CHAPTER 1

INTRODUCTION TO WIND ENERGY SYSTEMS

1.1 Background

Two major global problems that mankind is facing currently, are the energy shortage and the environment crisis. The natural resources like coal, petroleum and gas that have driven our industries, vehicles and power plants for many decades are getting finished at a very fast rate. With the fast depleting rate of fossil fuels and pollution problems renewable energy has become an important energy source.

Renewable energy including wind, solar, tidal, small hydro geothermal are environmental friendly, clean and can sustain for a longer period. Among the other renewable energy sources wind energy particularly is one of the most economical one. Undoubtedly, wind power is today’s most rapidly growing renewable energy source. Even though the wind industry is comparatively young from the point of view of power systems, significant positive steps have been taken in the past 20 years.

The worldwide installed capacity of wind power reached 369,553 MW by the end of 2014 Fig1. China (114,763 MW), US (65,879 MW), Germany (39,165 MW) and Spain (22,987 MW) are ahead of India in fifth position.

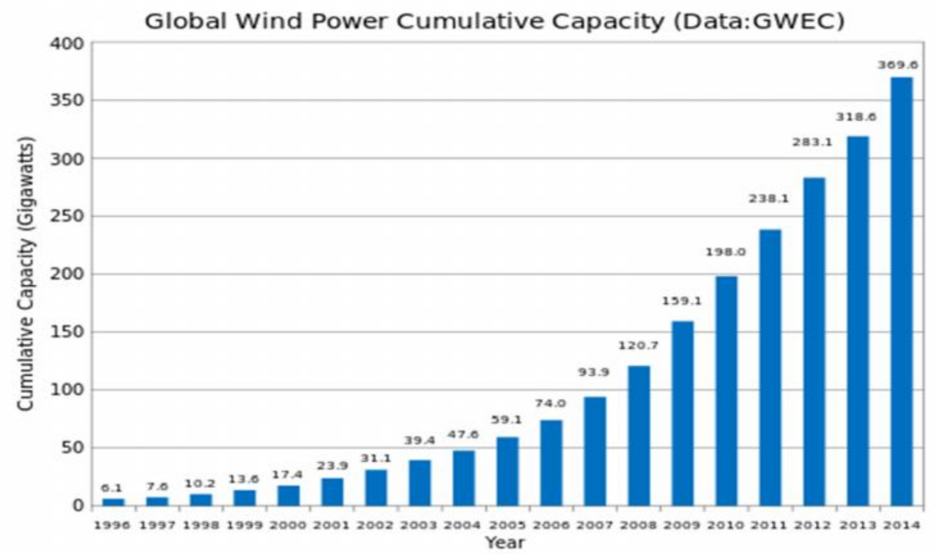

Fig 1.1 World Total Installed Capacity

India has several on shore and off shore wind energy sites. India has a lot of scope in terms of harnessing wind power using these sites. The development of wind power in India began in the 1990s, and has significantly increased in the last few years. As on March 2015 the installed capacity of wind power in India was 22,645 MW. Installed capacity of wind energy plants in different states in shown in Fig-2.

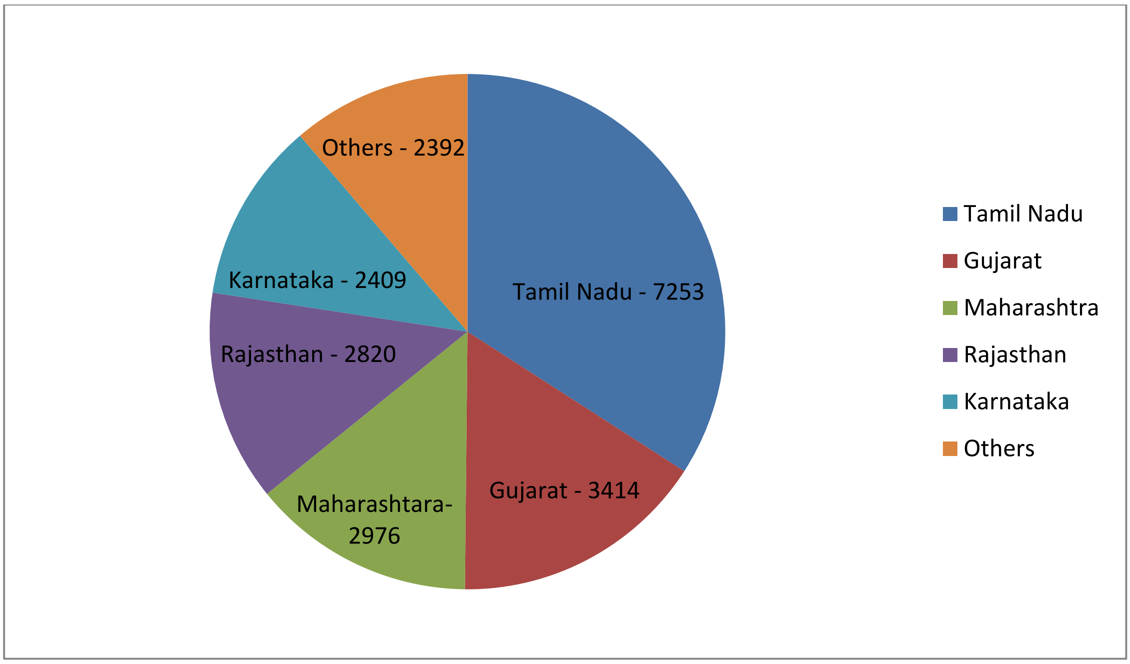

Fig-1.2 State wise Installed Capacity in India by March 2014

Wind turbine capacity has grown from 1-3 kW to machines producing 1-3 MW and more. Increasing reliability has contributed to the cost decline, with availability of modern machines reaching 97-99%. Wind plants have benefited from steady advances in technology made over past 15 years. Much of the advancement has been made in the components dealing with grid integration, the electrical machine, power converters, and control capability. The days of the simple induction machine with soft start are long gone. We are now able to control the real and reactive power of the machine, limit power output and control voltage and speed. There is lot of research going on around the world in this area and technology is being developed that offers great deal of capability. It requires an understanding of power systems, machines and applications of power electronic converters and control schemes put together on a common platform.

Unlike a conventional power plant that uses synchronous generators, a wind turbine can operate as fixed-speed or variable-speed. In a fixed-speed wind turbine, the stator of the generator is directly connected to the grid. However, in a variable-speed wind turbine, the machine is controlled and connected to the power grid through a power electronic converter. There are various reasons for using a variable-speed wind turbine:

1. Variable-speed wind turbines offer a higher energy yield in comparison to constant speed turbines.
2. The reduction of mechanical loads and simple pitch control can be achieved by variable speed operation.
3. Variable-speed wind turbines offer acoustic noise reduction and extensive controllability of both active and reactive power.
4. Variable-speed wind turbines show less fluctuation in the output power. The permanent magnet synchronous generator (PMSG) and doubly-fed induction generator (DFIG) are the two machines on which the variable-speed wind turbines are based.

1.2 Variable Speed Wind Energy System

Until the mid 1990s, most of the installed wind turbines were based on squirrel cage induction machine directly connected to the grid and the generation was always done at constant speed. Nowadays, most of the installed wind turbine are based on a doubly-fed induction generator (DFIG) sharing the market with the wound rotor synchronous generators (WRSG) and the new arrival of the permanent magnet synchronous generators (PMSG). All of these machine solutions allow variable speed generation.

In this section, the evolution of the variable speed generation systems is roughly analyzed. Attending to the generator used in the generation system of the wind turbine, the variable speed wind turbine basic topologies can be classified into three different categories:

1.2.1 Doubly Fed Induction Generator – Wound Rotor:

The doubly fed induction machine has been traditionally used in applications that require high power transmission and a relatively narrow range of speed. A doubly fed induction generator (DFIG) is a standard, wound rotor induction machine with its stator windings either directly connected to the grid or connected to the load (isolated mode operation) and its rotor windings connected to the grid through a frequency converter.

In modern DFIG designs, the frequency converter is built by two self-commutated PWM converters, rotor and grid side converter, with an intermediate DC voltage link. The rotor side converter controls the real and reactive powers of the induction machine, and the grid side converter controls the dc-link voltage and the reactive power absorbed from the gird by the converter. The grid side inverter works at the grid frequency (leading or lagging in order to produce more or less reactive power). The rotor side inverter works at different frequencies, depending on the blades speed. The DC link created by the capacitor in the middle decouples the operation of the two converters, thus allowing their design and operation to be optimized. A three winding transformer may be connected between the grid side inverter, the stator and the grid.

Using vector control technique, a bidirectional converter assures energy generation at nominal grid frequency and nominal grid voltage independently of the rotor speed. The converter's main aim is to compensate the difference between the speed of the rotor and the synchronous speed with the sliding control.

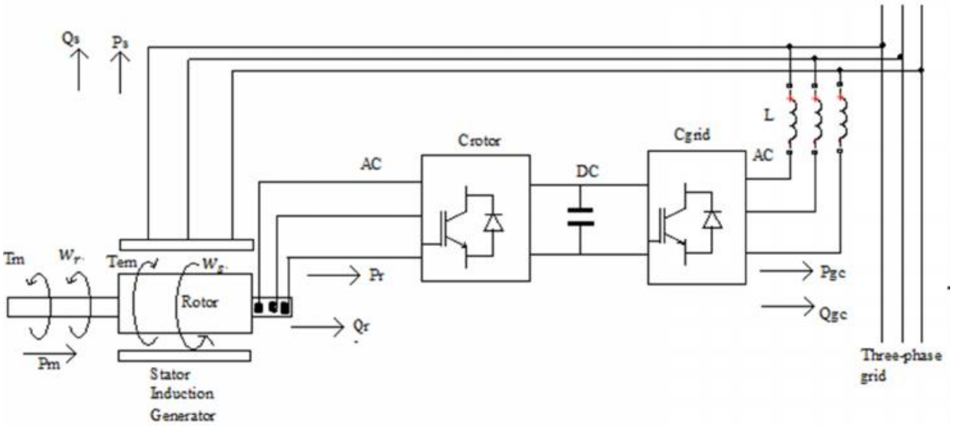

Fig 1.3 Doubly fed Induction Machine Based Wind Turbine System

The main characteristics may be summarized as follows:

- Limited operating speed range (-30% to +20%).
- Small scale power electronic converter, reduced power losses.
- Complete control of active power and reactive power exchanged with the grid.
- Need for slip-rings.
- Need for gear (normally two stage gear).

1.2.2 Full Converter Geared Solutions

The full converter with gearbox configuration is used with permanent magnet synchronous generator (PMSG) and squirrel cage induction generator (SCIG). Using vector control techniques again, a bidirectional converter assures energy generation at nominal grid frequency and nominal grid voltage independently of the rotor speed.

The SCIG uses a two stage gearbox to connect the low-speed shaft to the high-speed shaft. Although nowadays the PMSG machine also uses a two stage gearbox, the objective is to decrease the gearbox from two stages to one, since the nominal speed of the machine is medium.

Induction Generator – Squirrel Cage rotor: With main characteristics:

- Full operating speed range.
- No brushes on the generator (reduced maintenance).
- Full scale power electronic converter.
- Complete control of active power and reactive power exchanged with the grid.
- Need for gear (normally two stage gear).

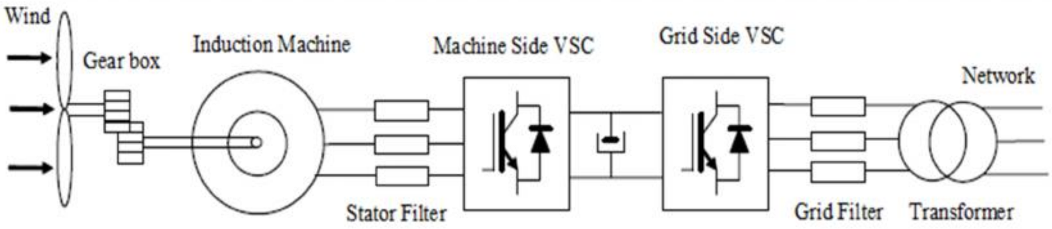

Fig 1.4 Induction machine (SCIG) based wind turbine.

Synchronous Generator – Permanent Magnet: With main characteristics:

- Full operating speed range.
- No brushes on the generator (reduced maintenance).
- Full scale power electronic converter.
- Complete control of active power and reactive power exchanged with the grid.
- Possibility to avoid gear.
- Multipole generator.
- Permanent magnets needed in large quantities.
- Need for gear (normally one stage gear).

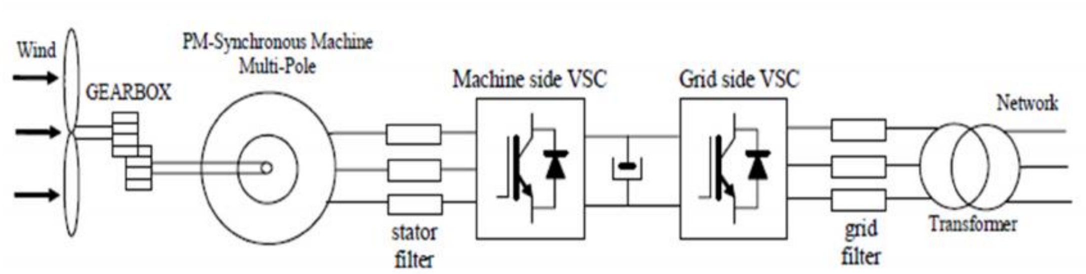

Fig 1.5 Synchronous machine (PMSG) based wind turbine

1.2.3 Full converter direct drive solutions

Two solutions are proposed in the market:

- Multipole permanent magnet generator (MPMG).
- Multipole wound rotor synchronous generator (WRSG).

The multipole permanent magnet generator allows connecting the axis of the machine directly to the blades of the wind turbine. Using vector control techniques, a bidirectional converter assures energy generation at nominal grid frequency and nominal grid voltage independently of the rotor speed.

The biggest disadvantage of this technique is the size of the bidirectional converter which must be of the same power level as the alternator. Also the harmonic distortion generated by the converter must be eliminated by a nominal power filters system. The advantage of this technique is the elimination of the mechanical converter (gearbox coupling), as the machine can operate at low speed. Disadvantage is that the multiple machines require an elevated number of poles, making the size of the machine bigger than the generator with the gearbox coupling.

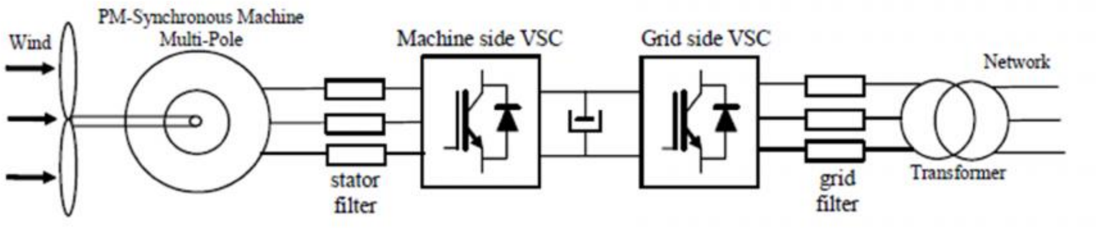

Fig 1.6 Synchronous machine direct drive based wind turbine.

1.3 Doubly Fed Induction Generator

Wound rotor induction generators are provided with three phase windings on the rotor and stator, to which energy can be supplied from both the terminals. This is why wound rotor induction generators are called as Doubly Fed Induction Generator or Double Output Induction generators. Provided the power electronics converter that supplies the rotor circuit via the slip-rings and brushes are capable of handling the power in both the directions, the machine can be operated in both motoring and generating mode of operation.

As a generator, the DFIG provides constant voltage V_s and frequency f_s power through the stator, while the rotor is supplied through a static power converter at variable voltage V_r and frequency f_r. The rotor circuit may absorb or deliver electric power. For constant frequency output, the rotor frequency ω_2 has to be modified in step with the speed variation. By controlling the voltage, frequency and phase sequence in the rotor circuit, the variable speed at constant frequency and voltage can be maintained. The main operation modes of DFIG are depicted in Fig 1.7 & Fig1.8, which corresponds to the sub-synchronous and super synchronous generation modes.

In DFIG the main output power is delivered through the stator, but in super synchronous operation, a good part, about slip stator power sP_s is delivered through the rotor circuit. With limited speed variation range the static power converter ratings and cost would corresponds to 20 to 25% of the stator deliver electric power.

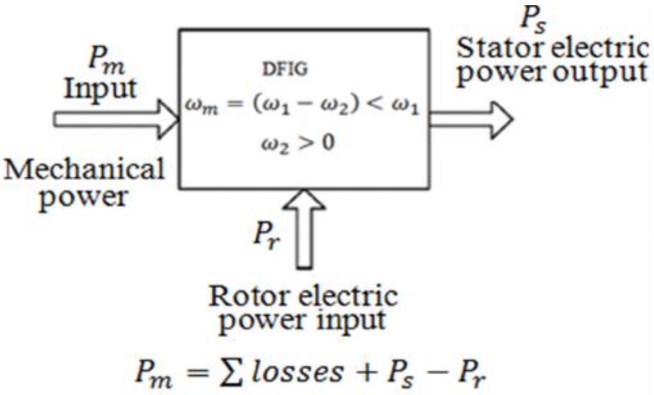

Fig 1.7 DFIG operation modes under sub-synchronous condition

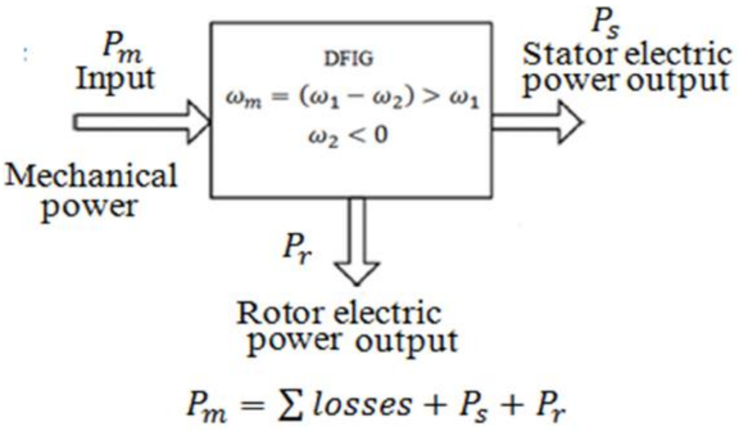

Fig 1.8 DFIG operation modes under super-synchronous condition

1.4 Wind Turbine Control Requirements

The general control strategy of a variable speed wind turbine can be divided into three different control levels.

7.1 The control level I, regulates the flow of power between the grid and the machine.

- The rotor-side converter is controlled in such a way that provides independent control of the electrical torque- stator active power and the stator reactive power.

- The grid-side converter provides a decoupled control of active and reactive power flowing between the converter and the grid.

- The crowbar converter protects the rotor-side converter when a voltage dip occurs.

7.2 The reference for control level I are generated by control level II.

- Extract the maximum power from the wind coordinating torque (stator active power) and pitch angle β references, always keeping the wind turbine into the speed limits.
- Respond to active and reactive references from the higher control level.

7.3 Control level III is depicted to the wind turbine grid integration.

- Provide ancillary services :voltage V_{grid} and frequency f_{grid} control
- Respond to active and reactive power references from the grid operated or wind farm centralized control.

1.4.1 General Control Requirements

1. Flexibility to control different magnitudes:

   The control strategy should be able to control different magnitudes such as the stator active and reactive power, the rotor flux and the torque, in order to accomplish different demands of higher demands of higher level control strategies. Under these circumstances, the control strategy should present appropriate steady-state, dynamic response and tracking behavior, according to the requirements of the wind energy generation system.

2. Generated power quality:

   The control strategy should present the capacity to directly or indirectly deal with the quality of the generated power, in terms of the harmonic distortion of the stator and rotor currents (THD), current harmonic frequency spectrum, as well as the mechanical torque harmonic spectrum.

3. General Aspects:
   - Fast dynamic response
   - On line implementation simplicity
   - Reduced tuning and adjusting efforts of the controllers
   - Reliability
   - Good perturbation rejection
4. Stability under grid fault:

   It has been proved that in a wind energy generation environment, the DFIG based wind turbines present complicated behavior during grid faults. The control strategy should present sufficient dynamic response capacity and should be designed in order to address this problem.

1.5 DFIG systems supplying isolated loads

Unlike the grid connected case, where large consumer loads can be operated without greatly affecting the grid performance, isolated DFIG systems have to be made robust and very good control systems have to be put in place in order to operate the required loads. This is mainly due the fact that there is usually only one generator supplying the settlement hence, the type of loads that the consumers use greatly affects the performance of the entire system.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction

Literature survey is the documentation of a comprehensive review of the published work from the secondary sources data in the areas of specific interest to the researcher .This chapter presents the relevant literature review done to carry out this thesis work. This paper presents an overview on various aspects of DFIG.

This chapter is organized as follows.

The section 2.2 presents an overview about DFIG. Section 2.3 gives a survey on parallel operation of induction generators. In Section 2.4, a literature survey related to DFIG feeding an isolated mode is discussed. Section 2.5 describes the operation of DFIG when fed with a DC supply.

2.2. Generator overview

Over the years wind power has gone through different phases of development to the present form of wind power conversion system as shown in the Fig 1.3[1].Different components of the wind turbine systems are shown in Fig1.3 .It is just a matter of including or excluding the optional components which is decided by the application and the type of generator used. Because of the various advantages provided by the induction machine like reduced cost, ruggedness, reduced size, ease of maintenance and self-protection against severe overloads and short circuits they are commonly used in wind power generation system. [1-5]

In wind energy conversion systems (WECS) mainly two types of generators are used, fixed speed generators (FSG’s) based wind turbine(WT) and adjustable speed generators (ASG’s) based WT.A detailed explanation on these generators are provided in [6-8].

ASGs are becoming more popular due to their overriding advantages in the WECS. The main advantage of this system is that the ASGs can operate at variable speed. Together with the usage of power electronic devices to work with variable speed generators have led to maximized generator output power at varying wind speeds, a major improvement compared to fixed speed systems. Two types of wind generators that have become increasingly popular in modern variable speed wind turbines are the synchronous generators and DFIG [1-3].

The main objective of extending the ability of the existing wind turbine design tools has been discussed in [4] in order to simulate the dynamic behavior of the wind turbine and the wind turbine-grid interaction.

The need to provide a constant frequency and output voltage from a variable speed system has led to the development of DFIG .This represents an asset in providing more flexibly in power conversion and also better stability in frequency and voltage control in the power system to which such generators are connected. A DFIG consists of a wound rotor induction generator with the rotor side connected to the grid through a back to back partially rated power converter. [5] The various advantage of DFIG over other types of the system has been listed in [1, 2].

2.3. Comparison and Parallel Operation of Induction Generators

Various types of induction generators are nowadays used for wind energy generation. Each of them have their own advantages and disadvantages. In [9] an overview of different wind energy generator systems that are currently in use is given along with a comparison amongst them. In [10] a performance comparison of different types of wind energy conversion systems using doubly fed induction generators (DFIG,s) and squirrel cage induction generators (SCIG's) where both are using similar kind of control strategies has been done.

In [11] the performance analysis of transient characteristics of grid connected wind power farms with DFIG's and SCIG's of different power ratings has been done. The analysis of a wind farm system of two parallel connected DFIG's under various wind velocities and small grid faults has been done in [12].

2.4. DFIG systems supplying isolated loads

The research work on the analysis of DFIG in isolated mode of operation is relatively less. Unlike the grid connected case, where large consumer loads can be operated without greatly affecting the grid performance, isolated DFIG system have to be made robust and very good control systems have to be put in place in order to operate the required loads. This is mainly due to the fact that there is usually only one generator supplying the settlement, hence the type of loads that the consumer use greatly affects the performance of the entire system.

The possibility of DFIG supplying an isolated load was proposed in [13] in which the steady state control problem was discussed. In [14] an isolated diesel-wind power system is used and a comparison is made between the different wind generator models. The simulation results pointed out that the system with DFIG has better response characteristics during wind fluctuation and DFIG can output reactive power to improve the reactive power control. DFIG are used to integrate the small size hydro plants which are originally constituted with fixed speed drive. A unified control strategy is proposed in [16] for the small size hydro plants which are upgraded to variable speed mode with the addition of DFIG. Dynamic modeling of isolated systems containing DFIG was proposed by Caratozzolo [17] whereby rotor voltage was controlled in order to control the DFIG characteristics. The load side converter of the DFIG has been utilized to control the grid voltage and frequency and to supply the neutral current and the load current harmonics demand maintaining the DFIG stator current balanced and free of harmonics in [18].

2.5. DFIG fed with DC supply

The DFIG is generally fed with a controlled three phase AC supply from the rotor side , but in [19] a new architecture supplying the rotor with a three lead direct current supply has been discussed and its advantages over the self excited induction generator provided with exciting capacitors under different loading conditions have also been provided. In [20] a boost derived hybrid converter has been implemented which can be used to supply simultaneous AC and DC loads. The switching scheme is implemented in such a way that the converters work both as an inverter and a boost converter in a single cycle in [20]. In [21] a novel DC excitation scheme applied to the rotor windings of an autonomous wound rotor induction generator for achieving voltage compensation has been presented. The DC excitation modulation is by means of a buck converter whose MOSFET switch is controlled by a microcontroller based on reduced instruction set computer (RISC) architecture. In [22] analysis and PWM control of boost derived hybrid circuit which supplies both dc and three phase ac outputs has been done.

CHAPTER 3

MODELING OF INDUCTION GENERATOR

The induction generator is represented by a fourth order state space model with all the variables and parameters referred to the stator. All the stator and rotor quantities are in the arbitrary two-axis reference frame (d-q frame) .

Fig. 3.1 and Fig. 3.2 shows the equivalent circuit of the induction generator in the d-q frame.

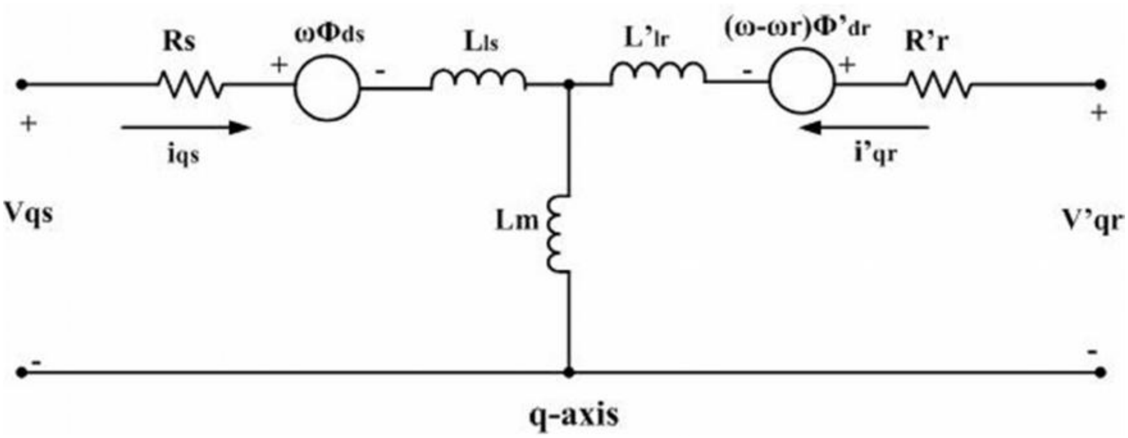

Fig. 3.1 Equivalent Circuit in Q- axis

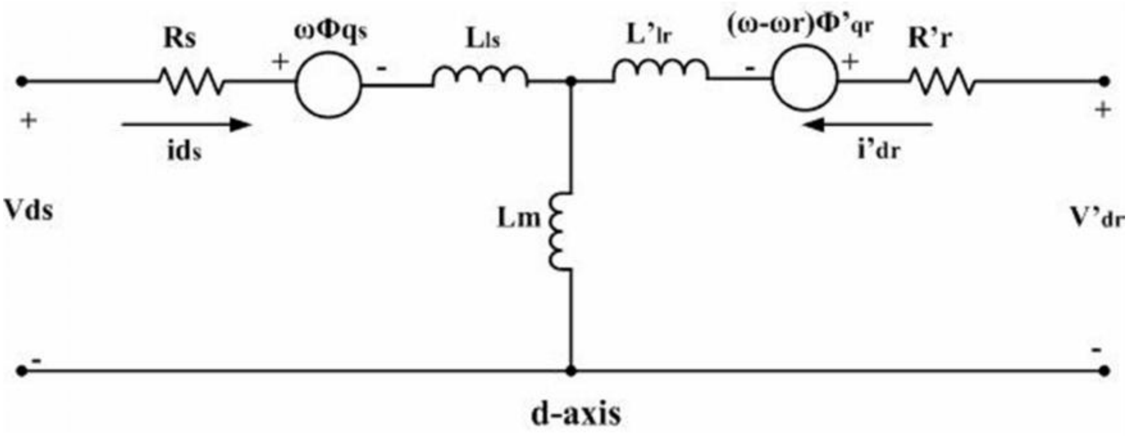

Fig. 3.2 Equivalent Circuit in D- axis

The equations representing the machine are given below.

$$V_{qs} = R_s i_{qs} + \frac{d(\emptyset_{qs})}{dt} + \omega\emptyset_{ds}$$

$$V_{ds} = R_s i_{ds} + \frac{d(\O_{ds})}{dt} - \omega \O_{qs}$$

$$V'_{qr} = R'_r i'_{qr} + \frac{d\left(\O'_{qr}\right)}{dt} + (\omega - \omega_r)\O'_{dr}$$

$$V'_{dr} = R'_r i'_{dr} + \frac{d(\O'_{dr})}{dt} - (\omega - \omega_r)\O'_{qr}$$

$$T_e = 1.5p(\O_{ds} i_{qs} - \O_{qs} i_{ds})$$

where,

$$\O_{qs} = L_s i_{qs} + L_m i'_{qr}$$

$$\O_{ds} = L_s i_{ds} + L_m i'_{dr}$$

$$\O'_{qr} = L'_r i'_{qr} + L_m i_{qs}$$

$$\O'_{dr} = L'_r i'_{dr} + L_m i_{ds}$$

$$L_s = L_{ls} + L_m$$

$$L'_r = L'_{lr} + L_m$$

The induction generator is provided with the speed input from the wind turbine based on the wind speed. The isolated load is connected on the stator side.

CHAPTER 4

COMPARISON OF DIFFERENT WIND ENERGY GENERATOR SYSTEMS AND THEIR PARALLEL OPERATION

4.1 Introduction

This chapter gives a detailed comparison between the various wind energy generators commonly used nowadays. The parallel operation of these different generators supplying an autonomous load is also presented in this chapter.

The development of modern wind power conversion technology has been going on since 1970's and the rate of development has considerably increased from 1990's. Wind generators based on different wind turbine concepts have been built. There are three different types of generator systems that exist for large wind turbines. The first type is a fixed speed wind turbine system using a multi-stage gearbox and a standard squirrel cage induction generator (SCIG) directly connected to the grid. The second type is a variable speed wind turbine system with a multi-stage gearbox and a doubly fed induction generator (DFIG), where the power electronic converter feeding the rotor winding has a power rating of about 30% of the generator capacity. The stator winding of the DFIG may be directly connected to the grid or to an isolated load. The third type is also a variable speed wind turbine, but it is a gearless wind turbine system with a direct drive generator, normally a low speed high torque synchronous generator and a full scale power electronic converter is used. With the reduction in cost of power electronics during recent past , wind energy conversion systems using back to back connected power converter is becoming an attractive option which can use squirrel cage induction generator (SCIG) or permanent magnet synchronous generator (PMSG). The concept using SCIG's is popular due to improvement in power electronics and lower cost of squirrel cage machines.

The above mentioned different types of wind energy conversion systems are discussed below.

4.1.1 SCIG based on fixed speed wind turbine

The fixed speed wind generator systems have been used with a multiple-stage gearbox and a SCIG directly connected to the grid through a transformer as shown in the figure below.

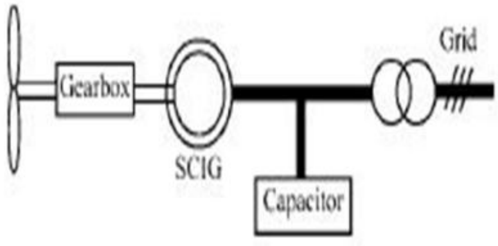

Fig. 4.1 SCIG system connected to the grid [9]

The fixed speed wind energy conversion system operates in a narrow range around the synchronous speed which generally uses the squirrel cage induction generator and is directly connected to the grid.

The well known advantages of SCIG are that they are robust easy and relatively cheap for mass production. Hence the SCIG's are readily available in the market and can withstand harsh environment. In addition it enables stall regulated machines to operate at a constant speed when it is connected to a large grid, which provides a stable control frequency. Although the stall control method is usually used in combination with the fixed speed SCIG for power control, the active stall control or pitch control have also been applied.

SCIG used with fixed speed wind turbine concept also has some disadvantages . The speed is not controllable and variable over a very narrow range, in which only speeds higher than the synchronous speed are possible for generator operation. It is necessary to obtain excitation current from the stator terminal of SCIG. This makes it impossible to support grid voltage control.

4.1.2 DFIG based on variable speed wind concept with a partial scale power converter

This configuration corresponds to a variable speed wind turbine with a wound rotor induction generator and a partial scale power converter on the rotor circuit as shown in the figure below.

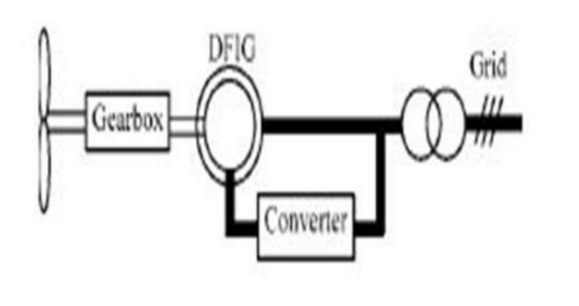

Fig. 4.2 DFIG system connected to the grid [9]

The stator is directly connected to the grid, whereas the rotor is connected through a power electronic converter. The power converter controls the rotor frequency and thus the rotor speed. This concept supports a wide range of speed operation. Typically, the variable speed range is +30% or -30% around the synchronous speed. The rating of the power electronic converter is only 25-30% of the generator capacity, which makes this concept attractive and popular from an economic point of view.

The rotor energy, instead of being dissipated can be fed into the grid by the power electronic converter. Moreover, the power electronic converter system can perform reactive power compensation and smooth grid connection.

However, the DFIG system also has some disadvantages. The slip ring which is used to transfer the rotor power by means of a partial scale converter requires a regular maintenance and can result in machine failures and electrical losses. A multi stage gearbox is still necessary in the drive train because the speed range for DFIG is far from a common turbine speed of 10-25 rpm. A gearbox is inevitable to have some drawbacks such as heat dissipation from friction, regular maintenance and audible noise.

4.2 Comparison of capabilities of SCIG and DFIG

In this section both the SCIG and DFIG of the same rating as given in appendix B are operated under the same conditions and their comparison has been done. The wind speed has been taken as 0.19 pu. The DFIG is fed with a three phase supply of rotor voltage equal to 0.64 pu and rotor frequency equal to 061 pu. The SCIG is supplied by shunt capacitance of 0.76 pu. The variation of stator voltage and frequency of both the generators with load has been shown in figure 4.3 and figure 4.4.

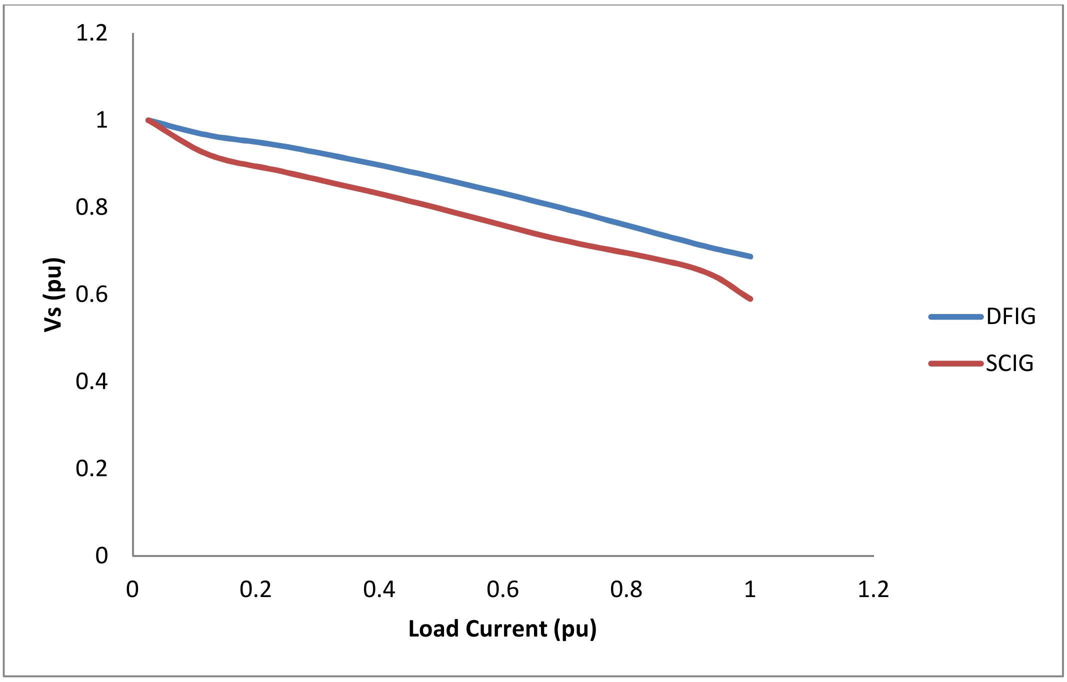

Fig. 4.3 Variation of stator voltage with load for SCIG and DFIG

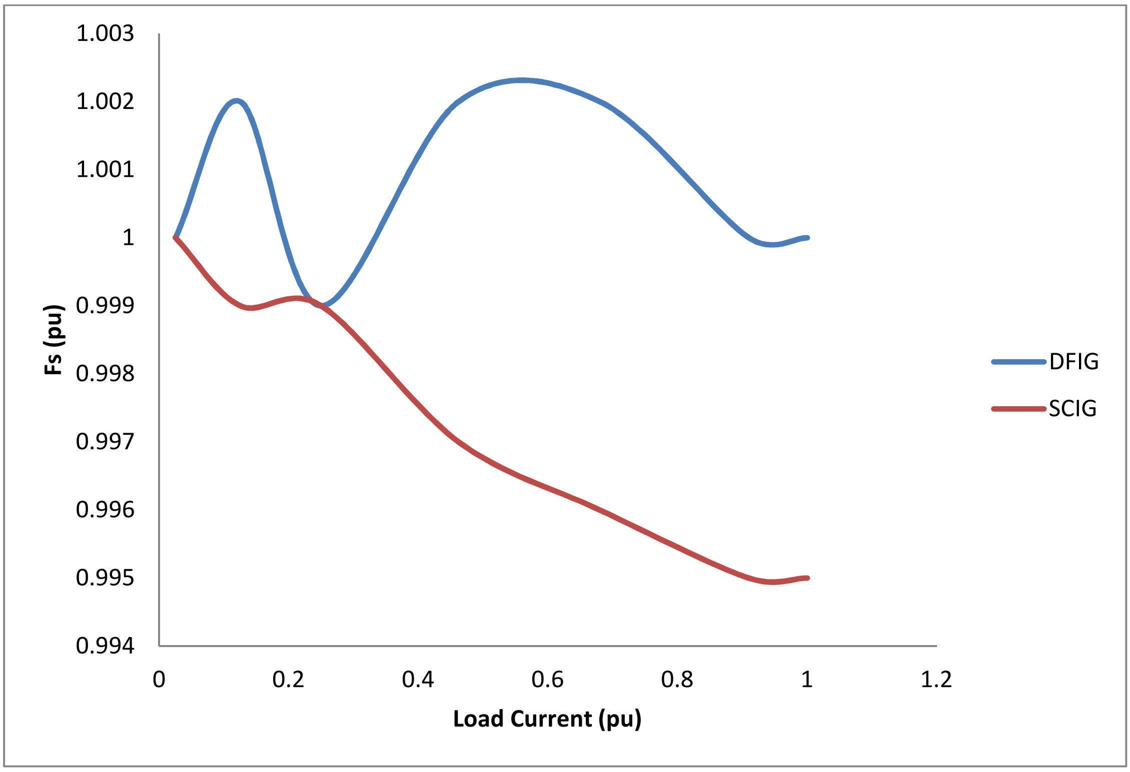

Fig. 4.4 Variation of stator frequency with load for SCIG and DFIG

It can be seen from figure 4.3 and figure 4.4 that the variation in stator voltage and frequency as the load is increased is more in case of SCIG as compared to DFIG. Therefore it can be concluded that the DFIG has better capabilities.

4.3 Parallel operation of two generators

In this section the study of parallel operation of two generators has been done taking both SCIG and DFIG individually and together.

4.3.1 Parallel operation of two SCIG's

The parallel operation of two SCIG's of rating as given in appendix B has been done first. The variation of output voltage and frequency with increasing load has been shown in figure 4.5 below.

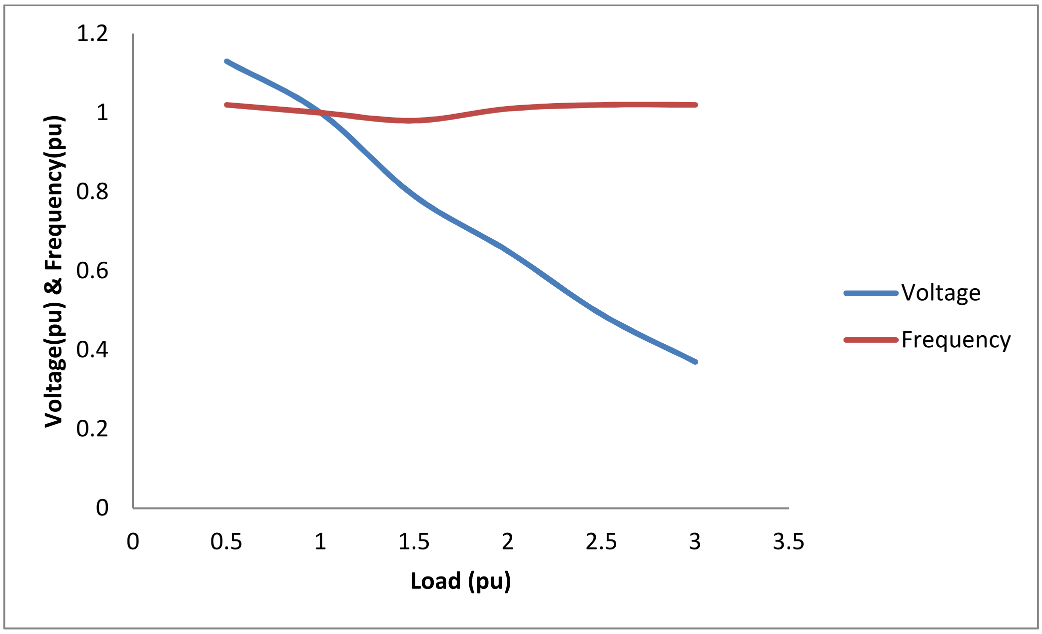

Fig. 4.5 Variation of voltage and frequency with load for two SCIG's operated in parallel

The same variation is now seen when a SCIG and DFIG are connected in parallel.

4.3.2 Parallel operation of a SCIG and a DFIG

In this section the study of the parallel operation of SCIG and DFIG has been done. Both the generators are of the same rating as given in appendix B. The wind speed of both the generators is assumed to be constant and equal to synchronous speed. The load is varied and its effect on voltage, frequency and active and reactive powers of both the generators has been studied. The simulink model used for parallel operation is shown in fig. 4.6 .

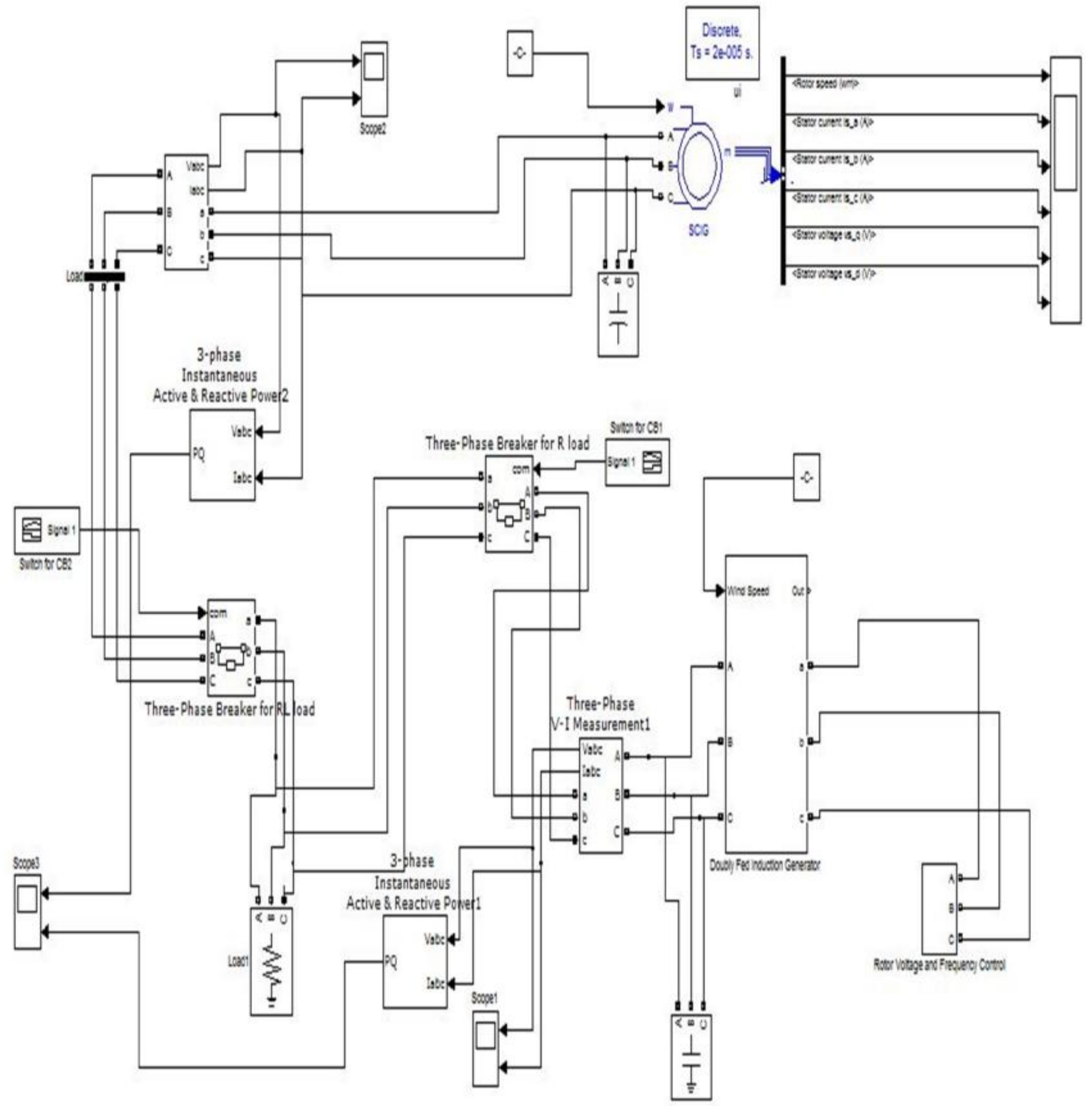

Fig. 4.6 Parallel Operation of SCIG and DFIG

As can be seen from the simulink model of fig. 4.6 both the generators are connected to the load via three phase circuit breakers. The voltage, current, active and reactive power is measured through the measurement blocks. The figure showing the above results are shown as fig. 4.7 and fig. 4.8.

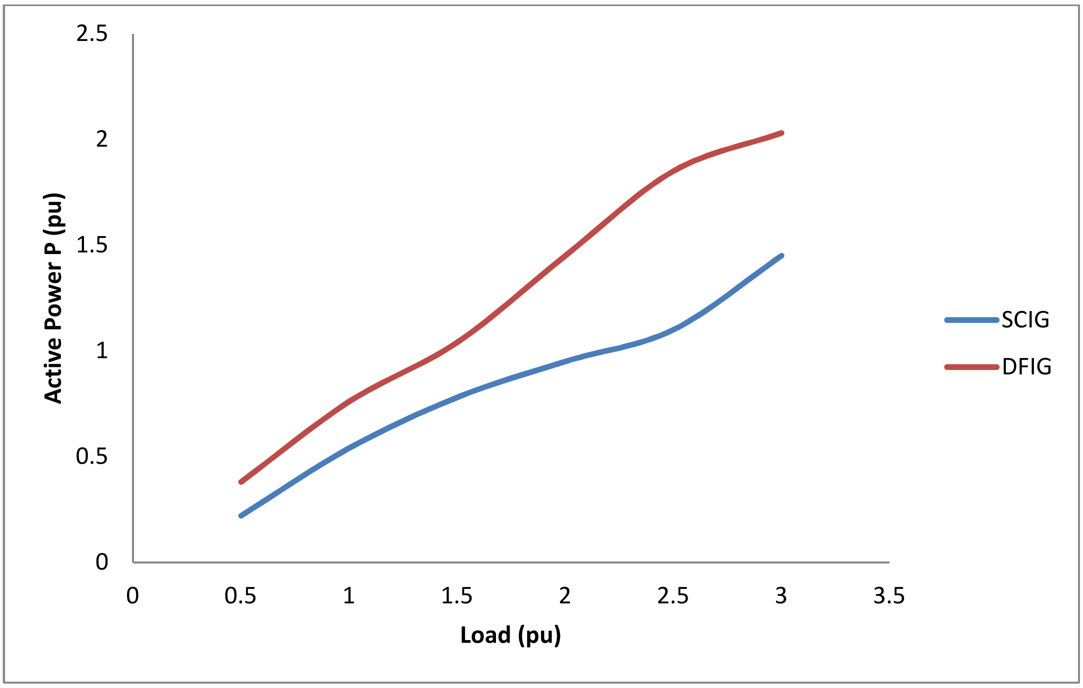

Fig. 4.7 Variation of active power supplied by SCIG and DFIG with load

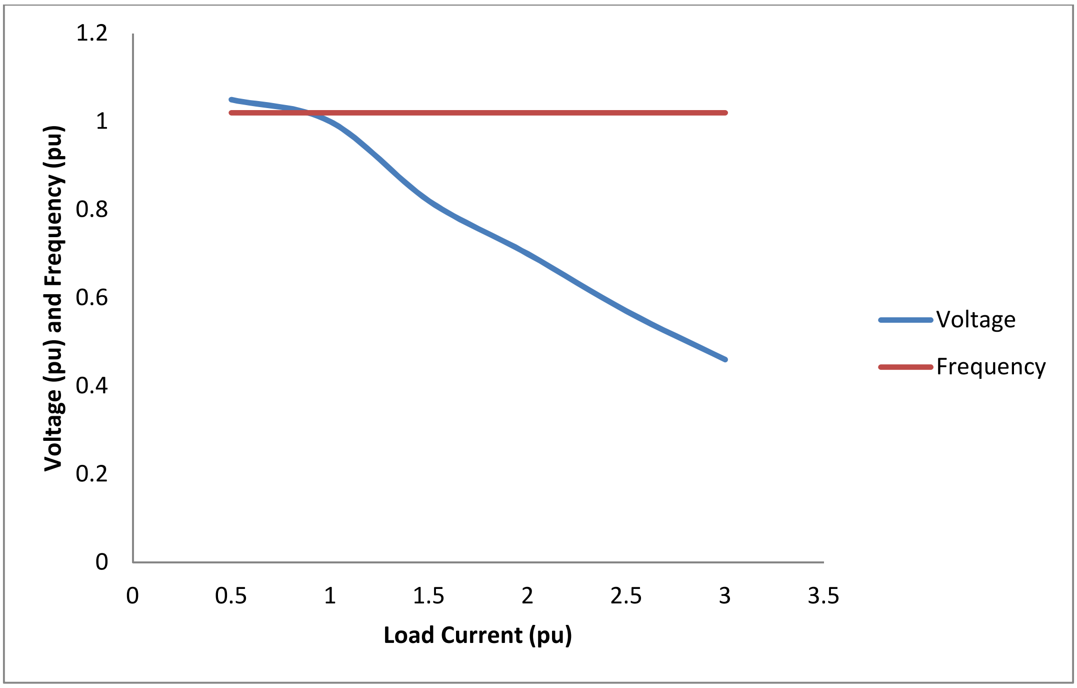

Fig. 4.8 Variation of Voltage and frequency with load for parallel operation of DFIG and SCIG

From the above figures it can be seen that as the load increases there is uneven sharing of power between the two generators and at higher loads DFIG supplies more power to the load.

4.3.3 Parallel operation of two DFIG's

In this section the two DFIG's of same rating as given in appendix B are operated in parallel and the corresponding variation of output voltage and frequency with load is seen. Fig 4.9.

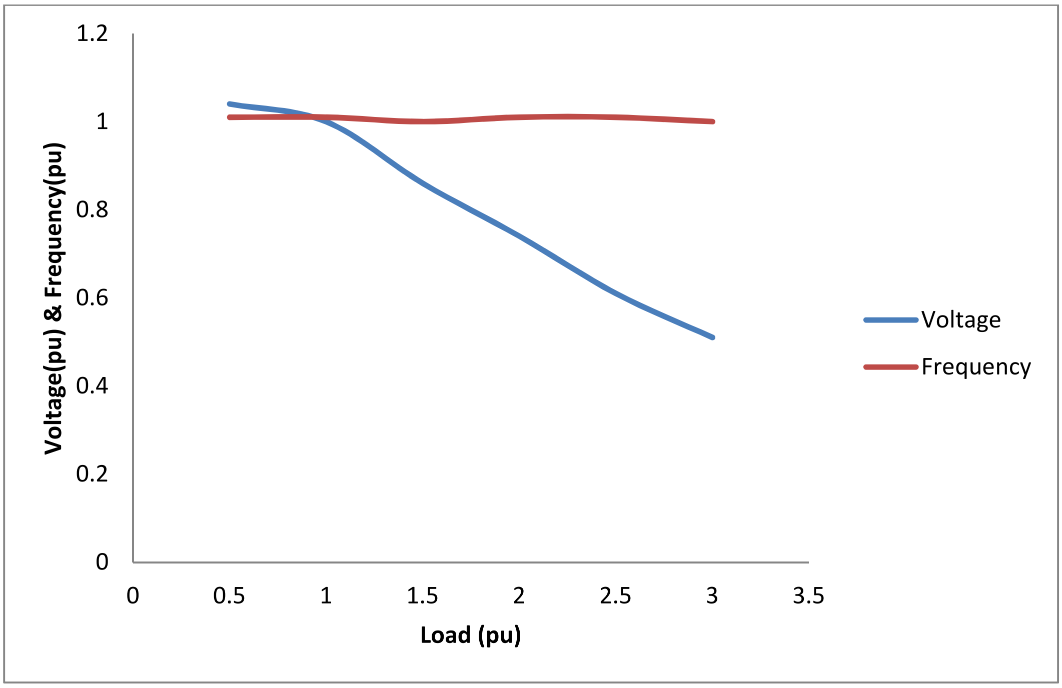

Fig. 4.9 Variation in voltage and frequency with load for two DFIG's operated in parallel

4.4 Results and Discussions

From figure 4.5, 4.8 and 4.9 it can be seen that voltage variation when two DFIG's are operated in parallel is lesser as compared to the other two cases for increasing load. The frequency variation is not much in all the three cases for resistive load as can be seen from the above figures.

It can also be conclude from fig. 4.7 seen that as the load increases there is uneven sharing of power between the two generators and at higher loads DFIG supplies more power to the load.

CHAPTER 5

DIFFERENT CONFIGURATIONS OF ISOLATED MODE DFIG

5.1 Introduction

Isolated power generation systems are in general required to provide power to various types of loads, e.g. linear, nonlinear, single phase, balanced and unbalanced. However, the current harmonics of the nonlinear load and the unbalance load current component will increase the DFIG internal heating losses and produce unwanted torque pulsations that will increase the system mechanical stress.

As, there are wider grid-connected systems the research and utilization of isolated mode or stand alone mode of operation of DFIG is not so common in most of the areas. However, for smaller developing tropical island countries, it becomes fairly impossible to supply isolated settlements using the grid. Hence it is in practice to operated DFIG in isolated mode operation in these areas. Unlike the grid-connected case, where large consumer loads can be operated without greatly affecting the grid performance, isolated DFIG systems have to be made robust and very good control systems have to be put in place in order to operate the required loads. This is mainly due to the fact that there is usually only one generator supplying the settlement; hence, the type of loads that the consumers use greatly affects the performance of the entire system.

In this chapter the DFIG is operated in the isolated mode with the load connected on the stator side and different configurations supplying input to the DFIG.

5.2 Isolated Mode Operation of DFIG fed with three phase supply

In this chapter isolated mode operation of DFIG is discussed when rotor is fed from three phase supply to get the required load voltage and frequency. The simulated model used to simulate the isolated mode operation of DFIG is shown in fig. 5.1

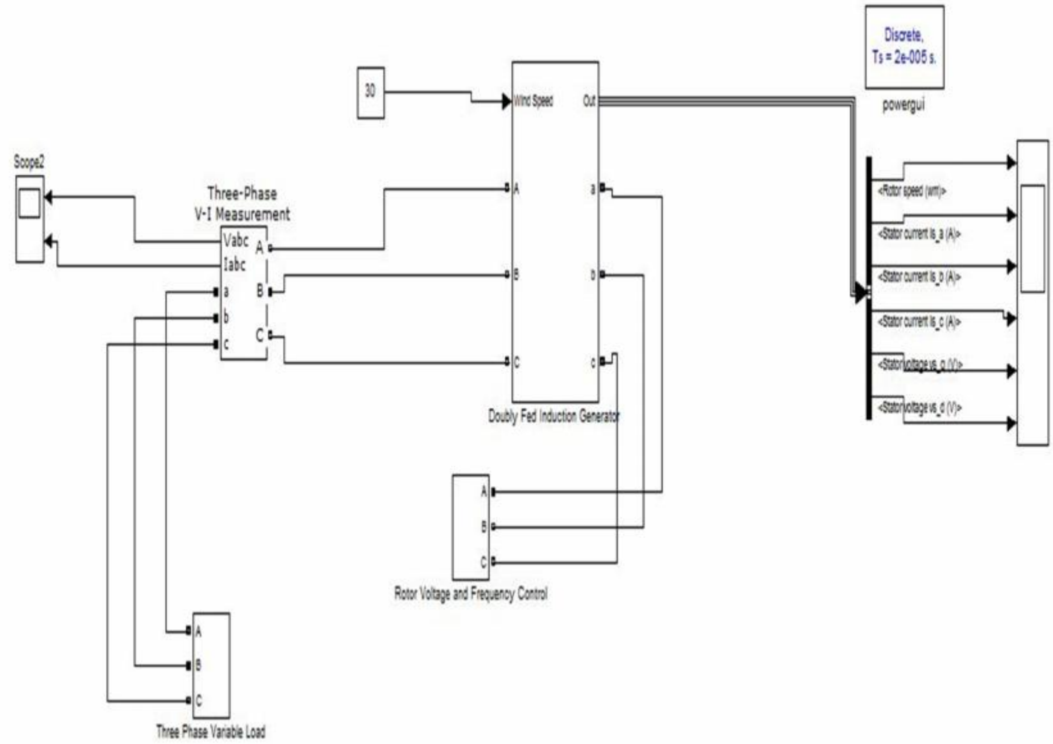

Fig. 5.1 MATLAB model showing DFIG fed from 3 phase supply

As can be seen from figure 5.1 the load is connected on the stator side while the rotor voltage and frequency is varied to get constant voltage and constant frequency operation for varying loads and varying wind speeds. Also variation of stator voltage and frequency for constant rotor voltage and frequency as the load is varied is studied.

For the machine mentioned in Appendix A simulation work was carried out to analyze the operation of DFIG in isolated mode. The variable voltage and frequency to the rotor side of the DFIG is provided by a controllable three phase voltage source . In order to verify the results of simulation a comparison is made between the experimental results obtained in [23] with our simulated results.

Fig. 5.2 gives the variation of rotor voltage for constant voltage and frequency output at the stator (load) side. Wind speed is varied and the load is considered resistive of 0.6462 pu. The constant voltage and frequency required at the load side are 1 pu.

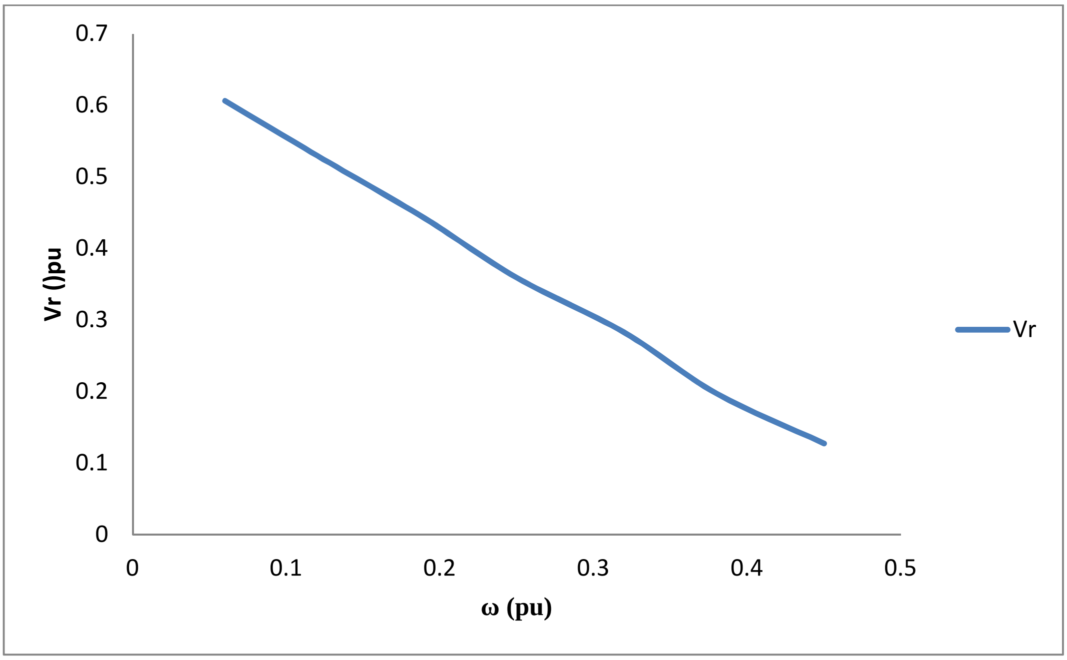

Fig. 5.2 Variation of rotor voltage for variable wind speed at rated output for fixed load of 0.6462 pu.

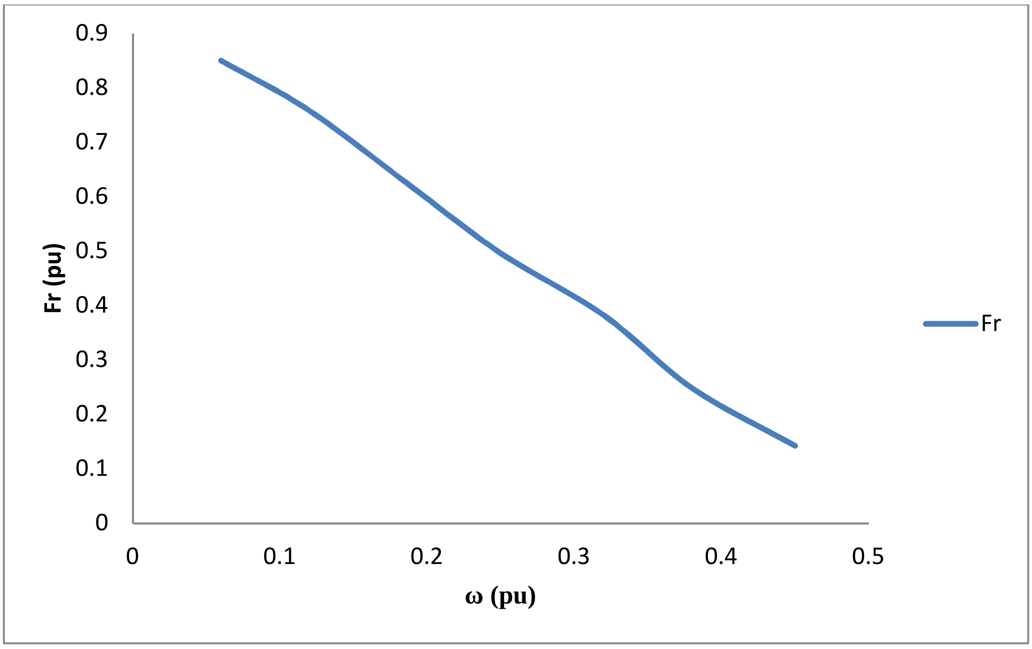

Fig. 5.3 Variation of rotor frequency for variable wind speed at rated output for fixed load of 0.6462 pu.

Fig. 5.3 gives the variation of rotor frequency for constant voltage and frequency output at the stator (load) side. Wind speed is varied and the load is considered resistive of 0.6462 pu. The constant voltage and frequency required at the load side are 1 pu.

As it can be seen from fig. 5.2 and fig. 5.3 that for high wind speeds, the rotor voltage and frequency required decreases for a particular load and for constant voltage and constant frequency operation.

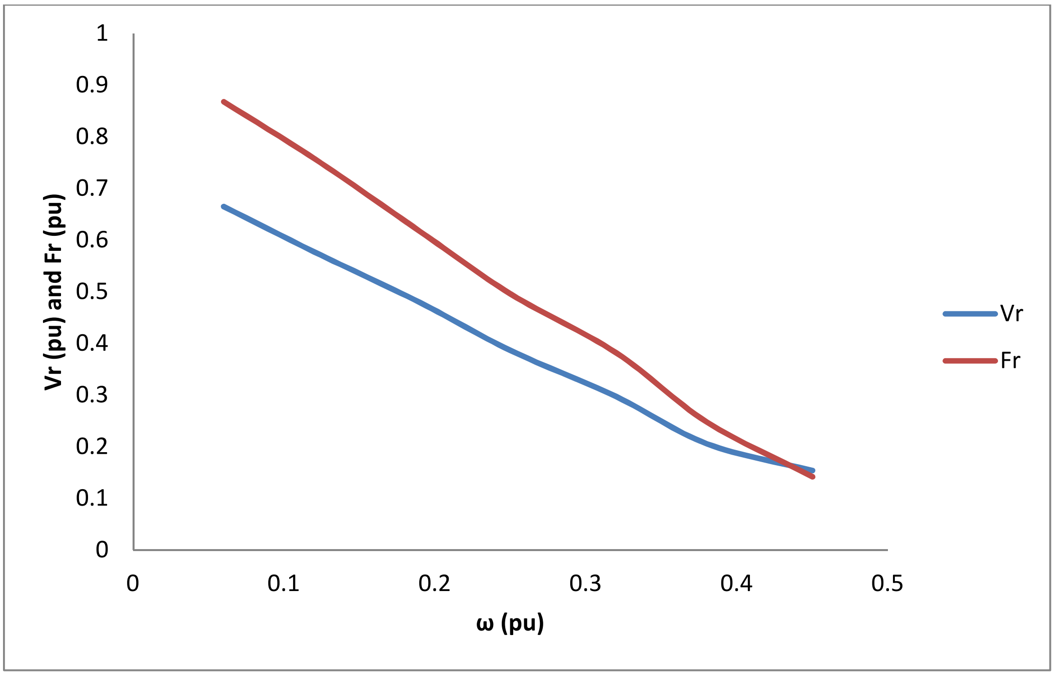

Fig. 5.4 Variation of rotor voltage and frequency for variable wind speed and inductive load of 0.714 pu and power factor of 0.9 pu.

Fig. 5.4 gives the variation of rotor voltage and frequency for constant voltage and frequency output at the stator (load) side. Wind speed is varied and the load is considered inductive with power factor of 0.9 and of 0.714 pu. The constant voltage and frequency required at the load side are both 1pu.

As it can be seen from fig. 5.4 that as the power factor decreases for the same value of resistance the voltage and frequency required at the rotor side increases for the same operation as mentioned above. Also it can be seen that the load current increases.

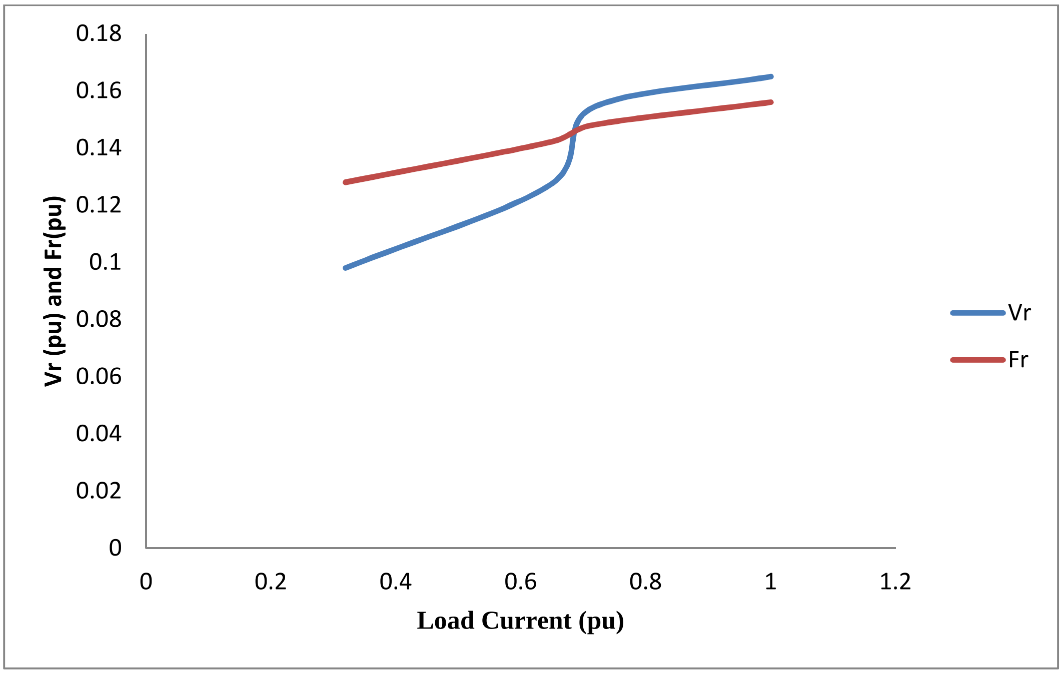

Fig. 5.5 Variation of rotor voltage and frequency for variable load at constant speed

Fig. 5.5 gives the variation rotor voltage and rotor frequency with variable load for a constant wind speed of 0.45 pu for constant voltage and constant frequency at the load side.

As it can be seen from figure 5.5 that as the load current increases , the rotor voltage and frequency required to generate rated output increases.

Fig. 5.6 is plotted by increasing the value of load current to 1pu and seeing the variation of rotor voltage and rotor frequency with variable wind.

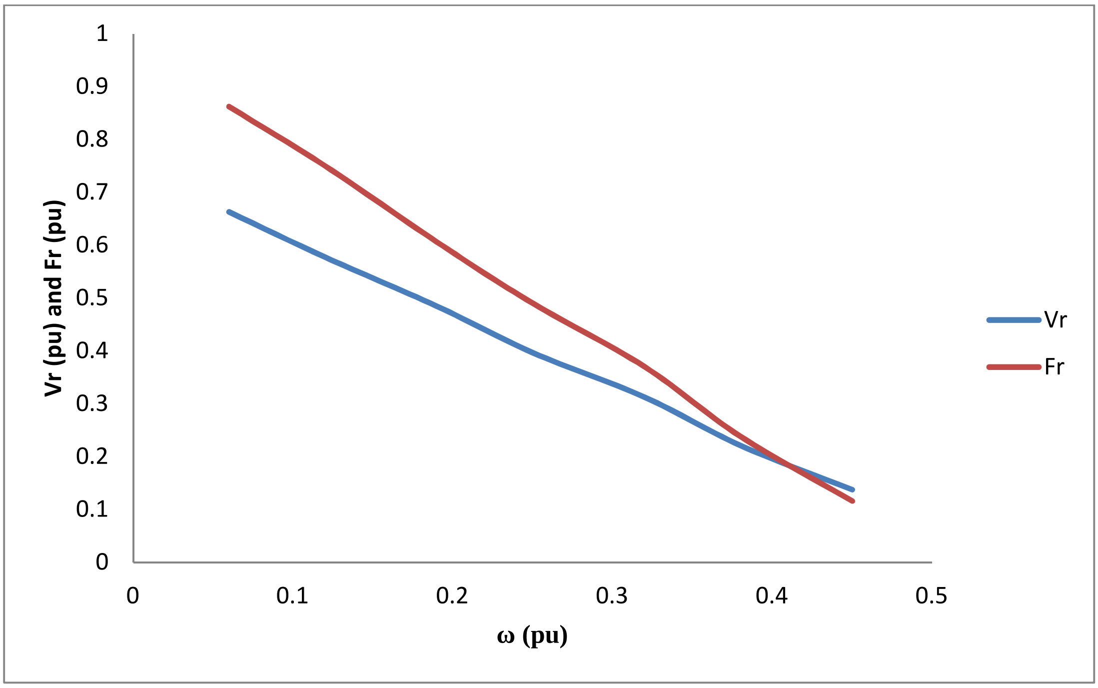

Fig. 5.6 Variation of rotor voltage and frequency for variable wind speed at rated load

Here it can be seen that as the load current increases to its maximum value, the rotor voltage required is the highest for constant voltage and constant frequency operation.

Now the effect of varying load on stator voltage and frequency for a constant value of wind speed and constant rotor excitation voltage and frequency is seen. Fig. 5.7 shows the above variation for a constant ω of 0.19 pu, V_r equal to 0.64 pu and f_r equal to 0.61 pu. Here a variable resistive load is taken.

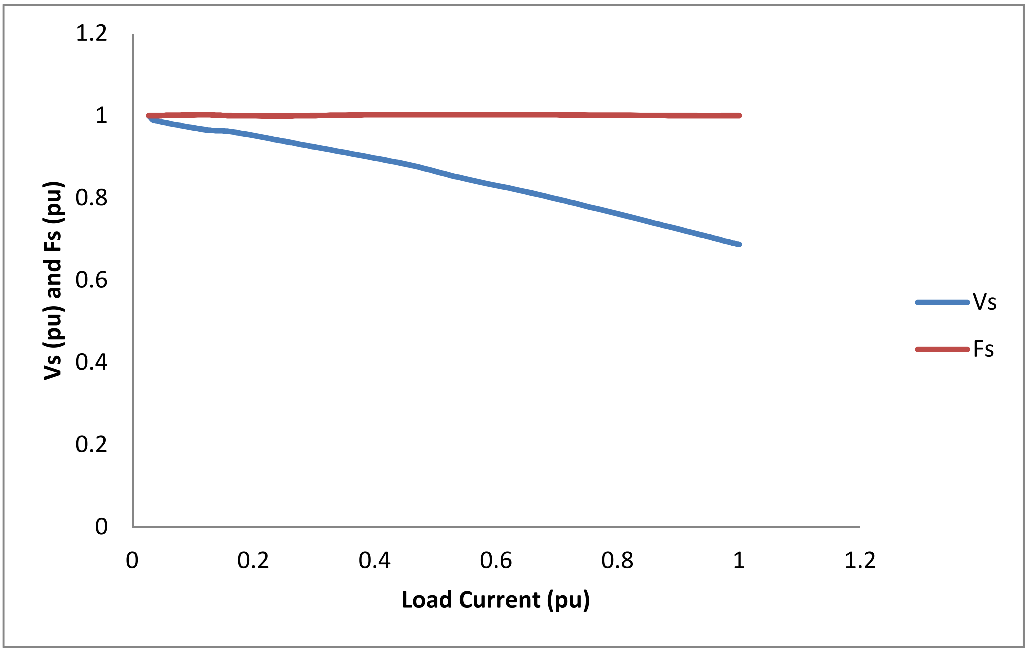

Fig. 5.7 Variation in stator voltage and frequency with varying load for a given wind speed and rotor excitation

Here it can be seen that as the load increases the voltage at the stator side decreases continuously if the rotor excitation is kept constant for a particular wind speed. Hence the voltage received by the load reduces. Therefore it can be said that to get a constant voltage and frequency at the load side a controller which controls the rotor excitation based on the wind speed is needed.

A table showing a comparison between experimental results obtained for the machine whose parameters are specified in appendix A and the simulated result for the same machine is shown here as table 5.1. The prime mover speed is considered equal to 401 rpm for a load of 80 ohms/phase and keeping the rotor induced voltage constant. The errors in voltage and frequency are specified in percentages.

Table 5.1 Comparative study of experimental and simulated results

SI. No	Rotor		Experimental Results		Simulation Results		Error in load voltage(%)	Error in load frequency(%)
			Stator		Stator			
	Vr	fr	Vs	fs	Vs	fs		
1	23.076	45.35	32.96	76.82	33.58	74.95	-1.88	2.43
2	23.662	46.43	33.07	77.77	34.08	76.03	-3.05	2.24
3	24.52	48.29	34.35	78.05	34.86	77.89	-1.48	0.21
4	25.3	50.1	34.73	80.04	35.21	79.7	-1.38	0.42
5	25.54	50.82	33.62	81.83	35.71	80.42	-6.21	1.72
6	25.46	52.7	31.95	82.49	34.64	82.3	-8.41	0.23
7	25.304	54.44	32.97	83.52	33.94	84.04	-2.94	-0.62

As can be seen that the error coming is very less therefore it can be said that the Simulink model rightly represents the actual system. The experimental results taken in table 4.1 are from [23].

The percentage error in the above table is calculated as follows

$$\% \, error = \frac{(Experimental\ value - Simulated\ value) \times 100}{Simulated\ Value}$$

5.3 Isolated mode operation of DFIG fed with DC supply

In this section the DFIG is operated in isolated mode with the load connected on the stator side and the rotor is fed through DC voltage via two lead and three lead connection. Various configurations supplying variable DC voltage have been made.

5.3.1 DFIG fed with three lead DC supply

Three lead connection is made by short circuiting any two phases of the rotor winding and supplying the DC voltage through the two terminals thus formed. In this section the variation of the load voltage with wind speed and varying load is considered. Accordingly, the DC voltage that needs to be supplied to get constant and rated load voltage is found out. Also the effect of connecting three phase variable capacitor bank in shunt with the stator is considered. The active and reactive power involved with the above variations is also shown in tabular form.

For the machine mentioned in appendix B simulation of the DFIG with three lead connection was done. The variable voltage at the rotor side is provided with a controllable DC voltage source. The Simulink model used to simulate the isolated mode operation of DFIG is shown in Fig. 5.8.

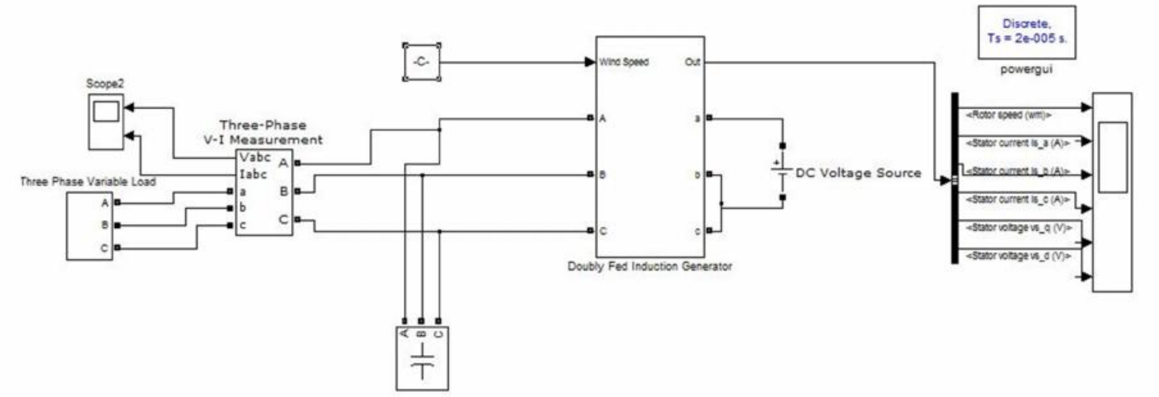

Fig. 5.8 MATLAB model showing DFIG fed from DC supply with 3 lead connection

The three phase load is connected to the stator through a circuit breaker and a measurement block which measures the stator voltage and current as can be seen from fig. 5.8.

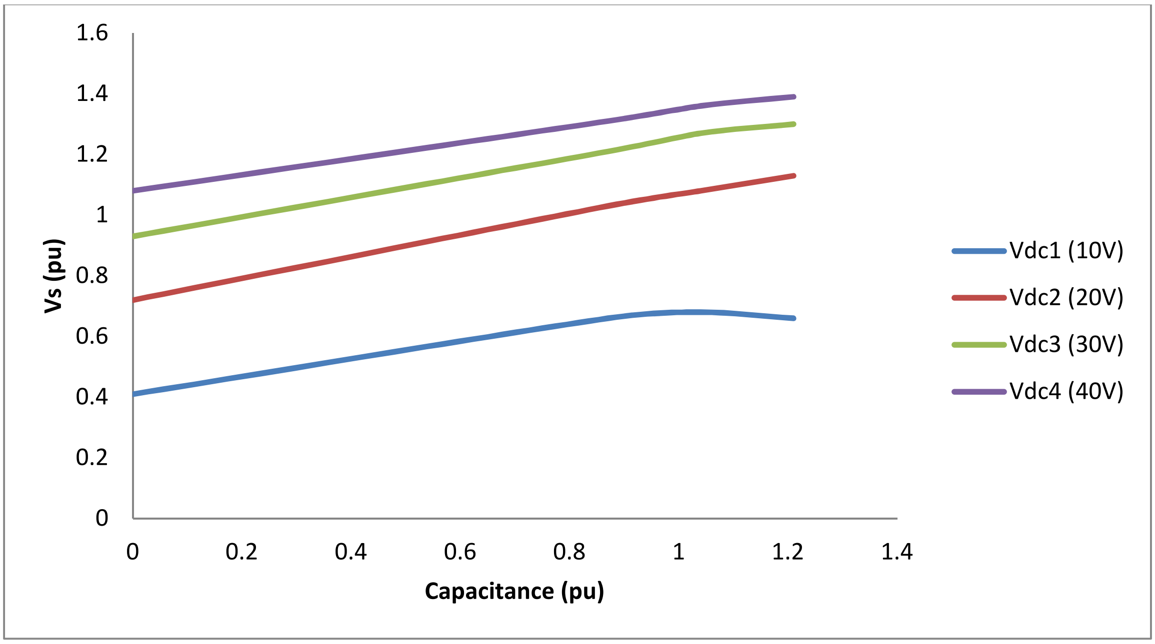

Fig. 5.9 Variation of load voltage with shunt capacitance for different values of applied DC voltages

Figure 5.9 gives the variation of load voltage with shunt capacitance for different values of applied DC voltages for a given constant load of 0.67 pu and given wind speed of 1 pu. It can be seen from the figure 5.9 that for a constant value of shunt capacitance, as the applied DC voltage is increased, the generated load voltage is also increased. Also it can be seen that for a constant applied DC voltage , the generated load voltage increases with the increase in value of shunt capacitance.

Table 5.2 gives the variation of applied DC voltage to obtain rated voltage at the load. The variations in load, wind speed and capacitance is considered and the three lead connected DC voltage is varied accordingly to obtain constant rated voltage at the load. The variation in stator, rotor and capacitor current along with the mechanical active power and also the reactive power supplied by capacitor has also been shown in the table.

Table 5.2 Variation of input DC voltage with load, wind speed and capacitance for three lead connection

Load (W)	Speed (rpm)	Capacitance (µf)	V_{DC} (V)	RMS Stator Volts (Ph-N)	RMS Stator Current (A)	Rotor Current (A)	RMS Capacitor Current (A)	P_m (W)	P_r (W)	Q_c (VAR)
250	1364.25	No external capacitance	38.2	219.3	0.38	3.28	NIL	255	126	NIL
250	1364.25	15	20.5	219.3	1	1.80	0.94	277	37	618
250	1364.25	18	17.3	219.3	1.19	1.53	1.12	288	27	742
250	1364.25	21	14.4	219.3	1.38	1.28	1.31	301	19	866
250	1500	No external capacitance	31	219.3	0.38	2.7	NIL	254	84	NIL
250	1500	15	13.1	219.3	1.1	1.18	1.03	283	16	681
250	1500	18	10.5	219.3	1.3	0.95	1.24	297	10	820
250	1500	21	8.9	219.3	1.5	0.78	1.45	312	7	955
250	1635.75	No external capacitance	26.1	219.3	0.38	2.30	NIL	254	60	NIL
250	1635.75	15	8.8	219.3	1.18	0.79	1.13	288	7	750
250	1635.75	18	8.1	219.3	1.4	0.68	1.34	299	6	889
250	1635.75	21	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
500	1364.25	No external capacitance	41.5	219.3	0.76	3.56	NIL	518	148	NIL
500	1364.25	15	25.4	219.3	1.2	2.2	0.94	542	56	622
500	1364.25	18	22.7	219.3	1.35	1.97	1.13	553	45	745
500	1364.25	21	20.3	219.3	1.5	1.76	1.32	564	36	868
500	1500	No external capacitance	34.3	219.3	0.76	2.97	NIL	519	102	NIL
500	1500	15	18.8	219.3	1.3	1.64	1.04	546	31	684
500	1500	18	16.9	219.3	1.45	1.47	1.24	558	25	818

500	1500	21	15.8	219.3	1.62	1.35	1.45	571	21	950
500	1635.75	No external capacitance	29.5	219.3	0.76	2.58	NIL	519	76	NIL
500	1635.75	15	15.6	219.3	1.36	1.35	1.13	555	21	748
500	1635.75	18	15	219.3	1.55	1.26	1.35	564	19	887
500	1635.75	21	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
750	1364.25	No external capacitance	45.6	219.3	1.14	3.89	NIL	788	178	NIL
750	1364.25	15	31	219.3	1.49	2.67	0.94	810	83	619
750	1364.25	18	28.8	219.3	1.6	2.47	1.14	822	71	743
750	1364.25	21	26.8	219.3	1.74	2.29	1.33	833	62	867
750	1500	No external capacitance	38.4	219.3	1.14	3.3	NIL	787	127	NIL
750	1500	15	25.1	219.3	1.54	2.15	1.03	814	54	682
750	1500	18	23.8	219.3	1.69	2.03	1.24	833	48	819
750	1500	21	22,9	219.3	1.84	1.94	1.45	847	44	953
750	1635.75	No external capacitance	33.8	219.3	1.14	2.93	NIL	787	99	NIL
750	1635.75	15	22.4	219.3	1.6	1.91	1.13	823	43	749
750	1635.75	18	21.9	219.3	1.77	1.84	1.35	834	40	888
750	1635.75	21	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL

5.3.2 DFIG fed with two lead DC supply

In the two lead connection the two leads from the DC source are connected to any two phases of the rotor and the third phase is connected to a high resistance to complete the circuit as can seen in fig. 5.2. . In this section the variation of the load voltage with wind speed and varying load is considered. Accordingly, the DC voltage that needs to be supplied to get constant and rated load voltage is found out. Also the effect of connecting three phase variable capacitor bank in shunt with the stator is considered. The active and reactive power involved with the above variations is also shown in tabular form.

For the machine mentioned in appendix B simulation of the DFIG with two lead connection was done. The variable voltage at the rotor side is provided with a controllable DC voltage source. The Simulink model used is shown in Fig. 5.10.

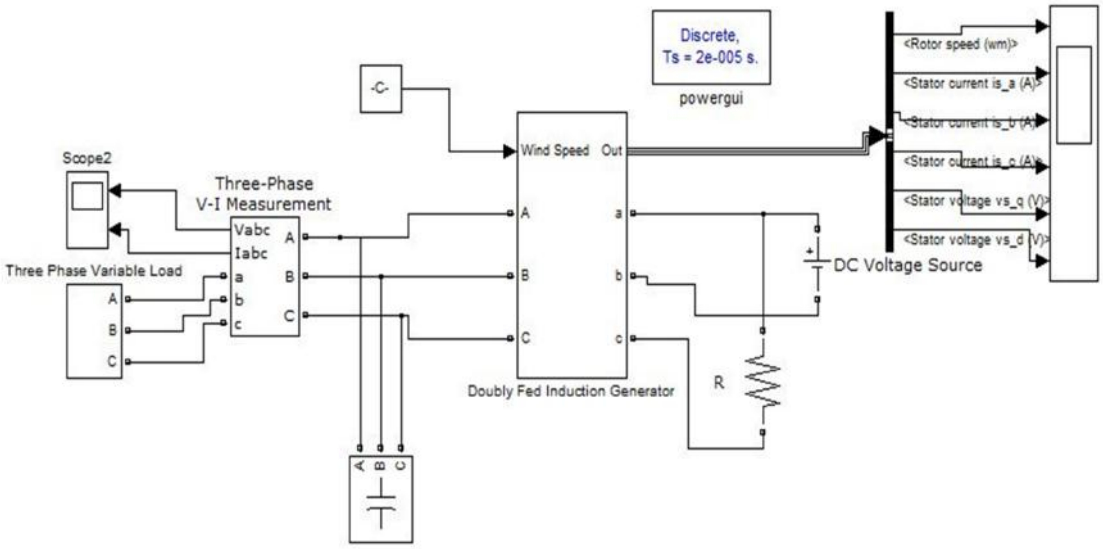

Fig. 5.10 MATLAB model showing DFIG fed from DC supply with 2 lead connection

Table 5.3 gives the variation of applied DC voltage to obtain rated voltage at the load. The variations in load, wind speed and capacitance is considered and the three lead connected DC voltage is varied accordingly to obtain constant rated voltage at the load. The variation in stator, rotor and capacitor current along with the mechanical active power and also the reactive power supplied by capacitor has also been shown in the table.

Table 5.3 Variation of input DC voltage with load, wind speed and capacitance for two lead connection

Load (W)	Speed (rpm)	Capacitance (μf)	V_{DC} (V)	RMS Stator Volts (Ph-N)	RMS Stator Current (A)	Rotor Current (A)	RMS Capacitor Current (A)	P_m (W)	P_r (W)	Q_c (VAR)
250	1364.25	No external capacitance	44.1	219.3	0.38	2.85	NIL	255	126	NIL

250	1364.25	15	23.5	219.3	1.02	1.56	0.93	277	37	618
250	1364.25	18	20	219.3	1.18	1.33	1.12	288	27	742
250	1364.25	21	16.7	219.3	1.37	1.12	1.31	301	19	866
250	1500	No external capacitance	35.9	219.3	0.38	2.7	NIL	254	84	NIL
250	1500	15	15	219.3	1.1	1.18	1.03	283	16	681
250	1500	18	12	219.3	1.3	0.95	1.24	297	10	820
250	1500	21	10.2	219.3	1.5	0.78	1.45	312	7	955
250	1635.75	No external capacitance	30.1	219.3	0.38	2.30	NIL	254	60	NIL
250	1635.75	15	10.1	219.3	1.18	0.79	1.13	288	7	750
250	1635.75	18	9.3	219.3	1.4	0.68	1.34	299	6	889
250	1635.75	21	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL
500	1364.25	No external capacitance	47.5	219.3	0.76	3.56	NIL	518	146	NIL
500	1364.25	15	29.3	219.3	1.2	2.2	0.94	542	56	622
500	1364.25	18	26	219.3	1.35	1.97	1.13	553	45	745
500	1364.25	21	23.5	219.3	1.5	1.76	1.32	564	36	868
500	1500	No external capacitance	39.5	219.3	0.76	2.97	NIL	519	102	NIL
500	1500	15	21.7	219.3	1.3	1.64	1.04	546	31	684
500	1500	18	19.5	219.3	1.45	1.47	1.24	558	25	818
500	1500	21	18.2	219.3	1.62	1.35	1.45	571	21	950
500	1635.75	No external capacitance	34	219.3	0.76	2.58	NIL	519	76	NIL
500	1635.75	15	17.8	219.3	1.36	1.35	1.13	555	21	748
500	1635.75	18	17.2	219.3	1.55	1.26	1.35	564	19	887
500	1635.75	21	18.1	219.3	1.76	NIL	NIL	NIL	21	1034
750	1364.25	No external capacitance	52.3	219.3	1.14	3.89	NIL	788	176	NIL

750	1364.25	15	35.9	219.3	1.49	2.67	0.94	810	83	619
750	1364.25	18	33.1	219.3	1.6	2.47	1.14	822	71	743
750	1364.25	21	31	219.3	1.74	2.29	1.33	833	62	867
750	1500	No external capacitance	44.3	219.3	1.14	3.3	NIL	787	127	NIL
750	1500	15	29	219.3	1.54	2.15	1.03	814	54	682
750	1500	18	27.4	219.3	1.69	2.03	1.24	833	48	819
750	1500	21	26.3	219.3	1.84	1.94	1.45	847	44	953
750	1635.75	No external capacitance	39	219.3	1.14	2.93	NIL	787	99	NIL
750	1635.75	15	25.8	219.3	1.6	1.91	1.13	823	43	749
750	1635.75	18	25.2	219.3	1.77	1.84	1.35	834	40	888
750	1635.75	21	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL

5.4 Novel architecture feeding DFIG with PV panel and Boost Derived Hybrid Converter

This section shows the integration of solar energy with wind energy generation system. The PV panel is used to extract the solar energy which it converts to DC voltage. The input to the PV panel is the insolation level. The practical model of the PV cell that is made consists of a series resistance and a parallel resistance along with an ideal single diode model as shown in figure 5.11.

The DC output from the PV cell is found out by writing the current equations and satisfying the Kirchoff's current law in figure 5.11. The output DC voltage of a PV cell is then multiplied by N_s which is the number of PV cells in series to give the cumulative DC output of the PV panel.

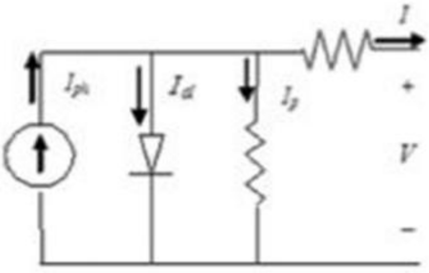

Fig. 5.11 Practical model of PV cell with R_s and R_p

This DC voltage is used to feed the boost derived hybrid converter (BDHC). The advantage of using the BDHC in place of a conventional boost converter is that it can simultaneously supply dc and ac loads. Here the DC output from the BDHC is used to supply the three lead connection of the DFIG and the AC output is supplied to a resistive load. The simulink model showing integrated PV panel and BHDC with DFIG is shown in fig 5.12.

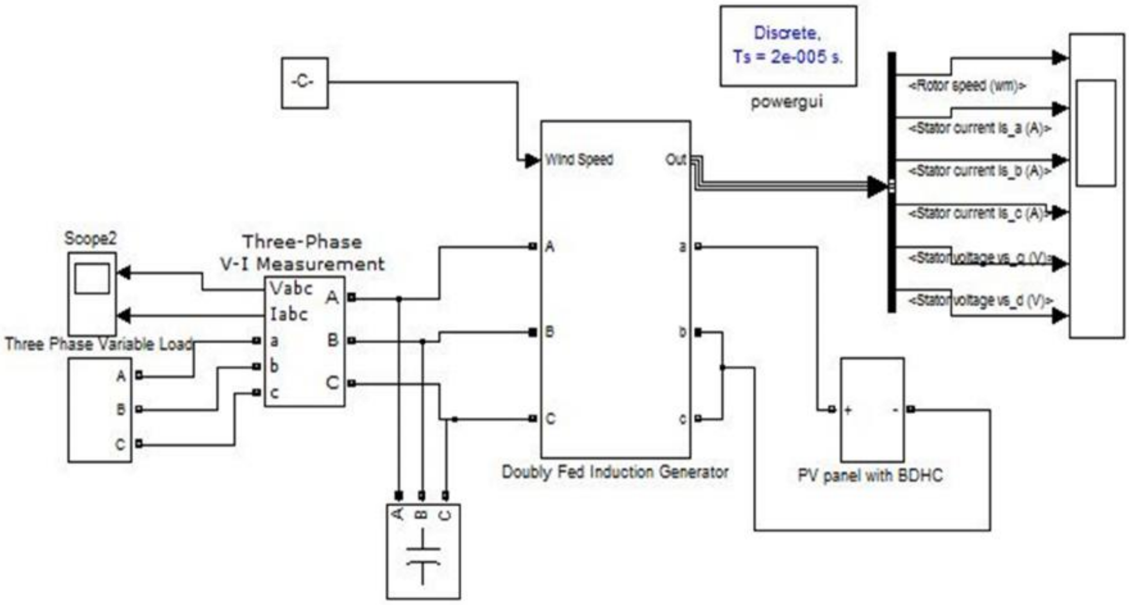

Fig. 5.12 MATLAB model showing DFIG fed from integrated PV panel and BDHC

5.4.1 Boost Derived Hybrid Converter

The boost derived hybrid converter is made by replacing the control switch of the conventional boost converter with a voltage source inverter circuit. The resulting hybrid configuration will provide both AC and DC outputs with a reduced number of switches required. The diagram of boost derived hybrid converter with a single phase inverter bridge network is shown in fig. 5.13.

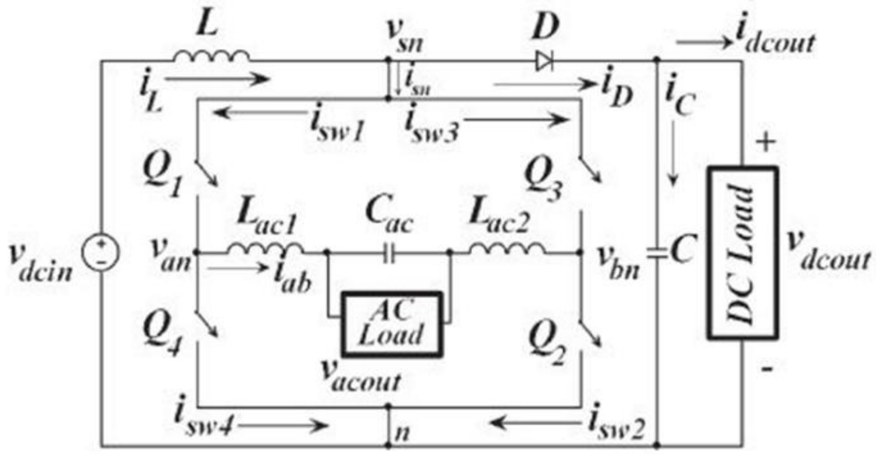

Fig. 5.13 Boost Derived Hybrid Converter with single phase inverter bridge network [19]

For the above shown boost derived hybrid converter , the hybrid outputs (containing both AC and DC) are to be controlled by only the four switches Q1-Q4. The simulink model using IGBT's as the power converters and the DC supply coming from the PV panel is shown in fig. 5.14.

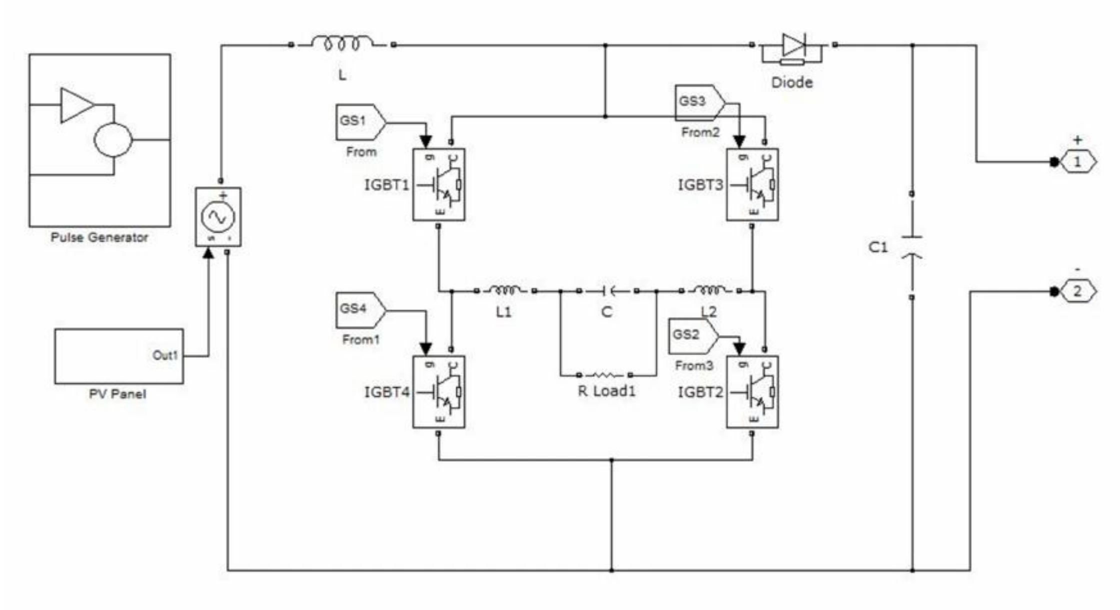

Fig. 5.14 Simulink model showing the boost derived hybrid converter

As can be seen from figure 5.14, each of the switches used in the inverter topology are bidirectional i.e. comprise of a combination of a switch and an anti-parallel diode. The switch 'ON' of the conventional boost operation can be obtained by turning on both the switches of a single leg i.e. (Q1 and Q4) or (Q2 and Q3) simultaneously. The ac output of the converter is obtained by using unipolar sine PWM switching scheme. These pulses are generated by the pulse generator as shown in fig. 5.14.

The operation of a boost derived hybrid converter during inverter operation is same as that of a conventional voltage source inverter. The reason for this is that although for conventional voltage source inverter the input required is stiff dc but the input is only used when there is a power transfer from the source. During all other intervals the, current freewheels in the inverter switches and during this period no input dc voltage is required and hence the input can be zero. The voltage v_{sn} shown in fig. 5.13 is the input to the inverter circuit. So the power transfer should take place only when this voltage is positive.

The simulink model which is used to produce unipolar sine PWM is shown in fig. 5.15 .

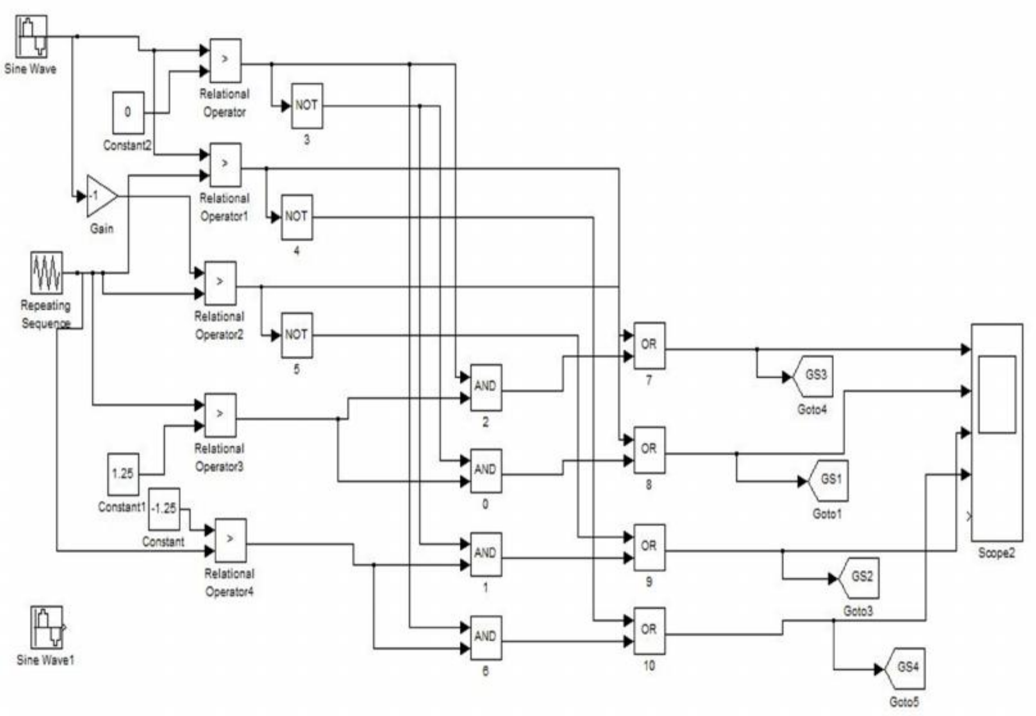

Fig. 5.15 Circuit to generate unipolar sine PWM

The switching pulses supplying the switches Q1-Q4 are shown in fig. 5.16.

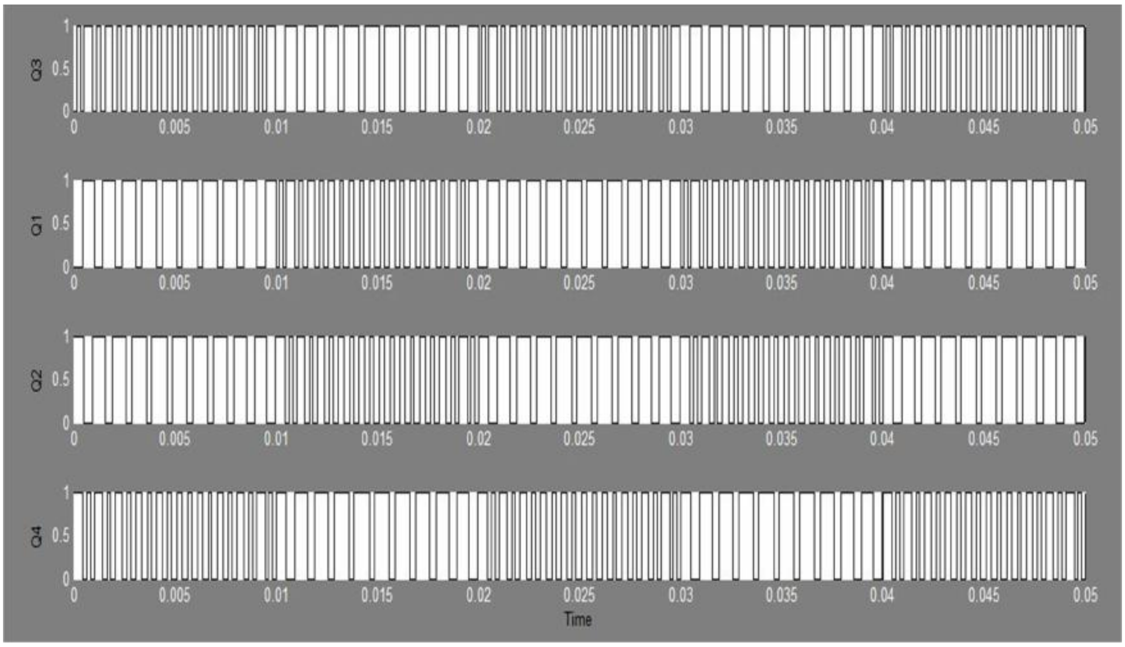

Fig. 5.16 Switching pulses for Q1-Q4

The three different switching intervals of boost derived hybrid converter are discussed below.

The *first interval* is the shoot through interval in which any two switches of the same leg are turned on and the diode 'D' is reverse biased. The shoot through interval decides the duty cycle of the boost operation.

The *second interval* is the power interval during which diode 'D' is conducting and either switches Q1,Q2 or Q3,Q4 are turned on.

The *third interval* is the zero interval during which the diode 'D' is conducting and the inverter current is circulating within the switches Q1-Q4.

5.5 DFIG fed with single phase AC supply

In this type of connection a single phase variable AC supply is used to feed the DFIG to generate three phase output as shown in fig. 5.17.

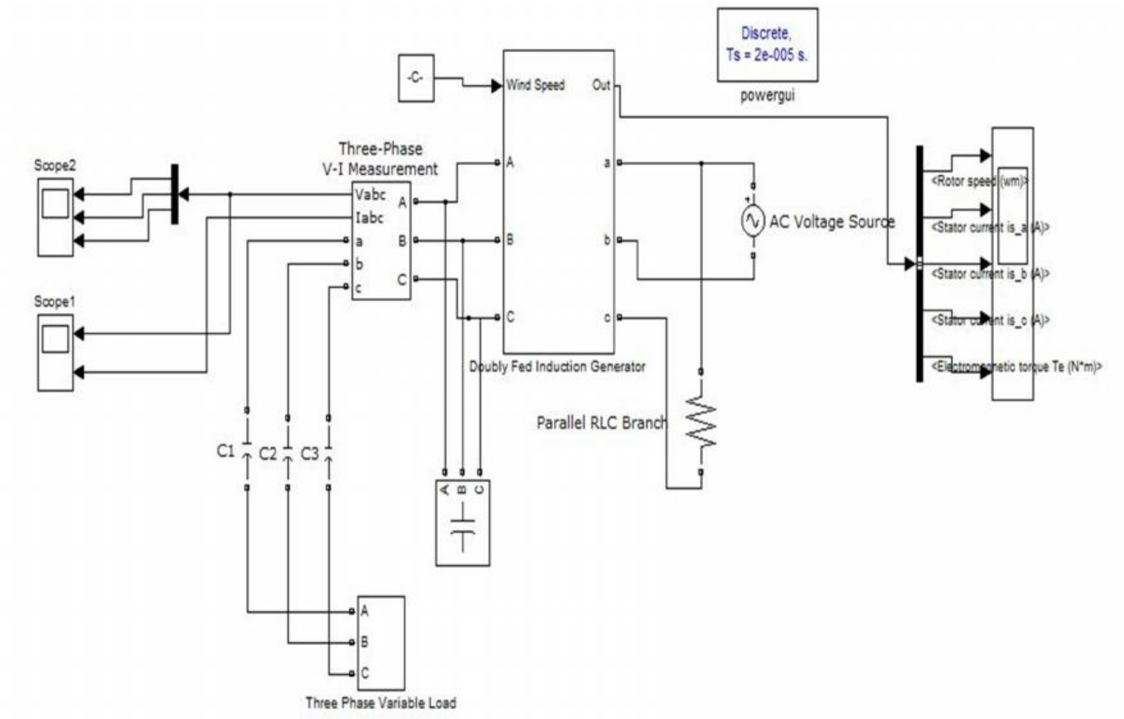

Fig. 5.17 DFIG fed with single phase AC supply with series compensation

In figure 5.17 we can see that a single phase AC source is supplying the DFIG from the rotor side and the load is connected on the stator through series compensating capacitors. The voltage generated in this case is unbalanced, the value of which is calculated by the voltage unbalance factor (VUF). The formula to calculate the voltage unbalance factor is given by the expression given below.

$$Voltage\ Unbalance = \frac{Maximum\ Deviation\ from\ mean\ of\ \{Vab, Vbc, Vca\}}{Mean\ of\ \{Vab, Vbc, Vca\}}$$

The effect of applying the series capacitance on the voltage unbalance factor for a constant load of 1pu , wind speed of 0.6 pu and applied voltage of 1pu magnitude and frequency is shown in fig. 5.18.

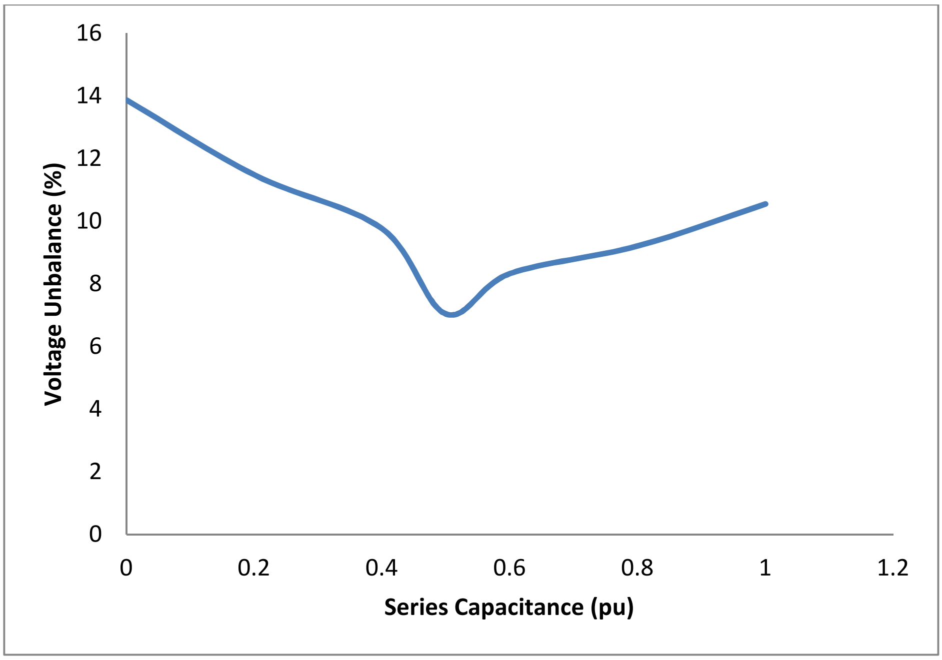

Fig. 5.18 Variation of voltage unbalance with series capacitance

As can be seen from fig. 5.18 the voltage unbalance is pretty high when no series compensation is provided. But as the value of the series compensation is increased the voltage unbalance gradually decreases till a point. As more compensation is provided the voltage unbalance starts increasing again. The point of minimum voltage unbalance is 0.5 pu as can be seen from fig. 5.18.

Now the variation in voltage unbalance with the load is seen keeping the series compensation at optimum value of 0.5 pu and applied voltage and wind speed conditions similar to the above case. Fig. 5.19 shows the given variation.

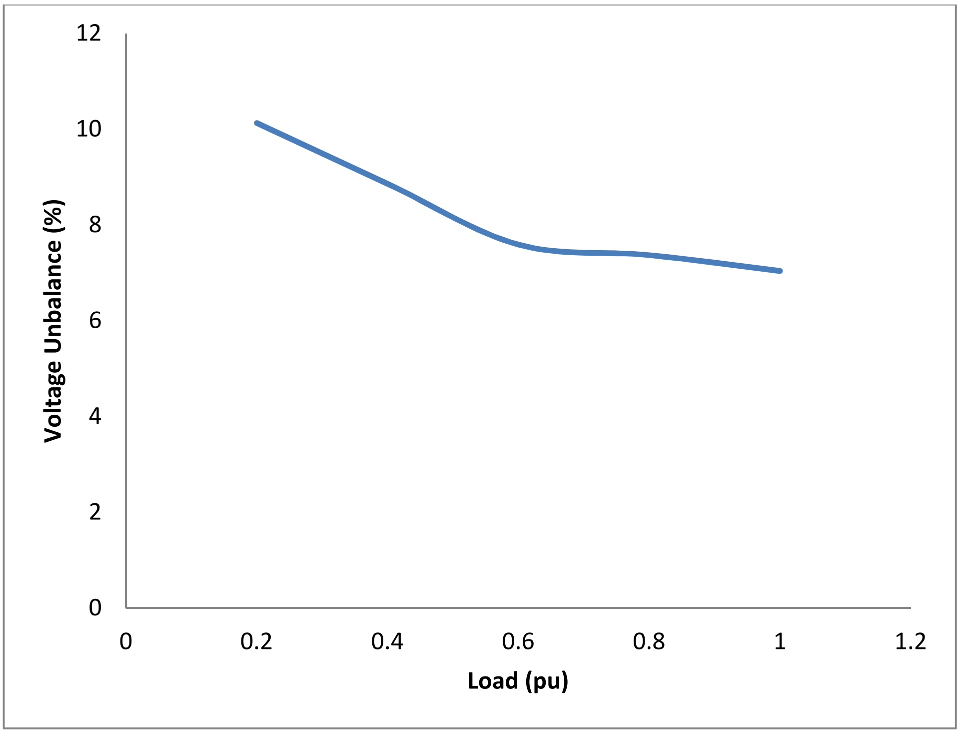

Fig. 5.19 Variation of voltage unbalance with load

It can be seen from figure 5.19 that the voltage unbalance is comparatively less at high loads than at low values of loads.

CHAPTER 6

CONTROLLED OPERATION OF DIFFERENT CONFIGURATIONS OF DFIG IN ISOLATED MODE

6.1 Introduction

In this section the closed loop operation of DFIG is done to generate rated voltage and rated frequency at the load side. The output voltage measured in per unit is compared with the reference voltage of 1 per unit. The error is sent to the PID controller which generates the control signal. The control signal is then sent to the PWM block. The PWM block generates the pulses which control the switching of the buck converter. The controlled output from the buck converter is supplied to the DFIG.

6.2 Wind Turbine and Pitch Control

The turbine is the prime mover of WECS that enables the conversion of kinetic energy of wind E_w into mechanical power P_m and eventually into electricity. The mechanical power from the wind turbine is given by:

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_\omega^3 \qquad 6.1$$

Where V_ω is the wind speed at the center of the rotor (m/sec), ρ is the air density (Kg/m3), $A = \Pi R^2$ is the frontal area of the wind turbine (m2) and R is the rotor radius. Cp is the performance coefficient which in turn depends upon the turbine characteristics (β - blade pitch angle and λ - tip speed ratio) that is responsible for the losses in the energy conversion process. Cp power coefficient of the turbine, which is a function of the blade pitch angle $\beta$and tip speed ratio, λ is defined as:

$$\lambda = \frac{R\omega_T}{V_\omega} \qquad 6.2$$

Where R is the blade length and ω_T is the turbine speed.

When the wind speed increases beyond the rated value, the electromagnetic torque is not sufficient to control rotor speed since this leads to an overload on the generator and the converter. To prevent rotor speed from becoming too high, the extracted power from incoming wind must be limited. This can be done by reducing the coefficient of performance of the turbine (the Cp value). As explained earlier, the Cp value can be manipulated by changing the pitch angle. Altering the pitch angle β means slightly rotating the turbine blades along the axis. The blades are considerably heavy in a large turbine. Therefore, the rotation must be facilitated by either hydraulic or electric drives.

6.3 Closed loop operation with three lead DC supply

The simulink model depicting the closed loop operation of DFIG is shown in figure 6.1.

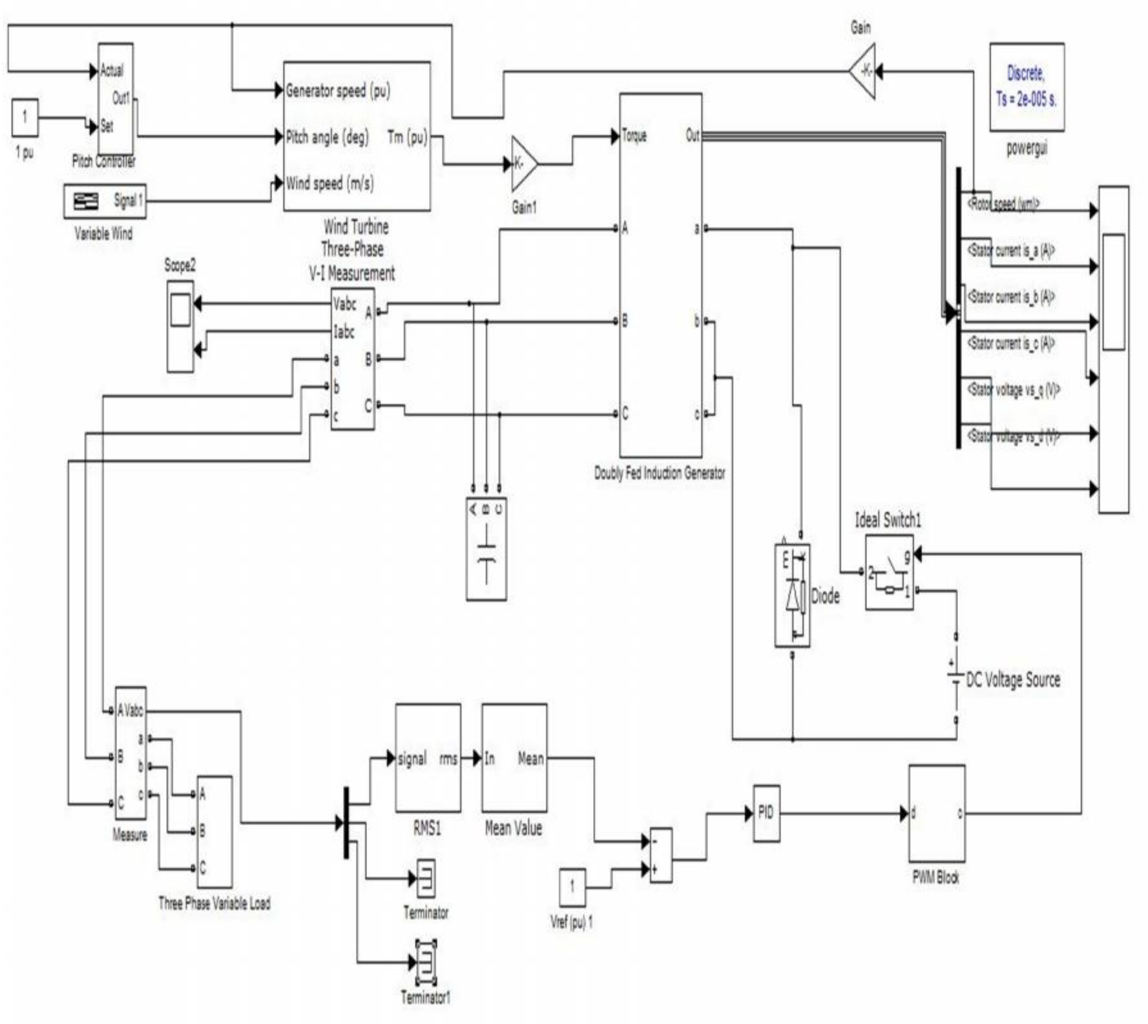

Fig. 6.1 Closed Loop Operation of DFIG with 3 lead connection

In fig. 6.1 it can be seen that a buck converter has been used to supply the DC supply to the DFIG through three lead connection. The switching of buck converter is done to maintain a constant rated output at the stator for variable loads.

6.4 Closed Loop operation with two lead DC supply

The simulink model depicting the closed loop operation of DFIG is shown in figure 6.2.

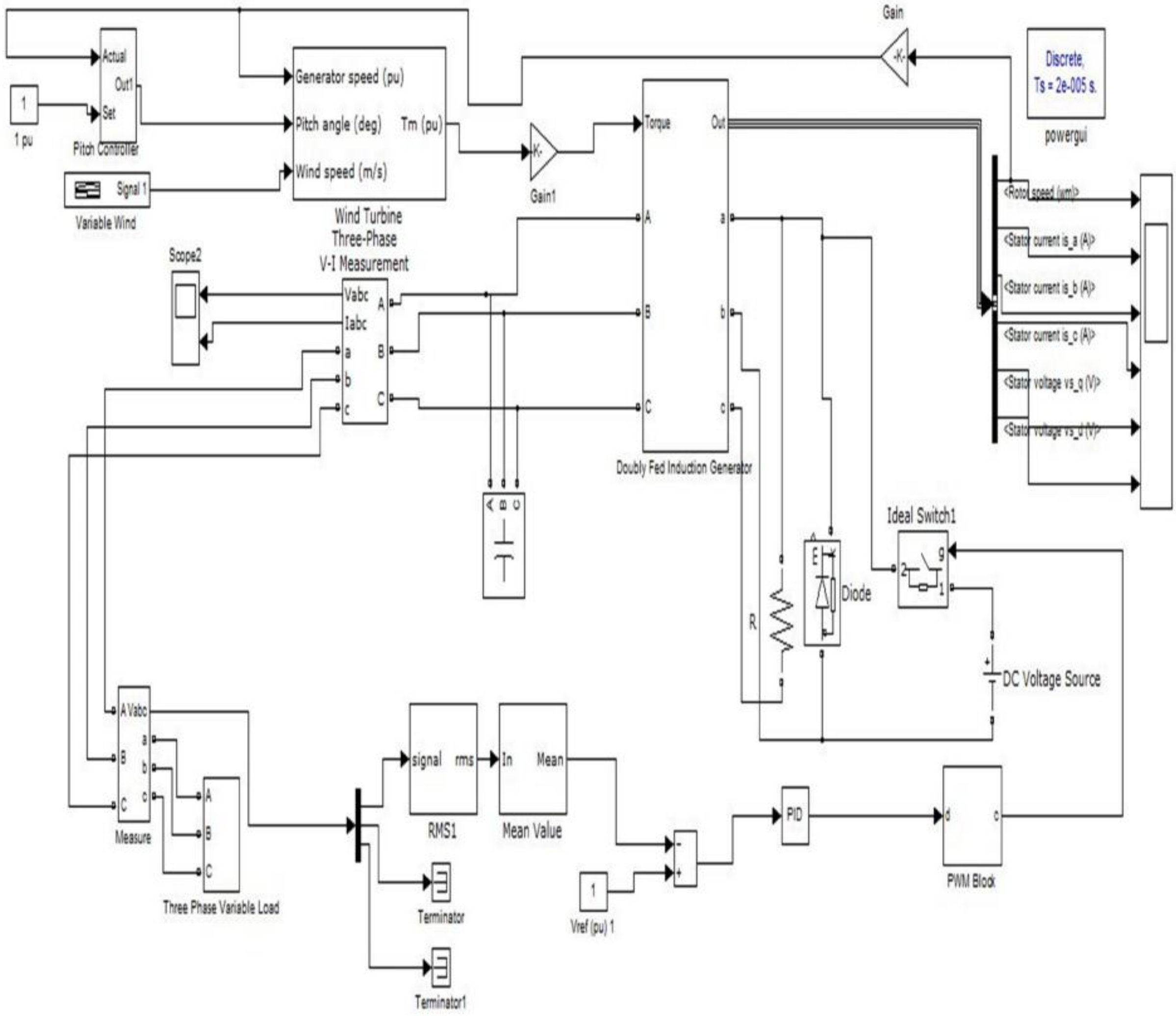

Fig. 6.2 Closed Loop Operation of DFIG with 2 lead connection

The three lead connection has been changed to two lead in fig. 6.2 The switching scheme remains the same where the buck converter is used to control the input given to the DFIG through PWM technique.

6.5 Results and Discussions

The effect of closed loop operation is shown in figure 6.3 and figure 6.4.

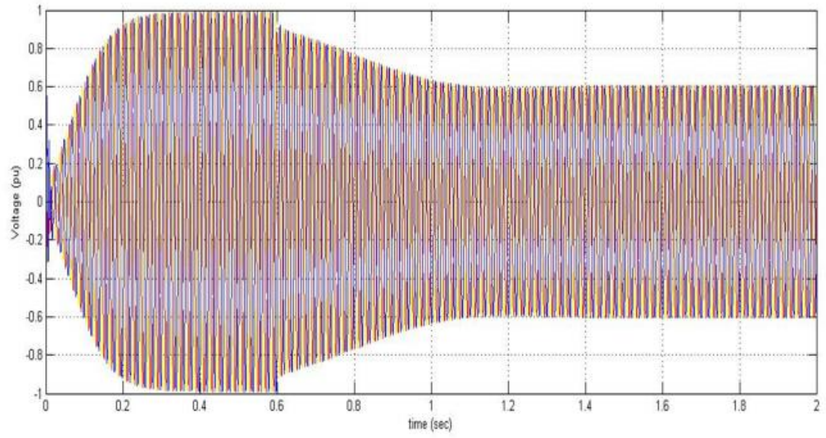

Fig. 6.3 Load Voltage for open loop operation with varying load

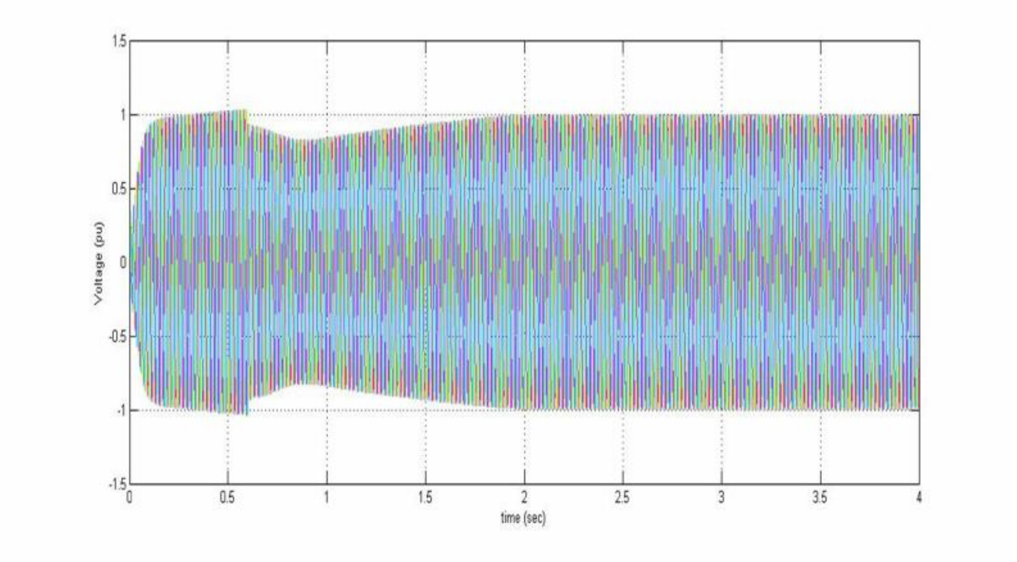

Fig. 6.4 Load voltage for closed loop operation with varying load

Figure 6.3 is that of open loop operation. In starting no load is connected to the DFIG and it generates rated voltage. But as soon as variable load is connected, the DFIG output falls below the rated value as it is an open loop operation.

Figure 6.4 is that of closed loop operation. Here also the DFIG is started at no load and it generates rated voltage. But as soon as the load is connected, an error signal is generated and is fed to the controller. The controller than generates the switching signal for the buck converter thereby controlling the input supplied to the DFIG and thus rated output voltage is produced on the load side.

The load in both the cases has been applied at time 0.6 seconds as can be seen from figure 6.3 and 6.4.

The load is now varied as shown in the figure 6.5 which shows the load current in per unit. As it can be seen from fig. 6.5. there is no load till t = 1 second. Then suddenly a load of 0.67 pu is connected and thus the load current increases. Further at t = 2 seconds the total load is increased to 0.8 pu and the load current rises.

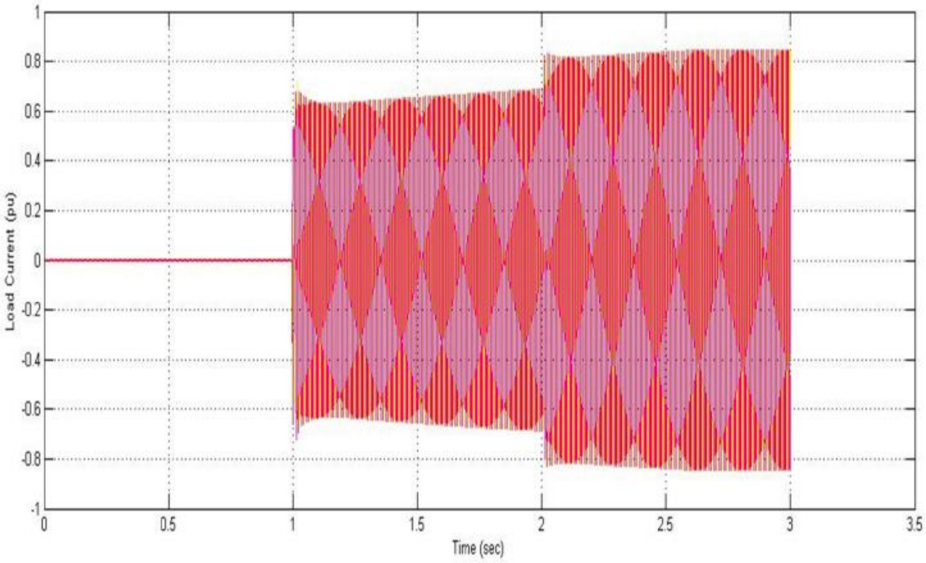

Fig. 6.5 Variation of load with time

The corresponding variation in voltage is shown in fig. 6.6. As the load is applied suddenly, the load voltage initially takes a dip but due to the controller action it again reaches the rated value. When the load is again increased, the initial dip in the voltage from the rated value occurs again. The controller action again shifts the load voltage to the rated value as shown in fig. 6.6.

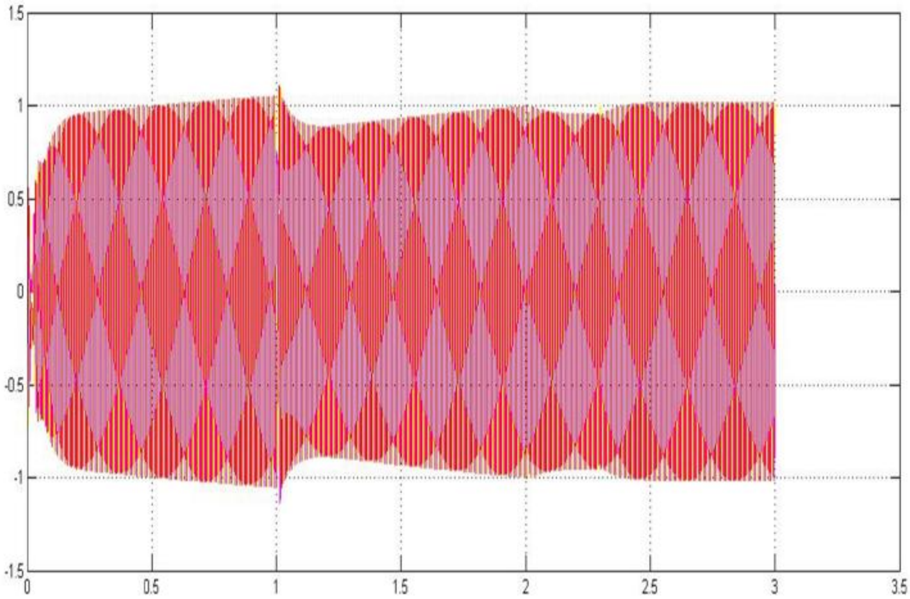

Fig. 6.6 Control of voltage with varying load

The controller also maintains the rated frequency as the variation in wind speed takes place. The variable wind speed is shown in fig. 6.7 and the corresponding frequency graph is shown in fig. 6.8. It can be seen from fig. 6.8 as the wind speed changes at t = 1 seconds there is a dip in frequency from the rated value. The controller action then again increases the frequency to the rated value. Also the wind speed changes at t = 2 seconds and similar action takes place as can be seen from figure 6.8.

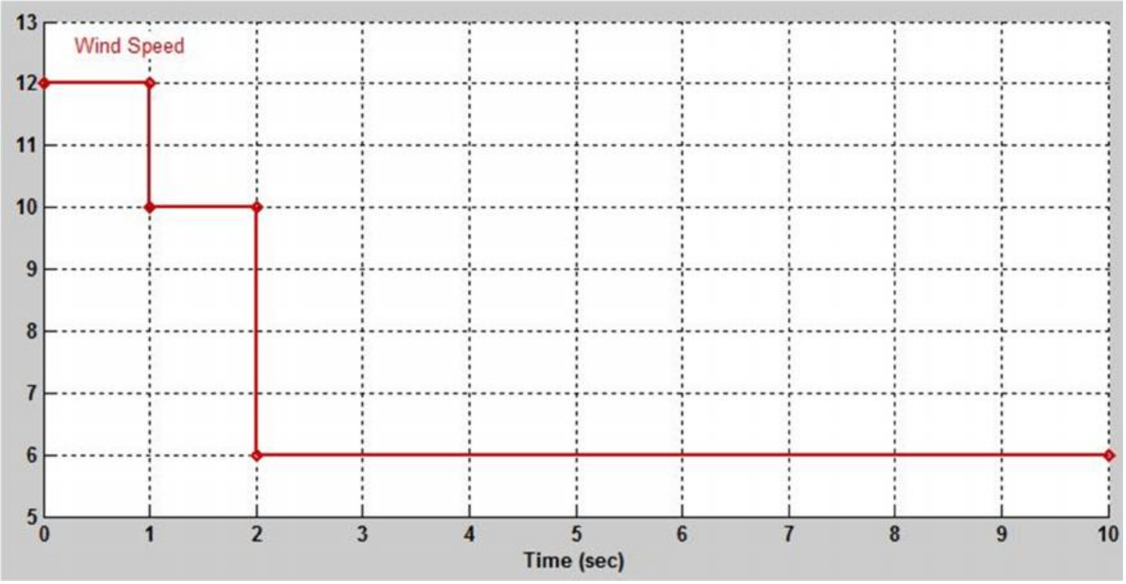

Fig. 6.7 Variation of Wind Speed with time

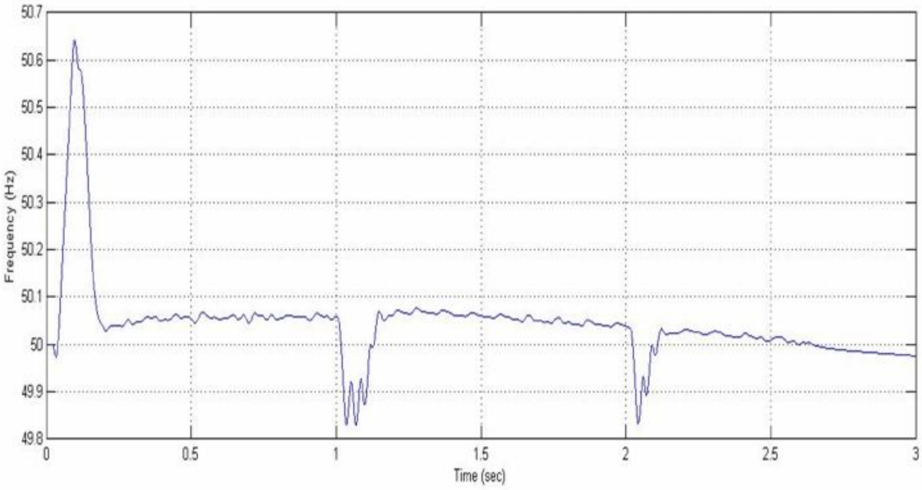

Fig. 6.8 Control of frequency with varying wind speed

As can be seen from figure 6.8, as the load is initially connected there is a change in frequency but the controller brings it back to 50 Hz. At changing wind speeds, the frequency is brought back to 50 Hz by the controller as can be seen from fig. 6.7 and fig. 6.8.

CHAPTER 7

CONCLUSION AND SCOPE FOR FUTURE WORK

7.1 Conclusion

The modeling of doubly fed induction generator operated in isolated mode has been done. The comparison between the operating capabilities different type of wind energy generation system under similar conditions has been done to deduce which one of them is better. The advantages of operating two generators in parallel have been shown.

The doubly fed induction generator has been operated under different configurations and the effect of varying load, wind speed and rotor supply have been studied. The comparison of simulated results with experimental results has been done. The closed loop operation for rated output at the load side has been done using the conventional PID controller for different configurations to conclude which of them is better.

7.2 Scope for future work

The present work done in this thesis can be extended to grid connected systems . To get the optimized operation various algorithms like genetic algorithm, particle swarm optimization etc. can be used. Also in place of conventional controllers, artificial intelligent controllers like fuzzy logic controller, neural network controller, ANFIS etc. can be used to get the controlled operation.

APPENDIX A :

Specifications

3-phase, 4 pole, 50 Hz , star connected induction machine

750W/1hp, 380 V, 1.9 A

Parameters

The equivalent circuit parameters for the machine are

$R_1 = 9.5\Omega$, $R_2 = 8.04\Omega$, $X_1 = X_2 = 8.84\Omega$

Base Values

Base Voltage = 219.3 V

Base Current = 1.9 A

Base Impedance = 115.4 Ω

Base frequency = 50 Hz

Base speed = 1500 rpm

Air gap Voltage

The variation of air gap voltage with magnetizing reactance at rated frequency for the induction machine is as given below.

$X_m < 169.2$	$E_1 = 512.69 - 2.13\ X_m$
$179.42 > X_m \geq 169.2$	$E_1 = 891.66 - 4.37\ X_m$
$184.46 > X_m \geq 179.42$	$E_1 = 785.79 - 3.78\ X_m$
$X_m \geq 184.46$	$E_1 = 0$

APPENDIX B :

Specifications

3-phase, 4 pole, 50 Hz , star connected induction machine

7 KW, 415 V, 14.7 A

Parameters

The equivalent circuit parameters for the machine are

$R_1 = 1.05\Omega$, $R_2 = 1.296\Omega$, $X_1 = 2.61\Omega$, $X_2 = 2.61\Omega$

Base Values

Base Voltage = 239.6 V

Base Current = 14.7 A

Base Impedance = 16.29 Ω

Base frequency = 50 Hz

Base speed = 1500 rpm

Air gap Voltage

The variation of air gap voltage with magnetizing reactance at rated frequency for the induction machine is as given below.

$X_m < 51.2$	$E_1 = 277.53 - 1.42 X_m$
$83.8 > X_m \geq 51.2$	$E_1 = 328.7 - 2.42 X_m$
$95.2 > X_m \geq 83.8$	$E_1 = 349.44 - 2.67X_m$
$161.2 > X_m \geq 95.2$	$E_1 = 116.144 - 0.22X_m$
$X_m \geq 161.2$	$E_1 = 0$

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