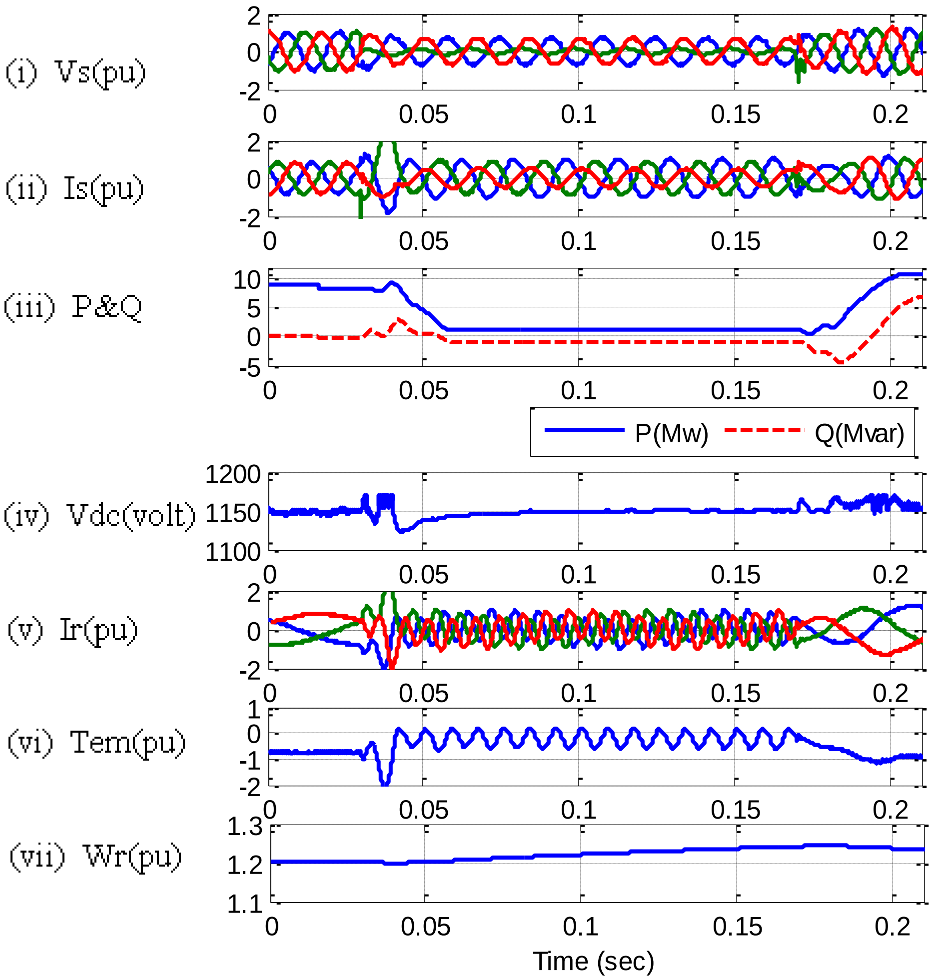

Fig. 4.8 Asymmetrical fault at CB resistance (0.0108 Ω)

Fig. 4.8 shows that when a CB of 0.0108Ω resistance is activated during the fault, the stator voltage reduced to 0.73 pu, the stator current increased to 1 pu and the rotor current increased to 1 pu asymmetrically. While the active power reduced to 1.15 Mw and the reactive power was -0.85 Mvar. The rotor speed peaks to 1.243 pu.

4.4.2 Symmetrical Fault With Crowbar Technique :

4.4.2.1 CB Resistance of (0.0045 Ω) :

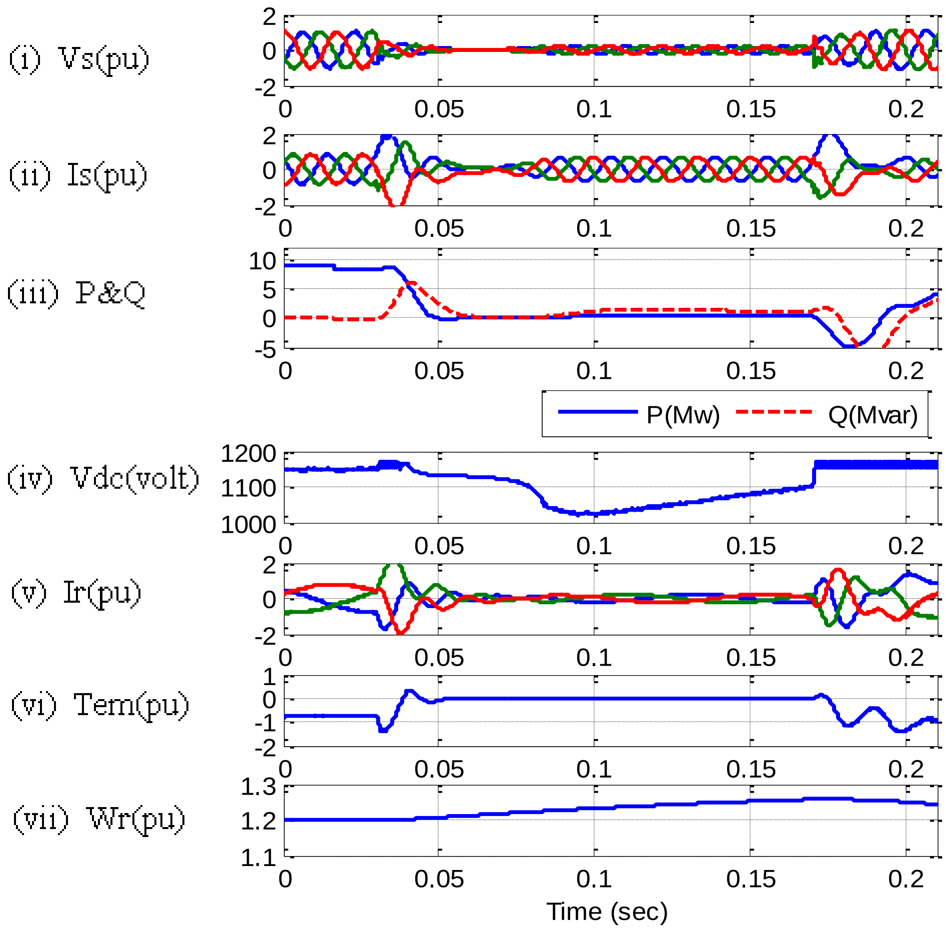

Fig. 4.9 Symmetrical fault at CB resistance (0.0045 Ω)

Fig. 4.9 shows that when a CB of 0.0045Ω resistance is activated during the fault, the stator voltage was reducing up to 0.04 pu and before the fault clearing it reached 0.21 pu. The stator current was reducing up to 0.2 pu and reached 0.65pu before the fault clearing. The rotor current still reduced up to 0.24 pu. While the active power was between 0 and 0.25 Mw and the reactive power increased from 0 and 1.2 Mvar. The rotor speed peaks to 1.259 pu.

4.4.2.2 CB Resistance of (0.009 Ω) :

Fig. 4.10 shows that when a CB of 0.009Ω resistance is activated during the fault, the stator voltage was reducing up to 0.05 pu and before the fault clearing it reached 0.23 pu. The stator current was reducing up to 0.1 pu ant it reached 0.73pu before the fault clearing. The rotor current still reducing up to 0.05 pu but before the fault clearing it reached 0.15 pu. While the active power increased from 0 to 0.3 Mw and the reactive power increased from 0 and 1.45 Mvar. The rotor speed peaks but didn't reach 1.26 pu.

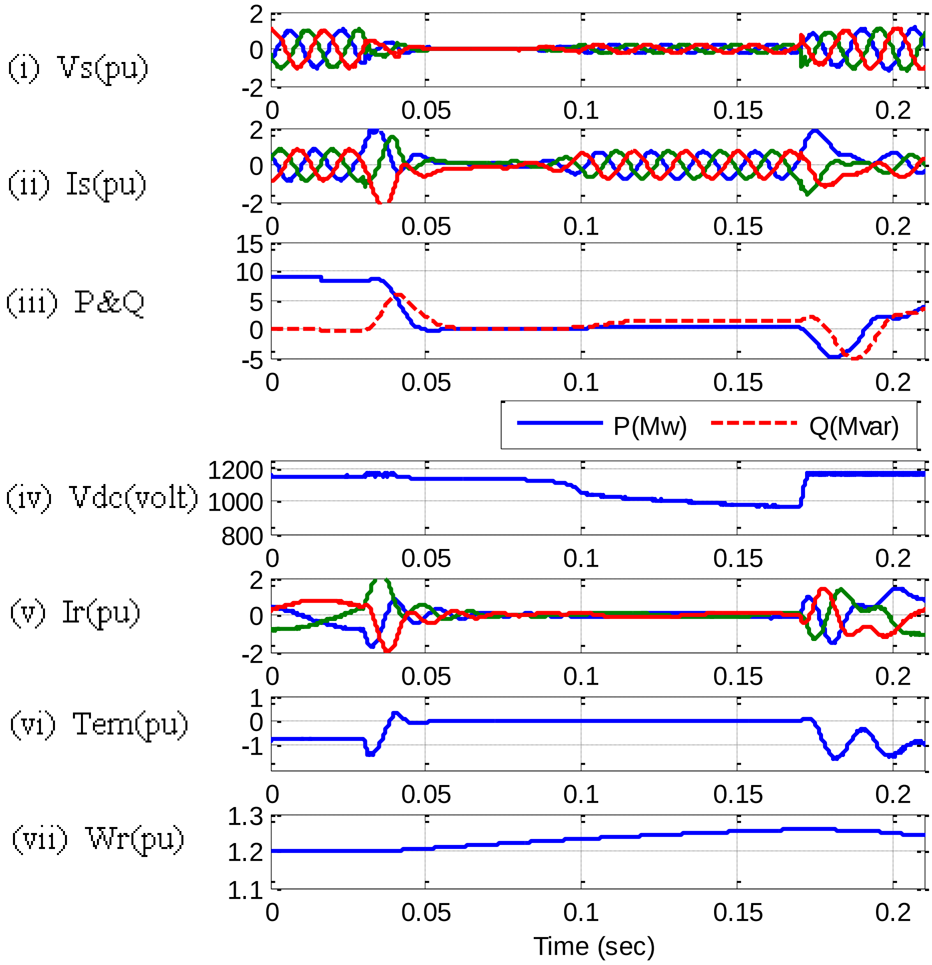

Fig. 4.10 Symmetrical fault at CB Resistance (0.009 Ω)

4.4.2.3 CB Resistance of (0.0108 Ω) :

Fig. 4.11 shows that when a CB of 0.0108Ω resistance is activated during the fault, stator voltage was reducing up to 0.02 pu but before the fault clearing it reached 0.23 pu. The stator current reduced up to 0.14 pu and reached 0.76 pu before the fault clearing. The rotor current still reducing up to 0.05 pu. While the active power reduced to 0.31 Mw and the reactive power increased from 0 and 1.48 Mvar. The rotor speed peaks to 1.26 pu.

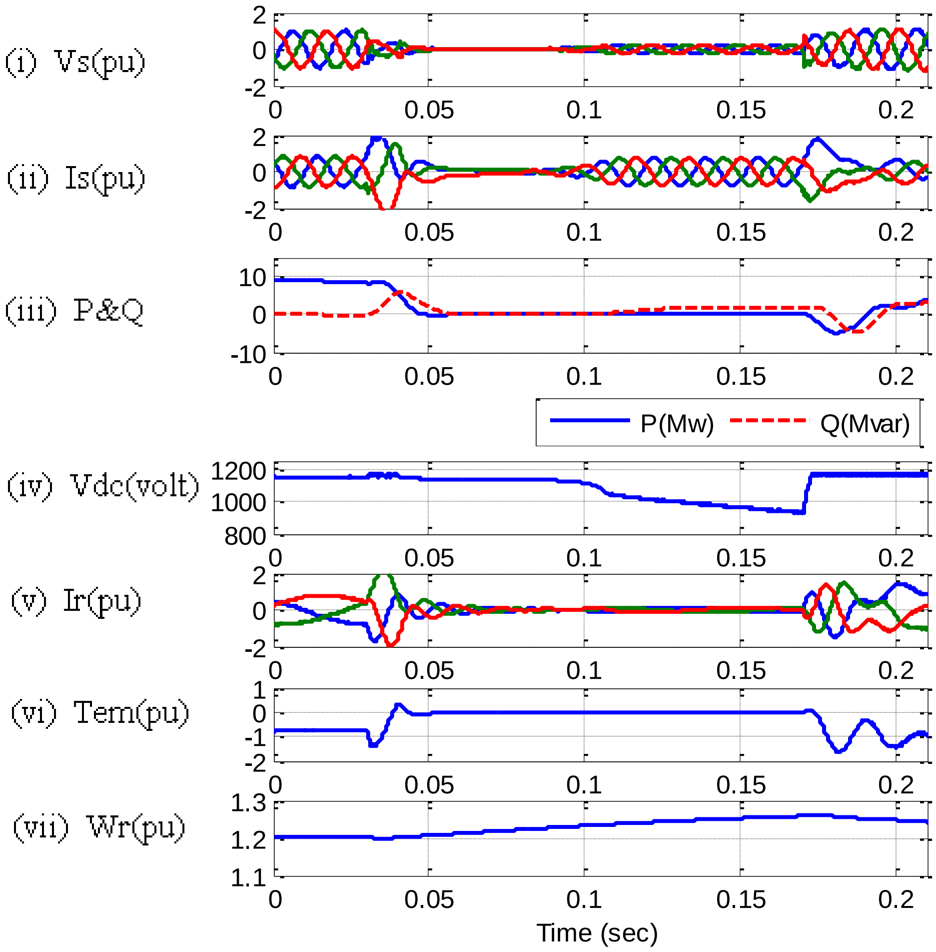

Fig. 4.11 Symmetrical fault at CB resistance (0.0108 Ω)

Referring to the simulation results in sections 4.4.1 and 4.4.2 which are summarized in table 4.2, it can be noticed that; First, concerning the DFIG behavior during the asymmetrical fault, as the CB resistance increased the stator voltage slightly increased. On the other hand, the stator and rotor current and the active power reduced. Therefore the rotor speed increased while the DFIG reactive power consumption reduced. Second, concerning DFIG behavior during the symmetrical fault, as the CB resistance increased the stator voltage and current and the active and reactive power increased while the rotor current decreased. The rotor speed is nearly constant.

CB	0.0045	0.009	0.0108
Vs (pu)	0.7	0.7	0.73
Is (pu)	1.3	1.09	1
Ir (pu)	1.25	1.08	1
P (Mw)	1.9	1.4	1.15
Q (Mvar)	-1.5	-1	-0.85
Wr (pu)	1.239	1.242	1.243

Table 4.2 CB technique results summarization during asymmetrical fault

CB	0.0045	0.009	0.0108
Vs (pu)	0.21	0.23	0.23
Is (pu)	0.65	0.73	0.76
Ir (pu)	0.24	0.15	0.05
P (Mw)	0.25	0.3	0.31
Q (Mvar)	1.2	1.45	1.48
Wr (pu)	1.259	1.26	1.26

Table 4.3 CB technique results summarization during symmetrical fault

4.5 <u>The DFIG Behavior with Rotor Connected DBR Technique</u>:

In this technique, a dynamic breaking resistor is connected in series with the rotor in order to limit the current in the rotor circuit. The resistances values is selected according to [28] so that, 0.0025, 0.005 and 0.0125 Ω.

4.5.1 <u>Asymmetrical Fault With Rotor Connected DBR Technique</u> :

4.5.1.1 <u>DBR of (0.0025 Ω)</u> :

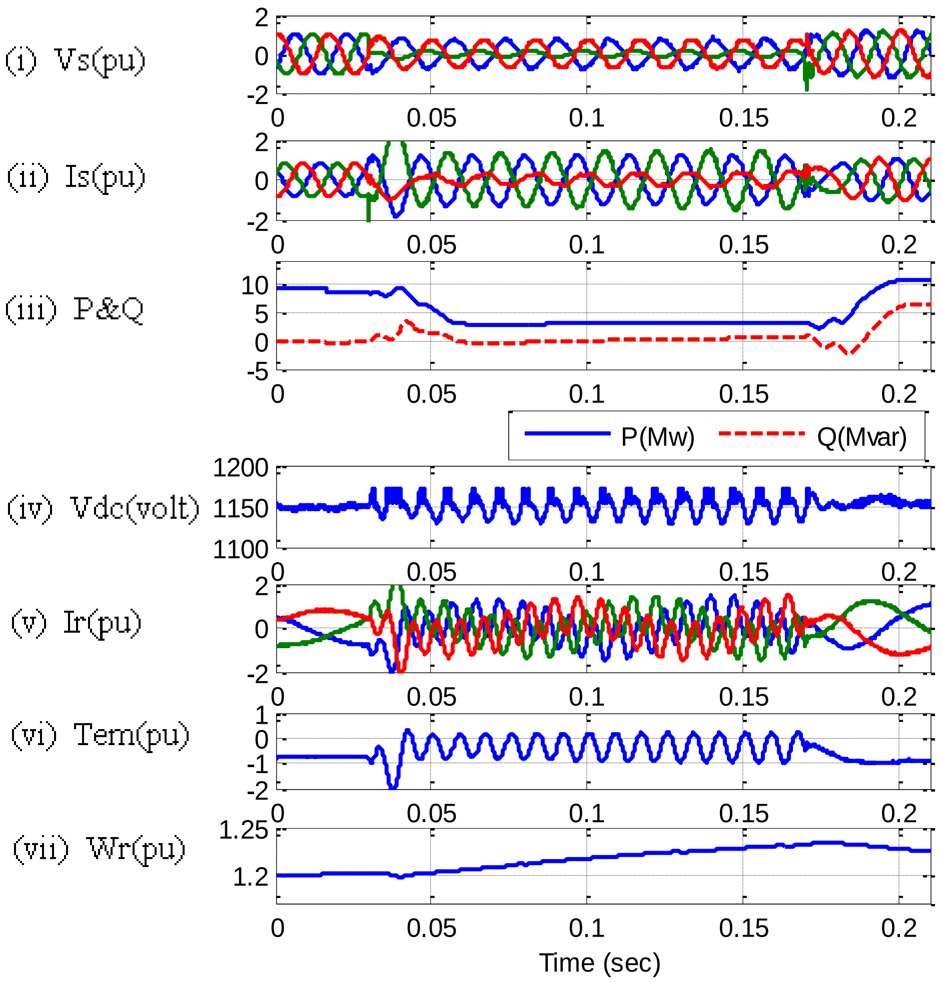

Fig. 4.12 Asymmetrical fault at rotor connected DBR (0.0025 Ω)

Fig. 4.12 shows that when a 0.0025Ω resistance is connected in series with the rotor windings during the fault, the stator voltage reduced to 0.8 pu, the stator current increased to 1.5 pu and the rotor current increased to 1.45 pu asymmetrically. While the active power reduced to 3.15 Mw and the reactive power peaks to around 0.7 Mvar. The rotor speed peaks to 1.233 pu.

4.5.1.2 <u>DBR of (0.005 Ω)</u> :

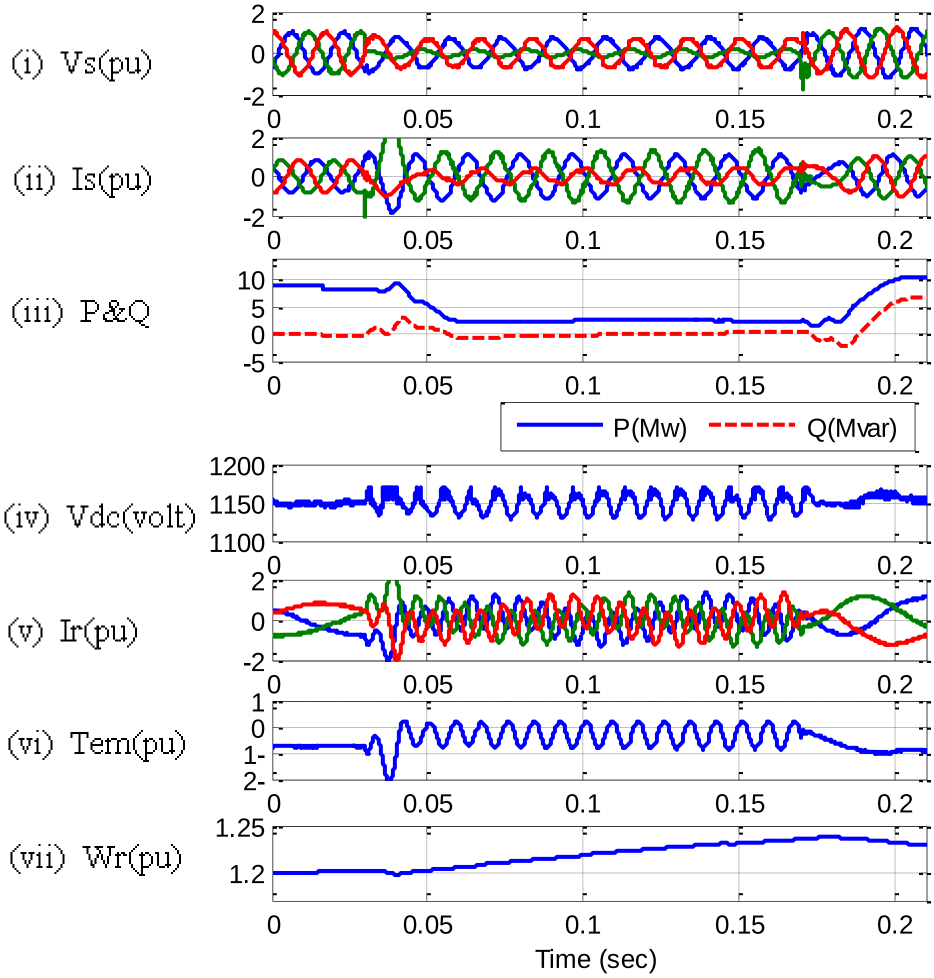

Fig. 4.13 Asymmetrical fault at rotor connected DBR (0.005 Ω)

Fig. 4.13 shows that when a 0.005Ω resistance is connected in series with the rotor windings during the fault, the stator voltage reduced to 0.8 pu, the stator current increased up to 1.4 pu and the rotor current increased up to 1.3 pu asymmetrically. While the active power reduced to 2.4 Mw and the reactive power peaks to around 0.4 Mvar. The rotor speed increased up to 1.237 pu.

4.5.1.3 DBR of (0.0125 Ω) :

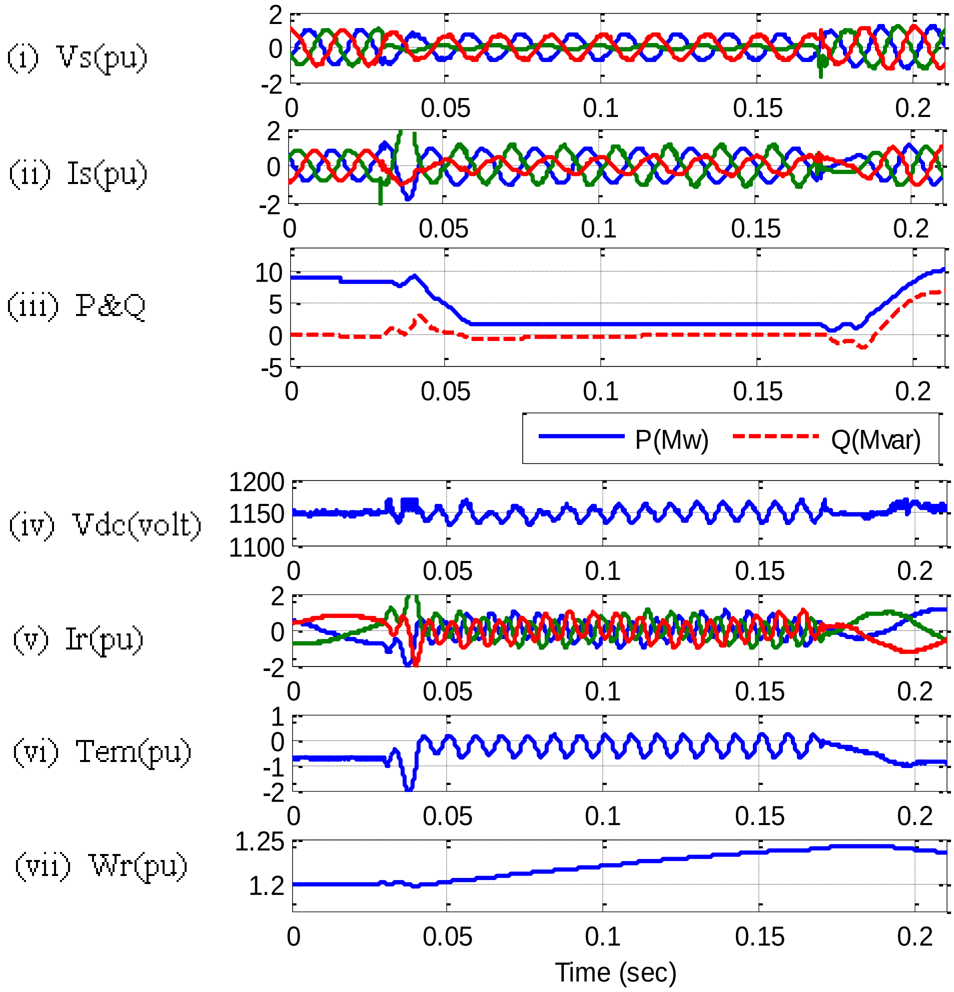

Fig. 4.14 Asymmetrical fault at rotor connected DBR (0.0125 Ω)

Fig. 4.14 shows that when a 0.0125Ω resistance is connected in series with the rotor windings during the fault, the stator voltage reduced to 0.8 pu, the stator current increased up to 1 pu and the rotor current increased up to 1.05 pu asymmetrically. While the active power reduced to 1.5 Mw and the reactive power peaks to around 0.05 Mvar. The rotor speed peaks to 1.242 pu.

4.5.2 Symmetrical fault with rotor connected DBR Technique :

4.5.2.1 DBR of (0.0025 Ω) :

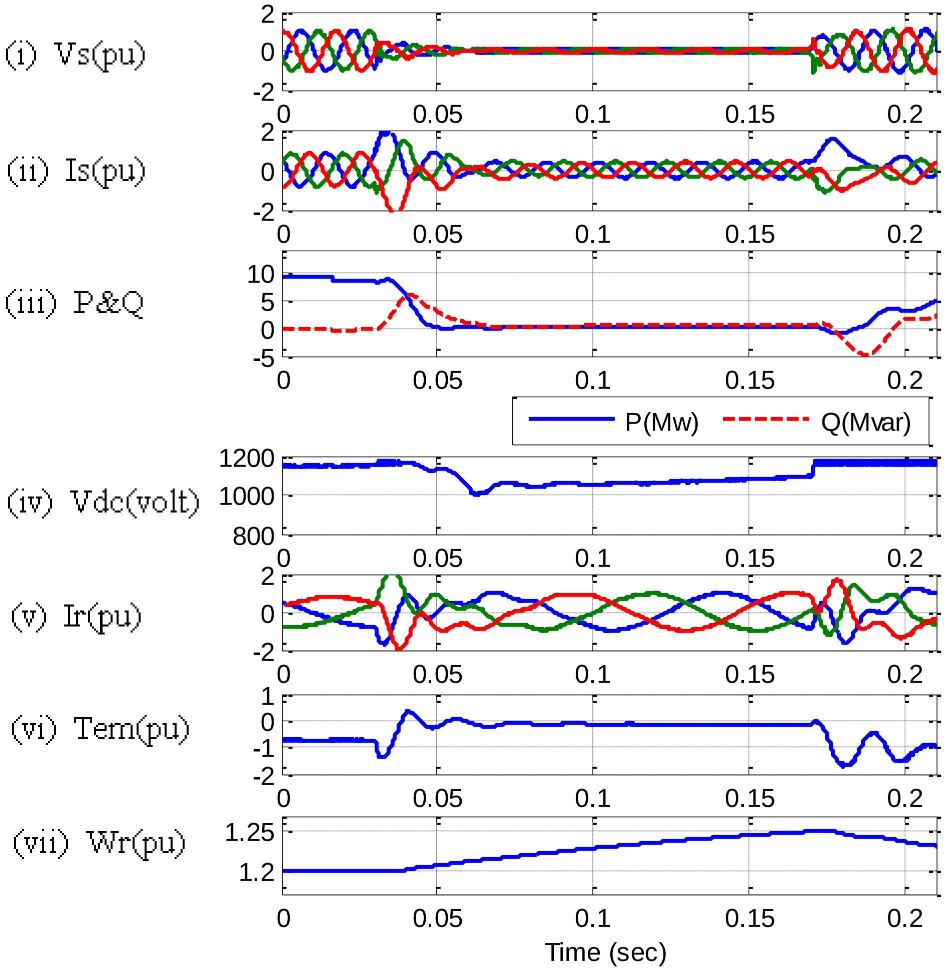

Fig. 4.15 Symmetrical fault at rotor connected DBR (0.0025 Ω)

Fig. 4.15 shows that when a 0.0025Ω resistance is connected in series with the rotor windings during the fault, the stator voltage reduced up to 0.13 pu, the stator current reduced up to 0.4 pu and the rotor current increased up to 1 pu. While the active power reduced to 0.1 Mw and the reactive power peaks to around 0.5 Mvar. The rotor speed peaks to 1.25 pu.

4.5.2.2 DBR of (0.005 Ω):

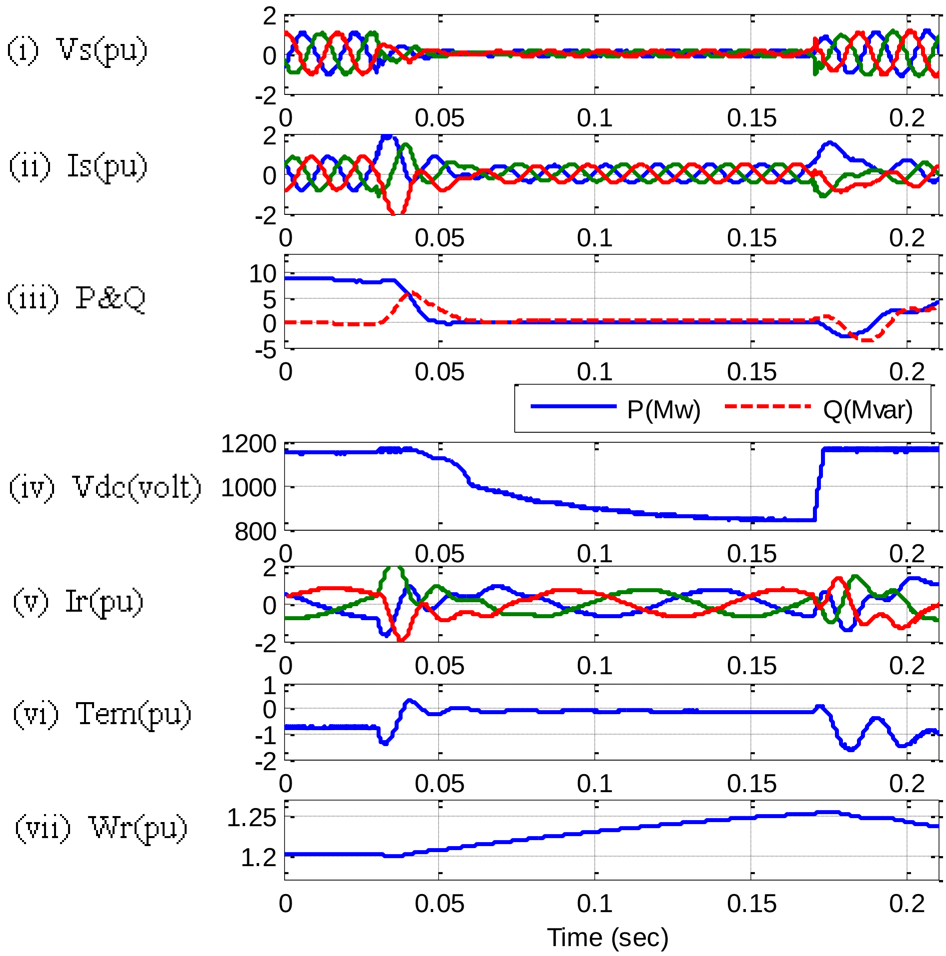

Fig. 4.16 Symmetrical fault at rotor connected DBR (0.005 Ω)

Fig. 4.16 shows that when a 0.005Ω resistance is connected in series with the rotor windings during the fault, the stator voltage reduced up to 0.14 pu, the stator current reduced up to 0.45 pu and also the rotor current reduced up to 0.7 pu. While the active power reduced to 0.13 Mw and the reactive power peaks to around 0.6 Mvar. The rotor speed peaks to 1.253 pu.

4.5.2.3 DBR of (0.0125 Ω):

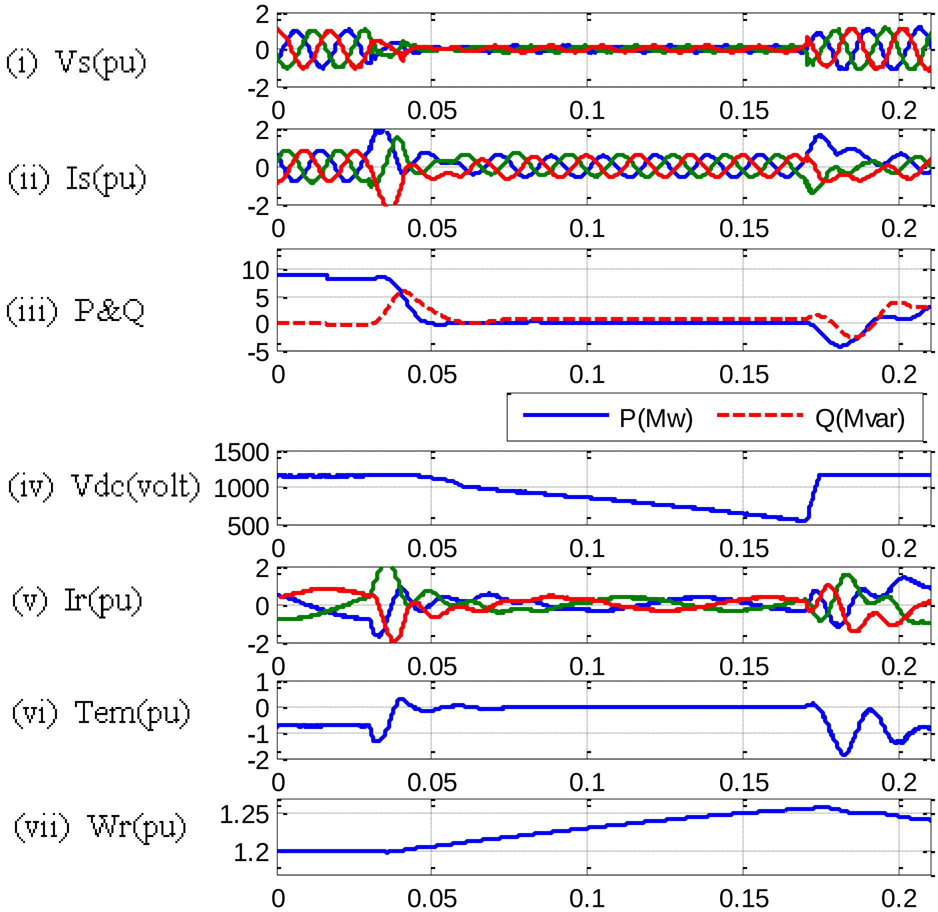

Fig. 4.17 Symmetrical fault at rotor connected DBR (0.0125 Ω)

Fig. 4.17 shows that when a 0.0125Ω resistance is connected in series with the rotor windings during the fault, the stator voltage reduced up to 0.18 pu, the stator current reduced up to 0.58 pu and also the rotor current reduced up to 0.36 pu. While the active power reduced to 0.18 Mw and the reactive power peaks to around 0.85 Mvar. The rotor speed peaks to 1.258 pu.

Referring to the simulation results in sections 4.5.1 and 4.5.2 which are summarized in table 4.3 it can be noticed that; First, concerning the DFIG behavior during the asymmetrical fault, as the rotor connected DBR increased the stator voltage is nearly constant while the stator and rotor current and the active and reactive power are reduced. The rotor speed increased. Second, concerning DFIG behavior during the symmetrical fault, as the rotor connected DBR increased the stator voltage drop reduced, consequently the active and reactive power increased. On the other hand, it should be noticed that, the rotor current increasing during the fault is inversely proportional to the DBR value. Therefore, as mentioned in chapter 3, the value of the DBR should be selected carefully to avoid rotor overvoltage or over current. Moreover, with the increasing of the DBR value the rotor speed increased.

Rotor Con. DBR	0.0025	0.005	0.0125
Vs (pu)	0.8	0.8	0.8
Is (pu)	1.5	1.4	1
Ir (pu)	1.45	1.3	1.05
P (Mw)	3.15	2.4	1.5
Q (Mvar)	0.7	0.4	0.05
Wr (pu)	1.233	1.237	1.242

Table 4.4 Rotor connected DBR technique results summarization during asymmetrical fault

Rotor Con. DBR	0.0025	0.005	0.0125
Vs (pu)	0.13	0.14	0.18
Is (pu)	0.4	0.45	0.58
Ir (pu)	1	0.7	0.36
P (Mw)	0.1	0.13	0.18
Q (Mvar)	0.5	0.6	0.85
Wr (pu)	1.25	1.253	1.258

Table 4.5 Rotor connected DBR technique results summarization during symmetrical fault

4.6 The DFIG Behavior with Stator Connected DBR Technique:

In this technique a dynamic breaking resistor is connected in series with the stator in order to limit the current and also to enhance the output voltage. The resistances values is selected according to the results appears in [30] so that, 0.01, 0.02 and 0.05 Ω.

4.6.1 Asymmetrical Fault With Stator Connected DBR Technique :

4.6.1.1 DBR of (0.01 Ω) :

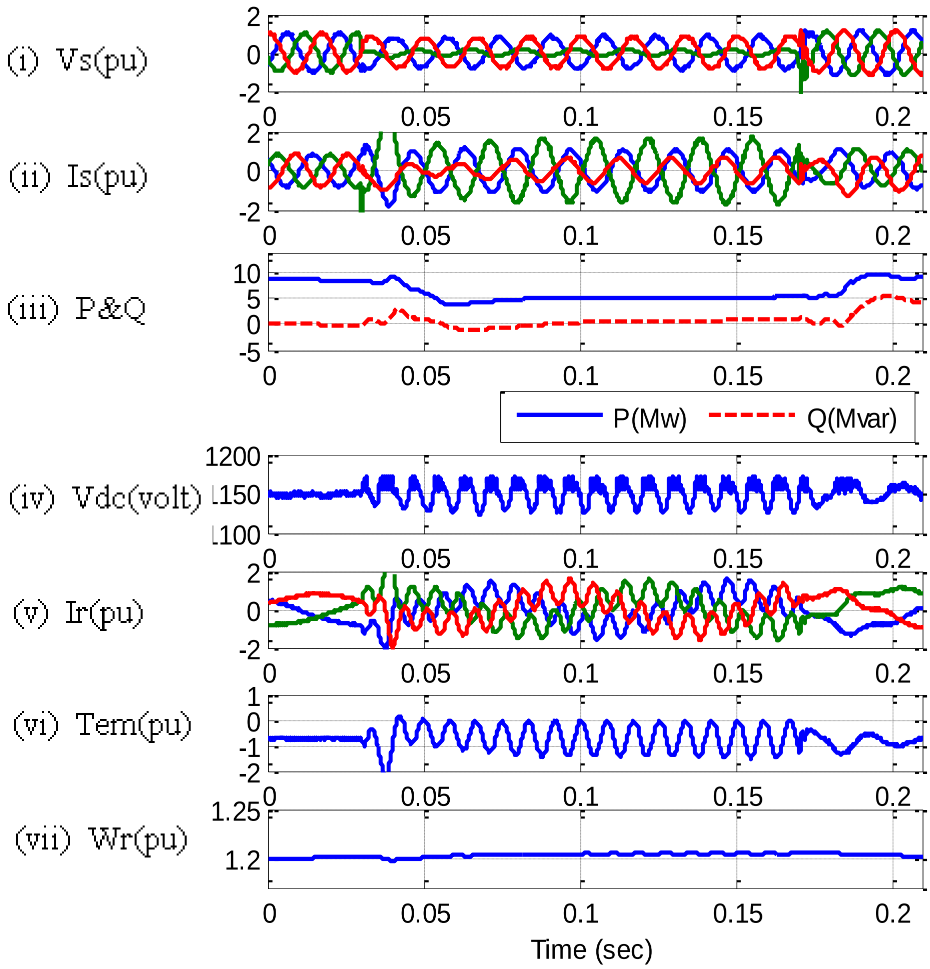

Fig. 4.18 Asymmetrical fault at stator connected DBR (0.01 Ω)

Fig. 4.18 shows that when a 0.01Ω resistance is connected in series with the stator windings during the fault, the stator voltage reduced to 0.9

pu, the stator current increased up to 1.65 pu and the rotor current increased up to 1.6 pu asymmetrically. While the active power reduced to 5.4 Mw and the reactive power peaks to around 1 Mvar. The rotor speed peaks to 1.205 pu (there are some ripples appears).

4.6.1.2 <u>DBR of (0.02 Ω)</u> :

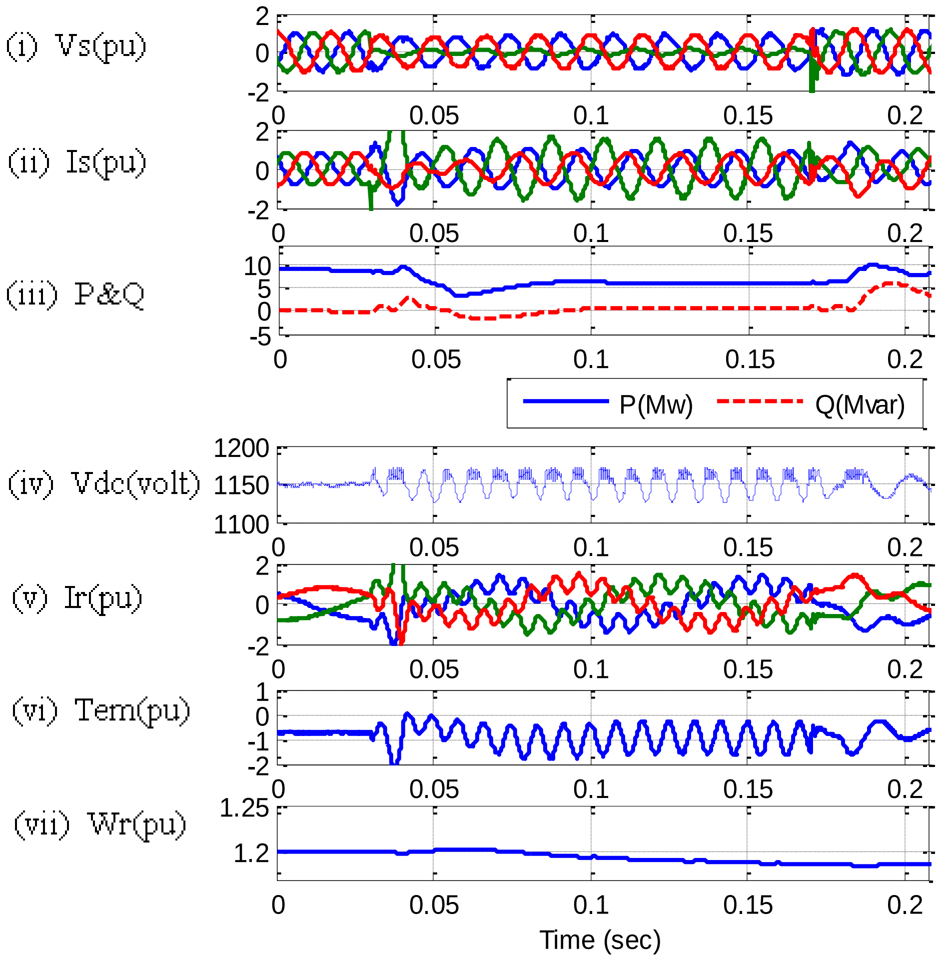

Fig. 4.19 Asymmetrical fault at stator connected DBR (0.02 Ω)

Fig. 4.19 shows that when a 0.02Ω resistance is connected in series with the stator windings during the fault, the stator voltage reduced to 0.92 pu, the stator current increased up to 1.6 pu and the rotor current increased up to 1.5 pu asymmetrically. While the active power reduced to 5.6 Mw and the reactive power peaks to around 0.6 Mvar, the rotor speed reduced to 1.186 pu.

4.6.1.3 DBR of (0.05 Ω) :

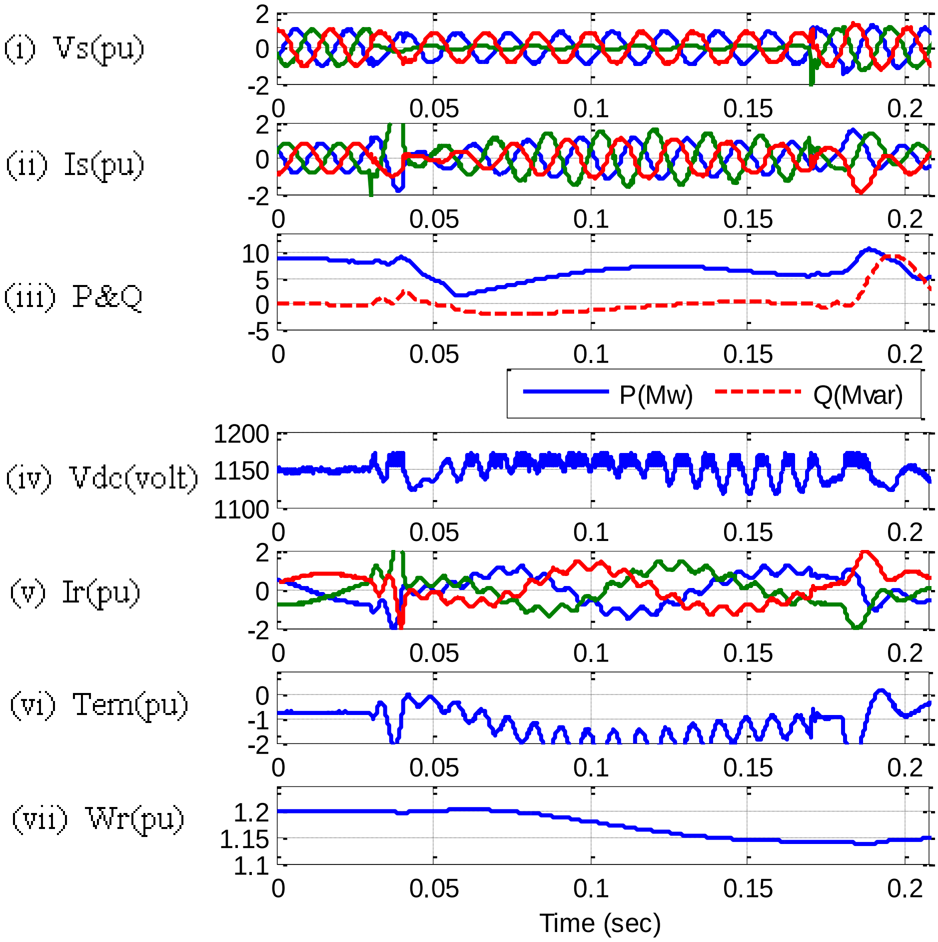

Fig. 4.20 Asymmetrical fault at stator connected DBR (0.05 Ω)

Fig. 4.20 shows that when a 0.05Ω resistance is connected in series with the stator windings during the fault, the stator voltage reduced to 0.94 pu, the stator current increased up to 1.6 pu and the rotor current increased up to 1.46 pu asymmetrically. While the active power reduced to 7.5 Mw and then 5.5 Mw and the reactive power peaks to around 0.35 Mvar. The rotor speed reduced until 1.173 pu.

4.6.2 Symmetrical fault with stator connected DBR Technique:

4.6.2.1 DBR of (0.01 Ω):

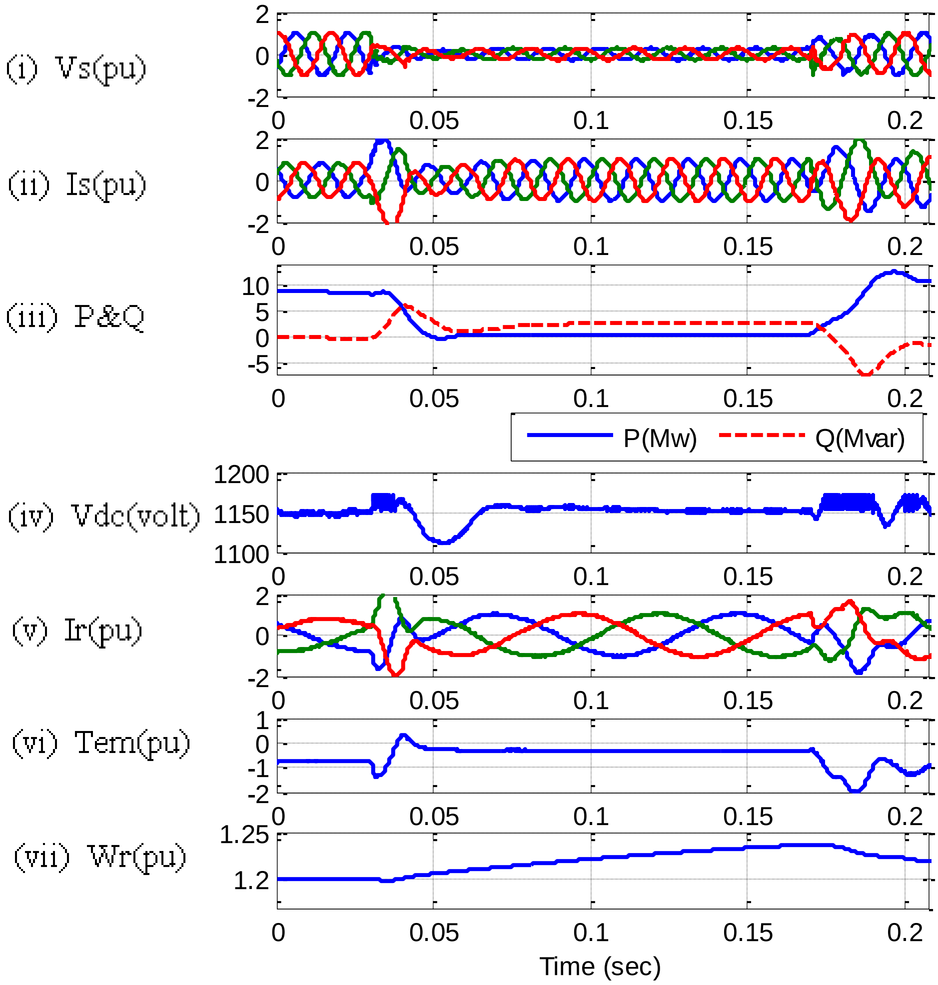

Fig. 4.21 Symmetrical fault at stator connected DBR (0.01 Ω)

Fig. 4.21 shows that when a 0.01Ω resistance is connected in series with the stator windings during the fault, the stator voltage reduced up to 0.3 pu, the stator current increased up to 1 pu and also the rotor current increased up to 1.05 pu. While the active power reduced to 0.5 Mw and the reactive power peaks to around 2.75 Mvar. The rotor speed peaks to 1.23 pu.

4.6.2.2 DBR of (0.02 Ω):

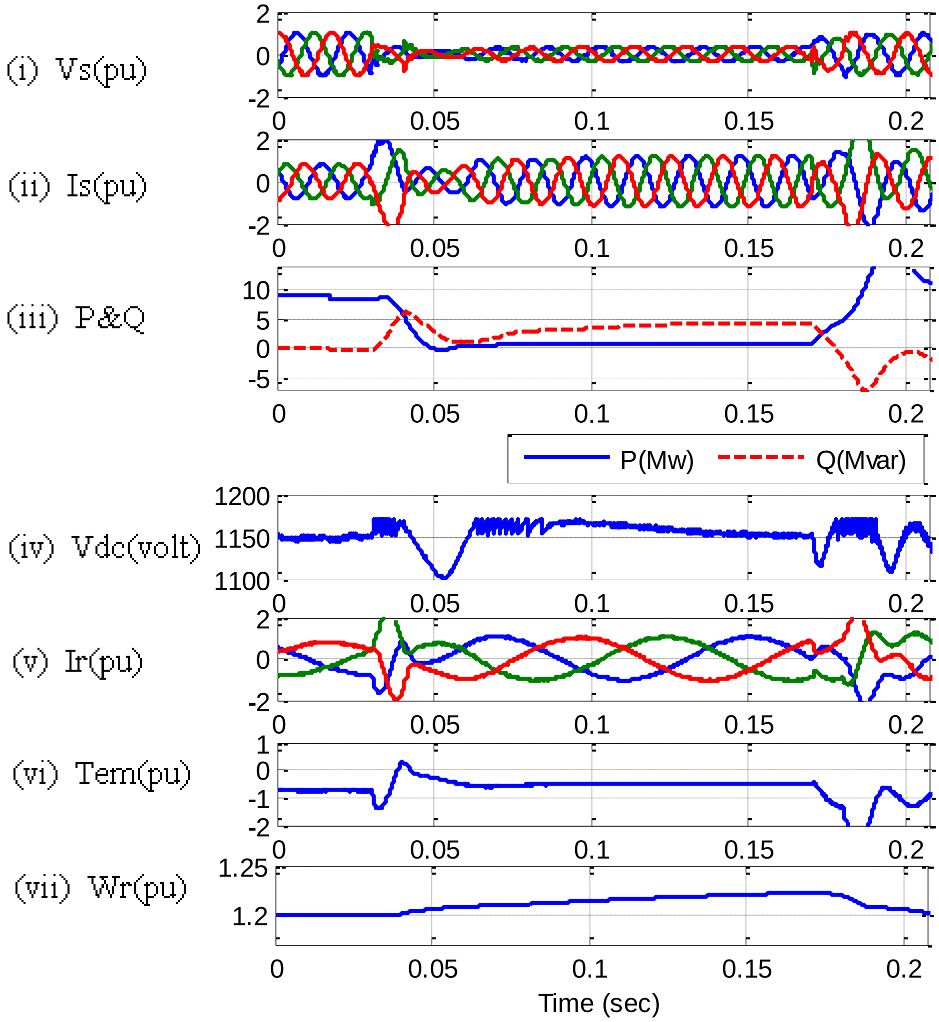

Fig. 4.22 Symmetrical fault at stator connected DBR (0.02 Ω)

Fig. 4.22 shows that when a 0.02Ω resistance is connected in series with the stator windings during the fault, the stator voltage reduced up to 0.36 pu, the stator current increased up to 1.2 pu and also the rotor current increased up to 1.06 pu. While the active power reduced to 0.8 Mw and the reactive power peaks to around 4.1 Mvar. The rotor speed peaks to 1.22 pu.

4.6.2.3 DBR of (0.05 Ω):

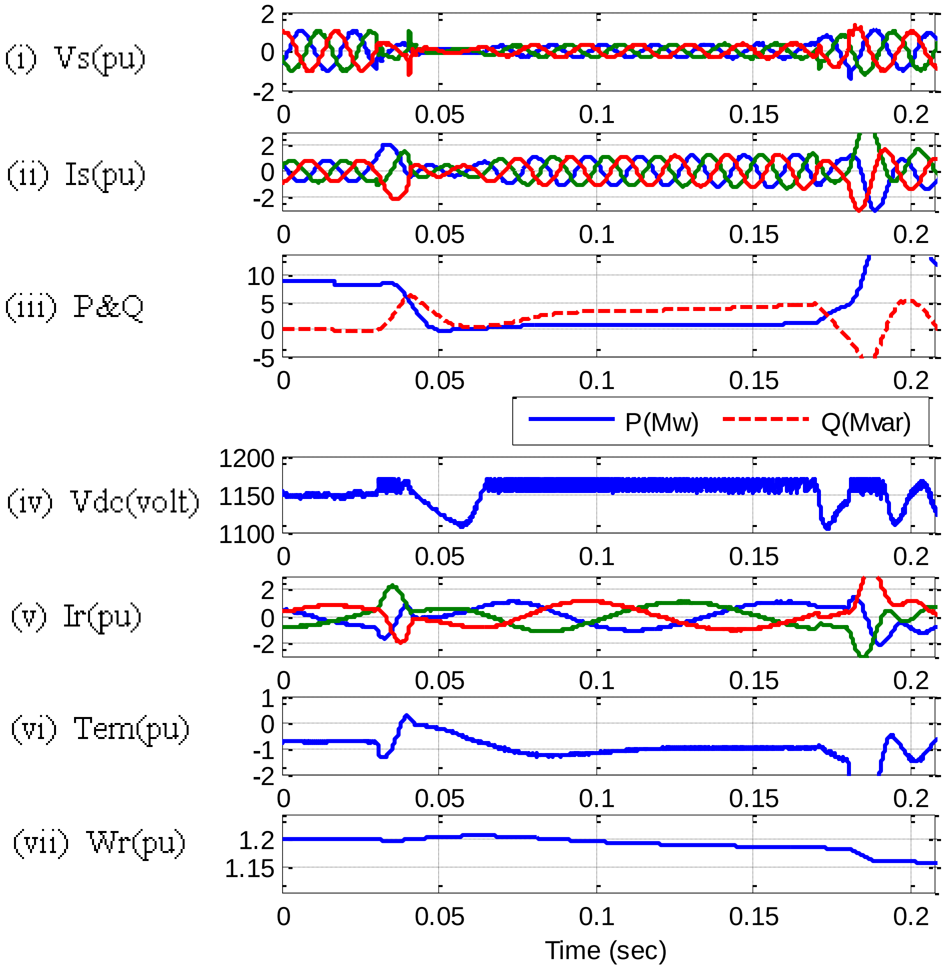

Fig. 4.23 Symmetrical fault at stator connected DBR (0.05 Ω)

Fig. 4.23 shows that when a 0.05Ω resistance is connected in series with the stator windings during the fault, the stator voltage reduced up to 0.4 pu, the stator current increased up to 1.3 pu and also the rotor current increased up to 1.05 pu. While the active power reduced to 1 Mw and the reactive power peaks to around 4.7 Mvar. The rotor speed reduced up to 1.18 pu.

Referring to the simulation results in sections 4.6.1 and 4.6.2, which are summarized in table 4.4 it can be noticed that; First, concerning the DFIG behavior during the asymmetrical fault, as the stator connected DBR increased the stator voltage and the active power increased while the rotor current and the reactive power reduced. The rotor speed have a remarkable drop particularly with DBR (0.02 and 0.05 Ω), this may be a results from the high overcurrent in the stator, also this can be noticed in the electromagnetic torque. Second, concerning DFIG behavior during the symmetrical fault, as the stator connected DBR increased the stator voltage also increased, consequently the active and reactive power also increased. However it should be noticed that, the wind turbine speed with DBR (0.01 Ω) increased to 1.23 and with DBR (0.02 Ω) increased to 1.22 but with DBR (0.05 Ω) the wind turbine speed reduced to 1.18 pu. This speed drop may reflects the overload which happen in the last case (DBR 0.05), which also can be noticed in the stator current which increased up to 1.3 pu in this case compared to 1 pu and 1.2 pu with DBR 0.01 and 0.02 Ω respectively. Concerning the rotor current, with the three DBR values it wasn't have any remarkable change also it wasn't increased hazardously.

Stator Con. DBR	0.01	0.02	0.05
Vs (pu)	0.9	0.92	0.94
Is (pu)	1.65	1.6	1.6
Ir (pu)	1.6	1.5	1.46
P (Mw)	5.4	5.6	7.5
Q (Mvar)	1	0.6	0.35
Wr (pu)	1.205	1.186	1.173

Table 4.6 Stator connected DBR technique results summarization during asymmetrical fault

Stator Con. DBR	0.01	0.02	0.05
Vs (pu)	0.3	0.36	0.4
Is (pu)	1	1.2	1.3
Ir (pu)	1.05	1.06	1.05
P (Mw)	0.5	0.8	1
Q (Mvar)	2.75	4.1	4.7
Wr (pu)	1.23	1.22	1.18

Table 4.7 Stator connected DBR technique results summarization during symmetrical fault

4.7 Conclusion :

The DC chopper technique should be used with another protection technique because it doesn't have a remarkable effect on the stator voltage and current.

The various protection techniques have different behaviors according to the fault type. The DC chopper technique is an auxiliary technique. The CB and rotor connected DBR techniques have a somehow similar performance because in both cases the resistance of the rotor is increased. However, the rotor connected DBR technique have a nearly constant response and more reasonable results than the CB technique specially during the asymmetrical fault. Regarding the stator connected DBR technique it has the most efficient performance during the symmetrical fault with respect to the stator voltage and the output active and reactive power moreover the rotor speed, however it is noticed that, during the asymmetrical fault the DFIG was overloaded.

Chapter 5

Conclusion and Future Work

Conclusion

Wind energy is one of the infinite and clean energy sources on the earth. The wind energy share in electrical power generation increased in the last two decades and still increasing worldwide. On the other hand, there are some technical and civil challenges facing the wind energy growing. Variable speed wind turbines have several advantages over fixed speed. Among all these advantages, the ability to capture more energy from the wind is considered as the most important one.

This thesis discusses different arrangement of wind energy systems. The wind turbines based doubly fed induction generator DFIG is introduced in details with its different control topologies. The advantages and disadvantages of the DFIG are also discussed. The discussion shows that the DFIG is the most attractive generator for variable speed systems however it suffers from its sensitivity during fault condition.

Different protection techniques of the DFIG and their advantages and disadvantages are also studied. The study shows that among all available techniques; the DC chopper, the crowbar, the rotor connected series dynamic resistor, and the stator connected series dynamic resistor techniques are simple, efficient, and easy to implement.

Finally, a simulation study for these techniques was conducted under different conditions (symmetrical and asymmetrical faults) using the SimPowerSystem library under the Matlab/Simulink. The simulation results show that, the DC chopper technique is an auxiliary technique, the CB and rotor connected DBR techniques have a somehow similar performance because in both cases the resistance of the rotor is increased, however, the rotor connected DBR technique have a nearly constant response and more reasonable results than the CB technique specially during the asymmetrical fault while the stator connected DBR technique have the most efficient performance during the symmetrical fault.

Future Work

1. Study the availability of adding a filter in the rotor circuit in order to suppress or block the undesired components during the fault periods as the frequency of that components is related to the rotor speed.

2. Implement the different protection methods of the DFIG experimentally and illustrate the limitations and boundaries of the different techniques compared to each other.

3. Study the suitability of the DFIG different protection methods with the LVRT capability of different grid codes.

4. Conduct a financial comparison between the DFIG different protection methods.

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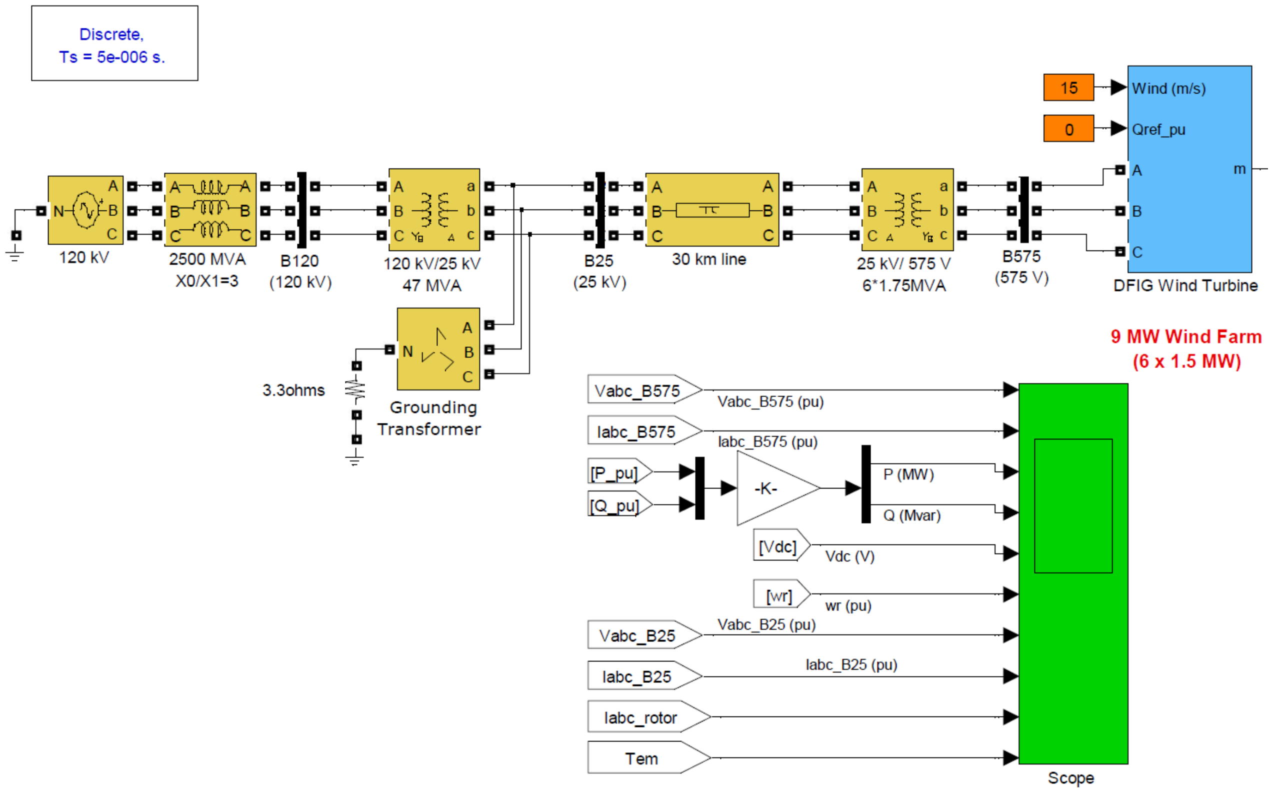
Appendix A

DFIG Detailed Model in Matlab/Simulink



Appendix B

Publications Out Of This Thesis

1- "Comparative Study Between The Crowbar And The Series Braking Resistance Topologies In Protecting The Doubly Fed Induction Generator"

Published In

The III. International Conference on Nuclear and Renewable Energy Resources, NURER2012
Held on 20-23rd May 2012 in Istanbul, Turkey

2- "Comparison Study Between two Dynamic Breaking Resistor Techniques in Protecting the Doubly Fed Induction Generator"

Published In

12. International Conference on Environment and Electrical Engineering, EEEIC2013
Held on 5-8 May 2013 in Wroclaw, Poland

الملخص العربي

الملخص العربي

تعتبر طاقة الرياح الآن من أهم مصادر الطاقة المستخدمة، و مع ازدياد استخدام طاقة الرياح في توليد الكهرباء فقد بدأت دول عديدة في تعريف شروط تشغيل جديدة لكي تحدد واجبات و مسئوليات المحطات الخاصة بتوليد الكهرباء باستخدام طاقة الرياح في جميع ظروف تشغيل شبكة الكهرباء.

تعتبر المولدات الحثية ثنائية التغذية من أشهر المولدات المستخدمة مع التربينات متعددة السرعات نظرا لمميزاتها العديدة ومنها تكلفة قليلة، وزن قليل و كفاءة عالية. وبالرغم من ذلك، فإن من أهم عيوب هذا النوع من المولدات أنه يتأثر بشدة من انخفاض جهد الشبكة. ولذلك فإن هناك العديد من الطرق المستخدمة لحمايته و تحسين أدائه أثناء انخفاض جهد الشبكة أو الأعطال التي تحدث بها حتى يرقى لمستوى المتطلبات الجديدة لتشغيل الشبكات.

تم في هذه الرسالة مناقشة كل من :

١. نظرية التشغيل الخاصة بالمولدات الحثية ثنائية التغذية

٢. نظم التحكم المختلفة للمولدات الحثية ثنائية التغذية

٣. أداء المولدات الحثية ثنائية التغذية أثناء حدوث الأعطال المختلفة (المتماثلة و غير المتماثلة) في الشبكة

٤. نظم الوقاية المختلفة للمولدات الحثية ثنائية التغذية

٥. عمل محاكاة للعديد من هذه الطرق تحت ظروف مختلفة باستخدام Matlab/Simulink.

الأكاديمية العربية للعلوم و التكنولوجيا و النقل البحري
كلية الهندسة و التكنولوجيا

حماية المولدات الحثية ثنائية التغذية

إعداد /
م. أحمد محمد خالد محمد

رسالة مقدمة للأكاديمية العربية للعلوم و التكنولوجيا و النقل البحري
لاستكمال متطلبات نيل درجة الماجستير في
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القاهرة ٢٠١٣