CHAPTER 1

INTRODUCTION

1.1 General

The depletion of reserves of fossil fuel-based energy resources are among the main concern of the present day energy market around the world. As a replacement the use of non-renewable energy resources motivates to discover the new avenues of alternative resources for clean, safe and reliable electricity generation which could serve the society for a long period.

As fossil fuel resources are limited and have a significant adverse effect on the environment by continuously increasing the contribution to global warming and other factors. Amongst various available renewable energy resources wind and hydro are more feasible for power generation. With a majority of the hydro reserves that are reaching their maximum capacity in terms of power that can be evacuated out of it. There is an increasing shift towards electricity generation from wind resources which are freely available and considered to be the most promising technologies to meet the ever increasing energy demand. It has been in use for a significant period of time and compared to other forms of alternative energy resources, shows the utmost prospective to trim down the power generation through conventional resources. The fraction of wind based generation in terms of total electricity generation has been evolving continuously in many parts of the world. Most wind farm installations have now become more competitive with existing conventional power plants in terms of cost as well as reliability which until recently was not possible.

The evolution of power extraction from wind energy in India began in the 1990s, and has significantly increased in the past few decades. India is the world's fifth largest wind power producer, with a generation capacity of approximately 18 GW. In 2009-10 India's growth rate was highest among the other top countries in terms of wind power generation. Wind power accounts for approximately 6% of India's total installed power capacity, and thus contributes to 1.6% of the country's power.

However, there exist various shortcomings associated with wind energy conversion systems (WECS) which makes energy producers be indecisive to invest, despite all its merits. With the increased penetration of wind energy conversion systems, new challenges with respect to the performance of the existing power grid are surfacing, especially in the area of energy reliability, grid stability, and planning issues. As wind source is unpredictable and the output power from the wind is highly influenced by its variable speed. Therefore, integration of variable sources of wind turbines into the existing electrical networks can significantly impact the design, operation, and control of the network require highly efficient control that can offer good stability when integrating wind farms into the system. Although wind power generation is well known and has already in use for several years, but because of the low penetration levels of wind turbines, focus of the researchers has been on the efficient and maximum extraction of power from the wind [1-2].

In case of wind farms, consisting number of WECS connected in parallel the resultant output power tends to have oscillations as a result of the averaging effect across all wind generators. For these reasons, added to the fact that reactive power and weak system interconnection are often of relevant concerns, wind parks are more susceptible to voltage and transient instability problems. Therefore, there is a need for sophisticated control that could provide greater stability to the system even under odd conditions. Also, the issue of power regulation is of even greater importance in small wind farms and for distributed generation (DG) [4]. The introduction of DGs into the power network opened a new era to the existing grid, where the power consumed by the loads could be produced from a number of diversified sources, power producers, and at various locations depending upon the accessibility of the resources. This creates the outline for a possible future grid with a more elaborate and flexible structure that ensure smooth and stable operation.

1.2 Wind Power In India

Wind energy being non-polluting and freely available energy source has witnessed tremendous growth in past two decades and has significant impact on the power generation. As the combustion of conventional fossil fuel across the globe has caused increased level of environmental pollution in the form of green house gases. This serious issue has motivated nations across the world to think about alternative forms of energy which utilize inexhaustible natural resources.

Efforts are being made to increase the contribution of renewable sources of energy in the overall energy market. Several countries have already formulated policy frameworks to ensure that renewable resources play a major role in future energy scenarios. India's growth rate was highest among the other top four countries in the year 2009-10 and now is aiming to produce approximately 200GW by 2020. As of March 2012, renewable energy accounted for 12.2% of total installed capacity, if compared to the production in 1995 which was just 2%. Wind power accounts for about 70 percent of the total installed capacity. By the end of August 2012, wind power installations in India had reached 17.9 GW.

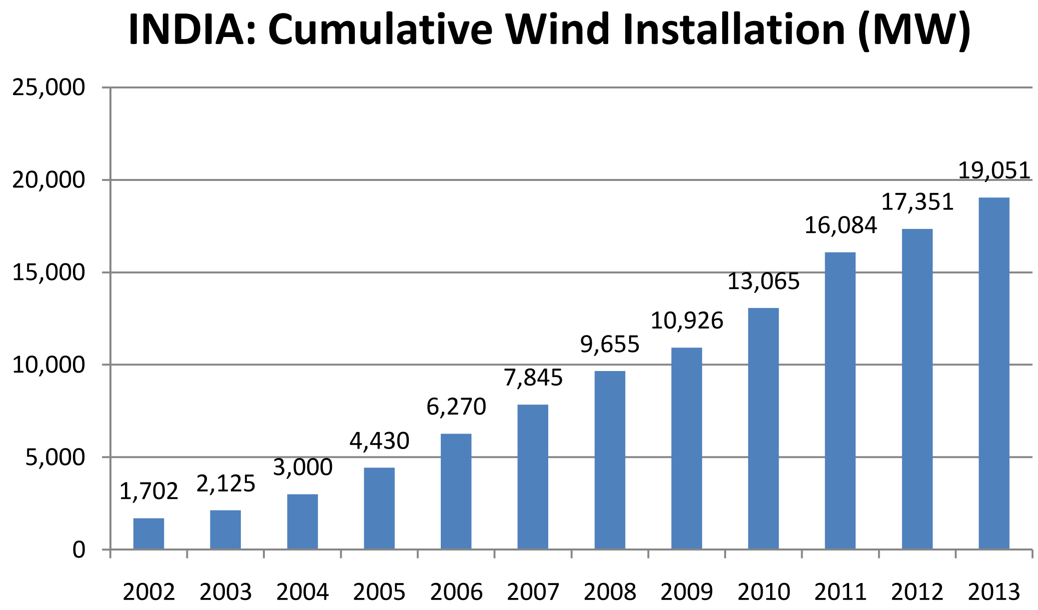

Fig.1.1 Cumulative wind energy generation capacity in India

1.3 Wind Energy Conversion Systems (WECS)

Several wind generating systems have been proposed in the literature to provide power to either isolated or in grid connected wind energy systems [2]. Whereas, coupling of wind energy systems into power grid faces several issues like poor voltage regulation and grid synchronization, variable reactive power demand, harmonics, negative sequence currents, voltage unbalance, system stability and power stability problems.

Wind generation technologies are broadly classified as fixed speed generation and variable speed generation. The fixed speed generators are designed to operate at a specific speed for which the maximum power is extracted from the turbine whereas variable speed turbines have maximum power tracking capability that allows maximum available power from the wind at different speeds. Also the variable speed operation limits the mechanical stresses on the turbine blades resulting from wind gusts thus improving system stability and lifetime of the turbine. It also helps to damp out oscillations in torques more efficiently. Thus variable speed generators are more commonly installed due to the fact that optimum power can be captured at different rotor speeds for different wind speeds. Thus, the synchronous generator is rarely used when directly coupled since it requires a mechanical means of regulating the wind speed and lacks the benefits associated with a variable speed wind turbine systems [9].

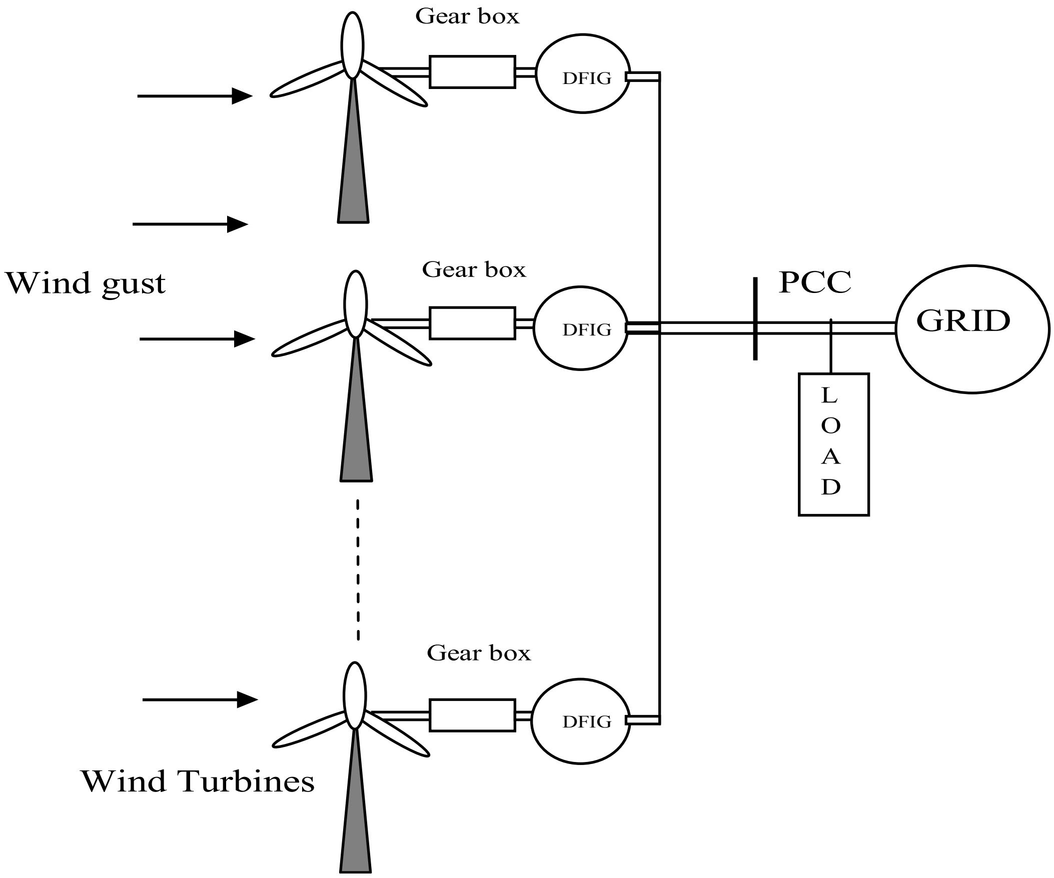

Fig. 1.2 A typical Wind farm consisting of number of wind turbine system connected in parallel at PCC

Induction generator has emerged as a suitable machine for power extraction through wind since it can generate at variable speeds, singly excited and rugged in structure. Two types of induction machines are more popular for WECS. Squirrel cage induction generator (SCIG) and doubly fed wound rotor induction generator (DFIG), depending upon their capacity, availability under continuous and steady wind conditions. DFIG is generally prescribed for high power evacuation [].

1.3.1 Fixed speed wind turbines(FSWT)

Squirrel cage induction generators (SCIG) are normally operated as constant speed turbines therefore suited for places where steady wind conditions exist. Since the output power generated fluctuates and varying reactive power is required their direct connection to grid could be only with stiff grids [25]. Whereas, non-stiff grid may fail due to large demand of variable reactive power and fluctuations in frequency and terminal voltage. It is therefore they are connected in a microgrid which in turn is connected to the main grid through power electronic grid coupling [26]. These machines are vulnerable to concentration of harmonics as it distorts its magnetization. It is therefore essential to maintain good quality of power at the microgrid. Since the machines are maintenance free and rugged therefore they are suited for installations in difficult terrains and offshore applications [8].

Although FSWT has the advantage of being simple and relatively cost efficient compared to other types of available wind turbines, but this type of wind turbine cannot offer independent control over active and reactive power, therefore any severe short-circuit near the wind farm i.e at PCC (refer fig 1.2) may cause significant voltage dip particularly when connected to weak power network. Thus, the risk of loss of synchronization increases significantly.

Since the rotational speed of the turbine is limited to a very narrow range determined by the slip of the induction generator, any fluctuations in mechanical torque due to variable wind speed will impact the network where the wind farm is connected.

1.3.2 Variable speed wind turbines (VSWT)

DFIG is subjected to less mechanical stress and can generate high efficiency even under fluctuating wind conditions, thus suited for variable speed operation. Due to placement of converters on the rotor side the size and rating are substantially reduced. DFIG in the true sense allows variable speed operation since it is capable of levelling the power fluctuations from the rotor circuit [5]. It can therefore be connected to weak A.C. grids without creating any threat of stability and also it need not form a microgrid to sustain its operation. In DFIG a back to back voltage source converter (VSC) feeds the three phase rotor winding which decouples power at rotor frequency and interface power to stator at grid frequency independent of the mechanical rotor speed. Besides these, such configuration is self supported for reactive power requirements and harmonics at the terminal of WECS [9-11].The operation with unity power factor and reduced current harmonic distortion makes it a suitable choice for its grid coupling [4], [7].

Table 1.1 Summarized features of FSWT and VSWT

STRUCTURE	FIXED SPEED WIND TURBINE	VARIABLE SPEED WIND TURBINE
MACHINES	Squirrel Cage Induction Generator (SCIG)	Permanent Magnet Synchronous Generator (PMSG), Doubly Fed Induction Generator (DFIG)
MERITS	• Simple construction • Low cost • Low maintenance	• Complete control of active and reactive power • High conversion efficiency • Suited in variable wind conditions also
DEMERITS	• Suited in steady wind conditions only • No control on real/reactive power • High mechanical stress on turbine • Less conversion efficiency • Poor power factor	• Expensive due to additional cost of power electronics converter • Limited fault ride through capability

1.4 Doubly Fed Induction Generator (DFIG) Based WECS

The wind energy conversion system (WECS) using a DFIG is shown in Fig. DFIG is considered to be the most popular machine topology particularly for wind power applications. It is the only variable speed generator which is suited most for high power generation (>1 MW). The power electronics converter involved also enables control over generator operating characteristics such as speed and reactive power which are lacking in SCIG. This also allows maximum power point tracking or output power regulation under fluctuating wind conditions [2-5].

The doubly fed induction generators consist of a three phase induction generator with three-phase winding on the rotor. Rotor converter supplies power to the rotor via slip-rings. The VSC is capable of handling power flow in both directions which allows DFIG to operate in both sub-synchronous and super-synchronous speeds [3]. It produces controlled voltage at grid frequency at stator terminal while at variable frequency at rotor [15]. The induction generator is a standard, wound rotor induction machine with its stator windings directly connected to the load and its rotor windings connected to the load through a back-to-back VSC, namely the rotor side converter (RSC) and the stator side converter (SSC). The controller regulates the DFIG to curb the wind power fluctuation due to varying wind speed and maintains the DC bus and also compensates the unbalanced currents being transacted by DFIG due to corruption of voltage at PCC [6].

DFIG Control

The ability to control the speed of the generator along with controllable power factor has been shown to improve both the efficiency as well as the stability of this generator [4], [10]. This is accomplished by decoupled control of the stator real and reactive powers. The control scheme for DFIG involves separate control for SSC and RSC connected back-to-back. The rotor terminals are connected to the power electronics converter which is capable of both supplying real/reactive power from the grid to the rotor as well as supplying power from the rotor to the grid whereas the SSC is connected in shunt with the line through coupling transformers to maintain constant voltage at dc-link besides reactive power support [8]. The DC-link thus provides the decoupling between the two AC sides at different frequencies. The LC filter at converter terminal mitigates the harmonics in the current, due to the switching of converter, and provides the impedance over which energy can be exchanged.

The compensation through DFIG allows use of converters, with lower power rating (20-30%) as they deals only with fraction of total power delivered to the system. Due to the fact that the rotor side voltages are at most 25% of the stator side voltage, the minimum kVA rating of the VSC is approximately 20-30% compared to that of a direct back-to-back converter coupled to turbines for variable speed operation [16]. This means that the DFIG can offer an operating range of 75% to 125% of the rated wind speed. Also the pitch control with maximum power tracking allows the DFIG to produce maximum power at different wind speeds thus increasing overall efficiency of the system. The rotor voltages are related to the stator voltages by:

$$|V_r| = s|V_s| \quad \text{... (1.7)}$$

Where, the machine slip, s is a measure of the rotor speed relative to synchronous speed, which is given by:

$$s = \frac{n_s - n_r}{n_s} \quad \text{... (1.8)}$$

Also, the minimum rating of the converter depends upon the upper speed limit of the rotor, which is taken to be 1.2 to 1.25 of the synchronous speed. However, practically a rating of 30-40% is chosen taking into account the ability to deliver reactive power from the stator. Typically a wind farm, where number of doubly fed generators is connected to a common bus when connected to a weak A.C grid, may amplify many power quality problems associated with a wind generators [17].

1.5 Scope of The Work

In this work, a variable speed wind energy conversion system is studied from the perspective of improving its interaction with the power system. Instead of following the paradigm of controlling the dynamics of the turbine to extract an optimal power from the wind, the concept of extracting a maximum power from the DFIG system will be explored. Toward the end, a control methodology will be developed that: achieves the regulation of system dynamics to provide requisite immunity to DFIG based WECS from various power quality problems

A direct current control of DFIG wind turbine system has been investigated for leveling of real power through rotor circuit and compensation of harmonic components, reactive power and unbalanced in current in stator circuit of DFIG based WECS. The detailed performance of back-to-back VSCs has demonstrated the capability of proposed control scheme to transact balanced current even amidst unbalanced condition at PCC, upf operation and supply of rated power by WECS from disturbances in power system and varying wind condition. It has also been observed that the proposed scheme has significantly improved the quality of power generated from the variable wind. The simulated result has been successfully validated the effectiveness of the proposed scheme for ensuring the sustenance of WECS against odd conditions on PCC and protect it from cascade tripping. The scheme is simple and easily implementable.

Research Objectives

The research work should achieve the following tasks:

- Analysis of stator and rotor active/reactive power allocation
- Overall converter rating minimization.
- Integration and control of energy storage system (ESS) into the DFIG converter system thus allows regulated output power under normal as well as fluctuating wind conditions.

- Investigate the steady state and dynamic operation of the DFIG based wind farm and role of controller to improve transient stability and power quality issues.
- To develop MATLAB simulation model of DFIG wind turbine system to validate the effectiveness of proposed work under various loading conditions.

1.6 Organization of thesis

This thesis is organized into six chapters. Chapter 1 introduces the details of the present wind energy scenario, introduction to several wind turbines for fixed speed and variable speed applications and also gives the introduction of the DFIG-based WECS and the motivation and organisation of the thesis. Chapter 2 provides a literature review for modelling and control of the DFIG-based WECS connected to power grid, steady and transient state reactive power control capability of the DFIG. Chapter 3 discuss about DFIG modelling and analysis in steady state as well as in dynamic conditions. Chapter 4 elaborates the proposed scheme for DFIG wind turbines as well as its advantages over various other control strategies. Chapter 5 discusses the effectiveness of the proposed control scheme under balanced as well as unbalanced load condition through a simulated MATLAB based results whereas, the conclusion and future scope of the proposed work is embodied in chapter 6.

CHAPTER 2

LITERATURE SURVEY

2.1 General

This chapter discusses the relevant literature review done to determine the scope of research work. Wind farm technology is undergoing through a drastic transformation over the last decade, utilizing the latest expertise in power electronics. However, the amount of energy extracted and converted from the wind by a DFIG based WECS depends strongly on how the turbine is controlled under fluctuating wind conditions. It involves survey and comparison of various approaches for the DFIG wind turbine system dynamics. In addition, a literature survey related to steady state analysis and reactive power handling capability of the DFIG system are also presented. It also describes the work carried out to offer dynamic voltage regulation in the DFIG wind turbine system using STATCOM under variable wind conditions. The interaction of the DFIG wind turbine system with the shunt compensated line is explored in details. Finally, work done on existing control methods for the stable operation of the DFIG based WECS under balanced as well as unbalanced condition on the feeder is also investigated through literature survey.

Several researchers have carried out work on DFIG-based wind turbines to demonstrate their possibility to provide separate active and reactive power control, making it the preferred choice for wind farm applications in comparison with the fixed-speed wind turbines wherein active and reactive power control is not independent. In this chapter, a modest attempt is made to review some of the pertinent research papers which emphasis on control and analysis of DFIG-based WECS and their role and contributions to a most effective system.

2.2 Survey of literature on control of WECS

With the increase in wind turbine size and power, its control system plays a major role to operate it in safe region and also to improve energy conversion efficiency and output power quality. Present day DFIG wind turbines systems mainly use the technology that was developed a decade ago [11]–[13] based on the *decoupled vector control* methodology. Several problems have also been reported recently on basis of various studies in different wind applications. In [14], it is examined through both theoretical and experimental studies that the conventional control strategies are sensitive and do not offer control over power quality issues. In [15]–[17], a control is discussed it is reported that wind farms perpetually experience unbalance and harmonic distortions when operating under variable wind speed with a non-linear load connected to it.

In [18] the DFIG control strategy has been discussed that enhances the standard speed and reactive power control with controllers that can compensate for various power quality problems caused by an unbalanced grid by balancing the stator currents and eliminating torque and reactive power pulsations.

Contents dealt in research paper [19] describe the DFIG voltage source controller to be controlled independently in positive and negative sequence. In order to implement the separated controllers for positive and negative sequence, two methods to segregate positive and negative sequence in real time are compared.

Similarly, in [20], a regulation of the reactive power control for a wind farm is examined. Weighted distribution strategy has been utilised in order to determine the reactive power reference for each wind generator. Thus, allowing compensation for various power quality issues.

In [21], [22], RSC control for compensation of DFIG torque pulsation under unbalanced voltage is investigated. The desired rotor compensating voltage is derived from the double-frequency oscillating terms of either torque pulsation or compensating currents. Thus it is required to tune the controller such that it can provide the required system response at double supply frequency. Similarly, in [23], a detailed investigation considering the affect of unbalanced stator voltages on the pulsations of DFIG stator and rotor currents, torque, and stator active and reactive powers is carried out. Various control schemes including minimising the stator and rotor currents unbalance, or stator active/reactive powers and torque oscillations have been proposed in literature []. However, it is not possible to achieve simultaneous elimination of both power and torque oscillations.

In [24], a direct torque control (DTC) method is introduced which controls the machine torque directly by selecting appropriate voltage vectors using the stator flux estimation. The stator flux is usually determined by integrating the stator voltages. However, the major problem associated with the basic DTC method is that its performance deteriorates during starting or low speed operation and this is primarily due to the fact that the method sets zero voltage vectors over and over again at low speed resulting in reduced flux owing to the stator resistance drop.

Thus, the above literature survey focuses on various control methods for DFIG based WECS. Several existing current/voltage control schemes are discussed in the subsequent section;

a) Decoupled d-q conventional vector control

The concept of decoupled d-q vector control is primarily employed for DFIG grid side converter [73], based on which an integrated control strategy is developed for wind energy extraction, reactive power and grid voltage support controls of the DFIG wind turbine system. In this control method, the d-q reference frame is oriented along the stator voltage vector. The voltage balance equation is thus defined as:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} \qquad \text{... (2.1)}$$

Fig. 2.1 shows the schematic of the GSC with a dc-link capacitor on the left and ac voltages on the right.

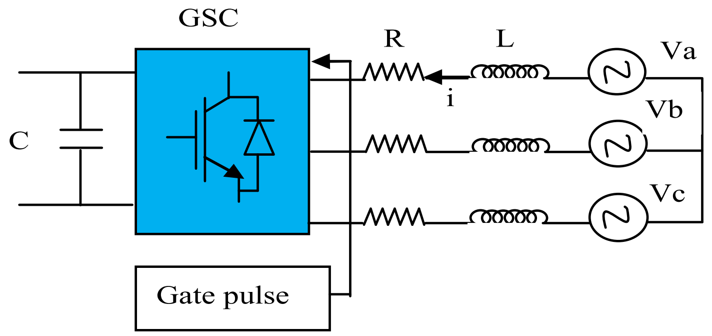

Fig. 2.1 Schematic of grid side converter for vector control method

Where L and R are the line inductance and resistance of the transformer or the grid filter. When transforming above equation to the d-q reference frame that has the same frequency as that of the grid voltage, it can be rewritten as eq. 4.2 where ω_s is the angular frequency of grid voltage.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_s L \begin{bmatrix} -i_d \\ i_q \end{bmatrix} + \begin{bmatrix} V_{d1} \\ V_{q1} \end{bmatrix} \qquad \text{... (2.2)}$$

On aligning the d-axis of the reference frame with the stator voltage vector, v_q is considered to be zero and since the amplitude of the voltage at stator terminal is assumed to be constant, v_d is also assumed constant. Therefore, the active and reactive power will be proportional to i_d and i_q respectively. This is the conventional foundation for the decoupled d-q controls by vector control method.

b) Direct current based vector control

Field oriented vector control has considered being one of the most popular control techniques used for DFIG-based wind turbines applications so far [70]–[72]. The basic theory of the direct current based vector control approach for the GSC is discussed in [50] and [51], which are based on d-axis and q-axis currents estimation for independent control of active and reactive power. But, unlike the conventional vector control approach that generates a d-axis or q-axis voltage vectors from a GSC current loop controller, the direct current vector control generates a current signal at d or q-axis control loop [75] thus offers easy control.

In this control method, the control loop is employed to achieve an independent/decoupled control over active and reactive powers of the machine. PI current controllers are then used in cascade with the control loop to regulate the output current within a specified range. The phase angle of the stator flux space vector is usually used for the controller synchronization [52]. However, the overall performance of the vector control scheme will be highly dependent on the accurate detection of the stator-flux position and thus can be a critical problem under distorted voltage condition or varying machine parameters. In [74], the virtual grid-flux-orientated frame (GFOF) has been introduced to address this problem. The overall algorithm for vector controlled GSC is such that it consists of d -axis current component for dc-link voltage control and q -axis loop for reactive power or grid voltage compensation. The error signal is then generated by comparing the measured value with the reference voltage to which the dc-link voltage is maintained [79]. The initial values of the PI current-loop controllers are tuned according to the fundamental intelligent control principle, i.e. minimizing the r.m.s. error between the reference and measured values [80].

But there are certain drawbacks associated with the above discussed control methods, which leads to the development of proposed control scheme based on direct current control technique.

2.3 Survey of Generators for WECS

The operation of the wind farm and its response to disturbances or other changing conditions on the power system has a very significant impact on system operation and performance in terms of the quality of power delivered. These concerns will continue to grow in importance as the amount of wind penetration increases.

Several wind energy generating systems have been proposed in the literature to supply power to either standalone or grid connected systems. As, WECS connected to utility grid experience numerous power quality problems; hence various control schemes have been proposed to address these power quality issues. Types of generating system and the way in which their conversion efficiency is limited during varying wind speeds, cut in and cut out speeds, generating systems types are classified as Squirrel cage induction generator, Doubly fed (wound rotor) induction generator, Direct drive synchronous generator and Doubly fed synchronous generators. The various generating systems are discussed in the subsequent sections;

2.3.1 Squirrel cage induction generators (SCIG)

Traditional wind generation units that consist of squirrel cage induction generators (SCIG) do not allow for reactive support, but on the contrary it acts as a variable reactive power consumer. To mitigate its reactive power demand, SCIG wind parks are typically equipped with external sources of reactive power, typically capacitor banks, SVC and STATCOM etc. Static sources like shunt capacitors are relatively inexpensive compared to dynamic resources such as SVCs [65]. Directly grid coupled squirrel cage induction generator is usually employed in wind farm application since it has low cost, simple and rugged construction. The slip, and hence the rotor speed of a squirrel cage induction generator varies with the amount of power generated. However, the variations in the rotor speed have to be very small, approximately ranging between 1 to 2 per cent [25]. Thus, this wind generator type is normally referred to as a constant speed or fixed speed generator. Also, because of the operation at constant speed, it has a problem that its output power and terminal voltage fluctuates due to wind speed fluctuations. Consequently, the active and reactive power variations can cause fluctuation in the voltage at the point of common coupling (PCC) [26]. Thus, large capacitor is required to improve the power factor by locally supplying reactive power to the generator. Therefore, power quality issues i.e voltage flicker etc are the major limiting factors for coupling wind turbine generator system into power grid, especially the wind turbines with fixed-speed induction generators [27]. Also, SCIG has a possibility of becoming unstable when voltage at PCC drops due to occurrence of fault in the power network. In such situations, rotor speed accelerates and consumes large amount of reactive power [28].

2.3.2 Permanent Magnet Synchronous Generator (PMSG)

Variable speed WTGS has recently become more popular than the fixed speed WTGS. Permanent magnet synchronous generator (PMSG) is a variable speed wind generator. In PMSG, the excitation is provided by permanent magnets placed on the rotor instead of using a DC excitation circuit [29]. These machines are characterized as having large air gaps which offers reduced flux linkages even in machines with multi magnetic poles [31], [35]. Hence, low rotational speed generators can be manufactured with relatively small sizes with respect to its power rating. Moreover, gearbox can be omitted due to low rotational speed in PMSG wind generators, resulting in low cost. Also, PMSG wind generator is coupled to the power system network through a fully controlled back-to-back power converter, equipped with generator side AC/DC converter, DC link capacitor, and grid side DC/AC inverter and the converter must be designed for the full rated power of the machine. The absence of mechanical components such as slip rings and brushes make the machine lighter, having a high power to weight ratio which means a higher efficiency and reliability [20].

2.3.3 Doubly Fed Synchronous Generator

Variable speed wind turbine equipped with power electronics converter has emerged as an alternative for SCIG based wind turbines as this can stabilize its output inspite of wind speed variations and offers effective control for reducing fluctuations in output power from the wind. Doubly fed synchronous generator is one of the expected systems for variable speed operation. It offers several advantages over induction generator; hence independent and rapid control of active and reactive power of DFSG can be carried out by secondary excitation control. Also, the converter involved for secondary excitation can be less than half of the rated capacity, and thus total cost reduces [36].

Under unbalanced condition, voltage drop can be recovered through the rapid injection of reactive power from DFSG to network thus, improving the transient stability of wind system. In [37], it is proposed that DFSG can not only recover the system voltage drop when unbalance occurs but also generates electric power as a wind energy conversion in steady state. Also, DFSG allows voltage regulation and thus it can generate constant power regardless of the wind fluctuations. Therefore, it is considered to be more effective than induction generator installed in a wind farm [38].

Though the stability analysis of synchronous generator has been done extensively in many literatures [29-34], but it is quite insufficient dealt when PM synchronous generator is used for wind power generation with full rating of power converter topology. In [35], the transient stability analysis of VSWT using field excited synchronous generator has been presented, where only unsymmetrical fault is considered as a network disturbance.

2.3.4 Doubly Fed Induction Generators

Among the wind turbine generators, the doubly fed induction generator (DFIG) is a popular wind turbine system due to its high energy efficiency, reduced mechanical stress on the wind turbine, separately controllable active and reactive power, and relatively low power rating of the connected converter. DFIG is projected as variable speed constant frequency wind generator capable of generating constant power output even with fluctuating wind speed by offering requisite reactive power control. DFIG is the recommended generator in the large size wind turbine, (WT) to achieve all the benefits of the VSCF systems [2], [8].

The stator of a DFIG is directly connected to the grid while the rotor winding is supplied through VSC. By varying frequency and magnitude of the rotor voltage the generated active and reactive power can be controlled independently. Active power control allows adapting rotor speed to the actual wind speed so that the maximum wind power utilization is achieved. The DFIG brings the advantage of utilizing the turns ratio of the machine, so the converter does not need to be rated for the machine’s full rated power [12]. The rotor side converter (RSC) usually provides active and reactive power control of the machine while the stator-side converter (SSC) keeps the voltage of the DC-link constant. However, the DFIG WTGS in domestic wind farm usually operates with constant power factor, and its fast and flexible reactive power regulation ability has not been fully used [15].

2.4 Conversion Systems

To disallow wind speed variations to impact the power system performance, an intermediate power electronic converter control can be used. Therefore, wind energy conversion systems generally can comprise of a wind turbine, an electric generator, power electronic converters or gearboxes and corresponding control systems. There are a number of wind turbine technologies, and they have different capabilities and effects with respect to the power systems issues like generation/load regulation, load following, voltage and frequency control. In light of such issues, wind turbine configurations and conversion systems are being more carefully examined to determine their potential and limitations [44], [45].

Initially, WECS were employed as constant speed turbines with induction machines and gearboxes connected directly to the grid [9]. It is the least flexible configuration, and has the greatest negative impact, sometimes necessitating the installation of compensating devices. Thus, conversion system including SCIG with SSC control to provide adequate dynamic reactive power support to the system under variable wind speeds [18]. The majority of large wind turbines being installed today are much more sophisticated, variable speed turbines with doubly fed induction generators (DFIGs). Such systems allow variable speed operation which is required to maximize energy capture at minimum cost [24]. They employ a back-to-back VSC to energize the rotor windings of the doubly-fed machine through a connection to the grid. Because of this, they also offer control of reactive power at the grid interface [13]. Another most flexible and efficient conversion system is one in which synchronous generator or induction generator in tandem with back to back VSC is coupled to grid. Where, one converter interfaces with the turbine generator while other interfaces with the grid.

2.4.1 SCIG directly coupled to grid

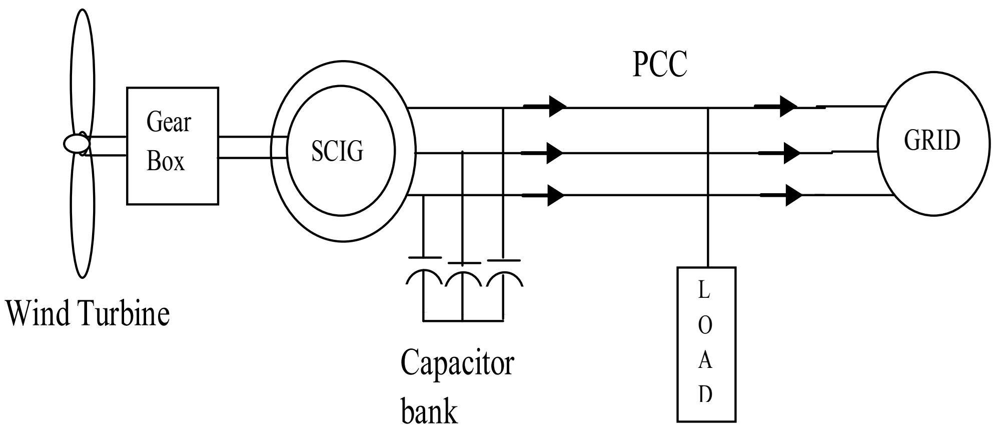

Fig.2.2 Block diagram representing directly coupled SCIG to the grid

Squirrel cage induction generator wind turbine when directly connected to grid for wind power generation is mainly employed for fixed speed operation. Such configurations are largely suited with steady wind conditions as they face various power quality problems when operated under fluctuating wind conditions [25]. As induction generators consume huge amount of reactive power in order to generate real power and with this conversion system large capacitors are required to be placed for locally compensating the reactive power demand of generators [8].

This makes the system bulky and more expensive. Also with variable wind speed, these fixed capacitors would not fulfil the dynamically varying reactive power demand, thus causing stability issues in the system [26]. Thus, the turbine speed cannot be adjusted to the wind speed to optimize the aerodynamic efficiency. Since the rotational speed of this type is limited to a very narrow range determined by the slip of the induction generator, any fluctuations in mechanical torque due to wind speed variation will impact the network where the wind farm is connected.

Although this type of wind turbine configuration has the advantage of being simple and relatively cost-efficient compared to other types of wind turbines, but the reactive power cannot be controlled, therefore any severe short-circuit near the wind farm may cause significant voltage dip in the weak network [27]. The configuration is referred in Fig 2.2.

2.4.2 SCIG with stator side converter (SSC) coupled to grid

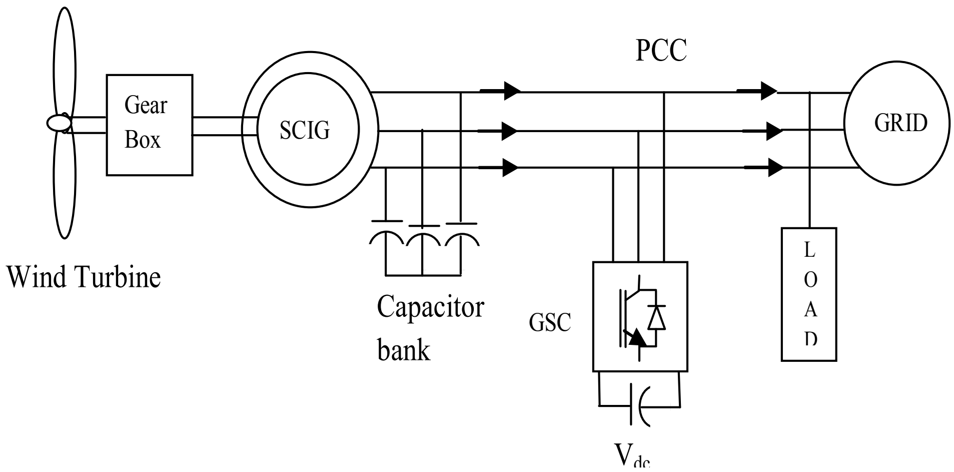

Fig. 2.3 Block diagram depicting STATCOM supported SCIG based WECS

When the wind generator is directly coupled, it is typically a squirrel cage induction machine because it does not need to be synchronized with the system. However, addition of reactive power sources is usually required since the generators consume

VArs under all modes of operation, and hence impact the voltage at the PCC, especially during transients.

This configuration involves SCIG along with the VSC converter connected in shunt at the stator terminals. In such configuration, SSC control is employed to provide requisite reactive power support to the system under fluctuating wind conditions without deteriorating the stability of the system [27]. This reduces the need for large capacitors. The configuration line diagram is presented in Fig 2.3.

2.4.3 PMSG/DFIG with back-to-back VSC converter coupled to grid

Variable speed systems equipped with converters reduce grid integration problems. This is partly because variable speed operation allows many fluctuations to be absorbed into the turbine as speed changes [30]. In addition to this partial buffering of power fluctuations, systems with power electronic converters can also regulate reactive power. The generator in this case can be doubly fed induction machine or a permanent magnet synchronous generator (PMSG). The block diagram of the configuration is depicted in Fig 2.4.

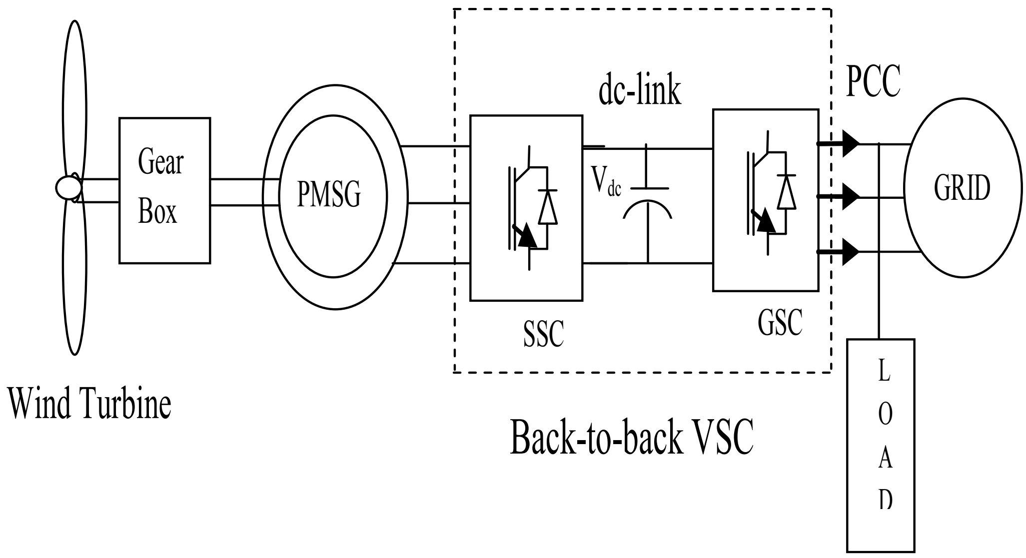

Fig. 2.4 Block diagram representing back-to-back PMSG based WECS

The advantages of PMSG over induction machines are the high efficiency and reliability, since there is no need of external excitation, smaller in size and easy to control [30]. Also PMSG has some disadvantages like higher cost and fixed excitation. The generator is connected through a full scale rated voltage source converter for energy conversion. Generator converter is used to control the torque and the speed and grid side converter used to control the power in order to keep the DC-link voltage constant. The two converters are connected by a DC link capacitor in order to have a separate control for each converter. Thereby the wind generator system emulates a synchronous machine at the PCC, with the exception that the output power is not completely controllable.

In [31], [32] detailed modelling and control of variable speed PMSG wind generator is discussed. But steady state and dynamic performances are not analyzed sufficiently. In [16], the transient characteristic of VSWT-PMSG is discussed for variable generator speed only under balanced condition on the feeder. In [34], the transient stability of VSWT-PMSG is analyzed when a network disturbance occurs in the power system and maximum power point tracking (MPPT) operation is discussed. The represented control strategy in [34] is suitable for the case of transient condition, where necessary reactive power is supplied depending on the grid terminal voltage when both symmetrical and unsymmetrical faults are considered as network disturbances.

2.4.4 DFIG with SSC and RSC coupled to grid

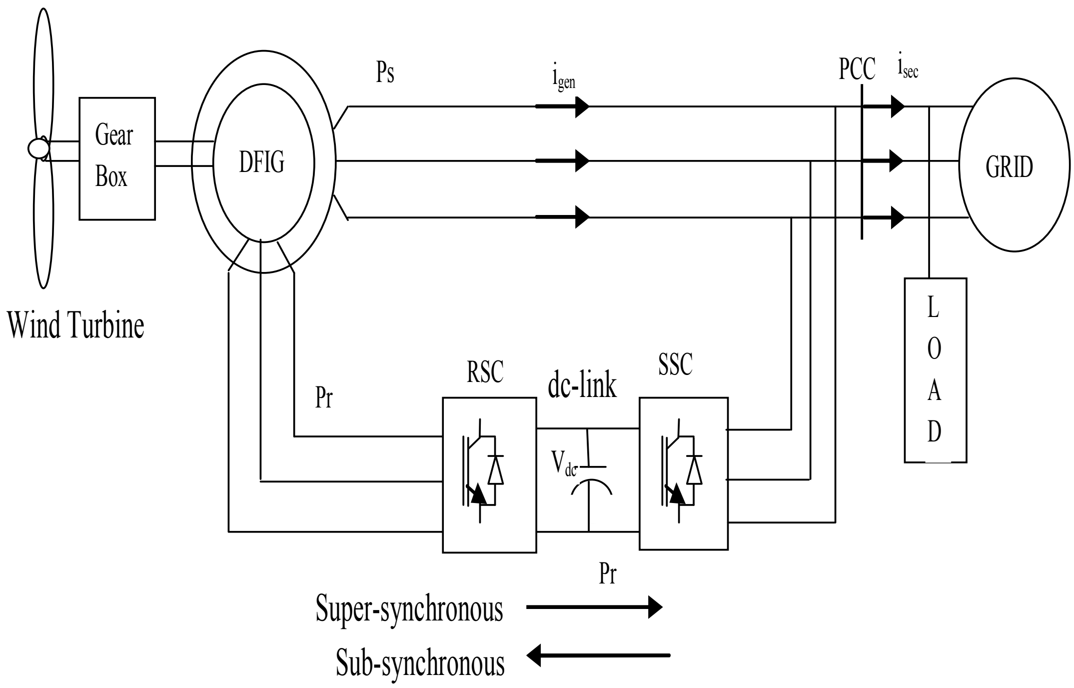

Fig.2.5 Block diagram representing DFIG based WECS

The response of wind turbines to grid disturbances is an important issue, especially since the rated power of wind-turbine installations steadily increases. Therefore, it is important for utilities to be able to study the effects of various voltage sags and, for instance, the corresponding wind turbine response.

This configuration presented in Fig 2.5 consists of a wind turbine with doubly fed induction generator. This means that the stator is directly connected to the grid while the rotor winding is connected via slip rings to a converter. This system has recently become very popular as generators for variable-speed wind turbines [49]. This is mainly due to the fact that the power electronic converter only has to handle a fraction (20–30%) of the total power [49], [5]. Therefore, the losses in the power electronic converter can be reduced, compared to a system where the converter has to handle the total power. In addition, the cost of the converter becomes lower. The stator circuit of the DFIG is connected to the grid side converter while the rotor circuit is connected to a RSC converter via slip rings. Between the two converters a dc-link capacitor is placed, as transient energy storage, to level the voltage variations (or ripple) on the dc-link. With the rotor-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the stator terminals, while the main objective for the grid-side converter is to keep the dc-link voltage constant. It has been reported that such configurations will be more common in the future.

Content dealt in [50] discusses a reactive power compensation control method which allows local compensation on the WG terminal and centralized compensation on the substation of wind farm using shunt capacitors, while the reactive power output capability of DFIG is not dealt extensively. In [51], the direct torque control (DTC) method is proposed that offers direct control over torque of the DFIG system by selecting appropriate voltage vectors using the stator flux position and torque information. But the performance of DTC scheme deteriorates during starting operation. The control scheme in paper [52], is in contrast with the conventional DFIG control method which mainly illustrates the direct current vector control, where GSC and RSC control is designed to extract maximum power from the wind, dc-link regulation, reactive power compensation, and PCC voltage support. But for high sag in PCC voltage, this scheme may not boost the voltage to the rated value. In [53], a technique to minimize the DFIG torque pulsations is presented under unbalanced grid voltage condition; hence sinusoidal current appears at stator terminal. The control scheme involved proportional integral and resonant (PI+R) controller based on space vector modulation. It offers independent control of torque and reactive power.

Table 2.1: Comparison of WECS configuration characteristics and costs

WECS configuration	Converter Rating	Var Control	Overall Cost
SCIG Directly coupled to WECS	No converter	Limited speed control using pitch angle	Inexpensive
DFIG based WECS	Converter rating is reduced to 20-30% of total rated power	GSC and RSC converter control	Low converter cost Machine is expensive
Back-to-back coupled PMSG	Full converter rating	SSC and GSC converter control	High converter cost machine is inexpensive

2.5 Problems Associated With WECS

The integration of WECS to a utility grid requires addressing of numerous power quality problems including real power levelling, reactive power compensation, unbalance in current and voltage, harmonic distortion, voltage sag/swell and stability issues. Several schemes have been proposed in the literature to investigate the methods of power quality improvement.

A. Harmonics-

Harmonics are redundant frequency elements which are integral multiple of the fundamental element. These are injected in the system due to switching of power electronics converter being non-linear in nature and operation with other non linear loads. The harmonic voltage and current should be limited to the acceptable level at the point of common coupling (PCC) where wind turbine is connected to the network. The harmonics when enters into the system distorts the voltage at PCC [5]. The rapid switching of VSC results in a large reduction in lower order harmonic current compared to the line commutated converter; hence high switching frequency is recommended in the literature. Usually THD of 5% is allowed up to 69kV systems as per IEEE-519 standards. The undesirable effects of the harmonics on WECS are as follows:

- De-rating of Machine
- Excessive heating / loss of insulation (life of Machine)
- Flux Distortions (voltage distortions)
- Saturation in Machine
- Lowers system power factor which could cause loading effect.

- Stability issues
- Resonance between Capacitors with coupling transformers.
- Protection coordination of WECS

B. Voltage Quality-

Voltage quality can be seen in terms of distortion and voltage variations. Voltage variations results due to the variable wind speed or generator torque. The voltage variation is directly related to real and reactive power variations which are generally in terms of:

- Under voltage / over voltages: Transient over voltage may occur in the wind farm feeders when the feeders are tripped and isolated from wind farm substation. [3], [12].
- Sag / Swell: Sag is short duration voltage dip due to a fault on a nearby power line leading to total system collapse. [8].
- Voltage dip is due to start up of wind turbine and it causes a sudden reduction of voltage. It is the relative % voltage change due to switching operation of wind turbine.
- Transients: The voltage flicker is caused due to dynamic variations in the network caused by wind turbine. The amplitude of voltage fluctuation depends upon grid strength, network impedance and *pf* of the wind turbines [15].
- Unbalance: A major cause for unbalanced network voltage is the uneven distribution of single-phase loads (commercial facility loads, single-phase electric traction systems, rural electric systems, etc.), causing mild unbalances, while larger short-term unbalances can be caused by power system faults. [3], [6], [9].

C. Reactive Power-

Doubly fed induction generators used in grid interfaced wind energy conversion systems are increasingly being called upon to address voltage regulation and provide adequate reactive power support due to the huge consumption of reactive power by asynchronous generators [61], [65]. The affect of reactive power compensation may be witnessed in:

- Power Flow Distribution: Affect the voltage stability and power flow distribution of the wind farm and local grid. [5]
- Causes voltage collapse in the system and under-voltage tripping.

- Sub Synchronous Resonance.

D. Power Fluctuations-

Due to variation of wind velocity the power input to the shaft varies. This variation in input power causes change in frequency of the generated voltage. The effect of such change is quite very predominant on WECS connected to weak grids and connectivity to the micro grids [71], [63]. Often intermittent gust of wind causes low frequency oscillations, which could not be levelled by pitch control of the blades. The grid coupling amidst power fluctuations may thus witness:

- Frequency Variation.
- Oscillations in power and torque

E. Unbalance Operation-

The unbalanced excitation of the WECS cause negative sequence operation, which in turn distorts the flux and cause unnecessary torsions on the shaft. This not only affects the efficiency of the WECS but further aggravate the problem by injection of unbalance voltage into the grid [1], [75]. When connected to weak grids or microgrid this may cause the cascading effect and leads to shutdown of the microgrid/ islanding of the WECS. Such unbalances in the voltage are caused by:

- Due to fault (Line to ground).
- One phase operation.
- Capacitor failure on one phase.

The location of the wind power plant also affects the quality of output power while integration into microgrid because different nodes have different capabilities of supporting reactive power and voltages, it may aggravate the severity of voltage fluctuation [5].

Also, SCIGs are susceptible to change in frequency with the electrical loading and harmonics whereas; DFIG is capable of having immunity to many power quality problems on the microgrid.

2.6 State of the art

The problem of this research is to understand and implement the control of a wind powered DFIG. The situation becomes more demanding when a WECS is required to produce constant voltage and constant frequency power in a weak grid or with unbalanced operations on the feeder at PCC. The control in grid connected mode is relatively much simpler in comparison with offgrid mode. Various solutions pertaining to problems associated with DFIG based WECS needs to be resolved which involves voltage as well as current control topologies for RSC and GSC controllers.

2.7 Research gaps/ Technical challenges

As the wind penetration increases, the manner in which it interacts with the power system becomes increasingly important. In majority of the cases, WTs are required to be taken off from the system for their own protection during odd conditions. Thus, in the absence of sophisticated controls, the PCC voltage may often fluctuate outside the acceptable operating range, and fast tripping of wind generators following under-voltages may lead to voltage collapse as discussed in literature. The fluctuations in output power from the wind results in a highly variable voltage at the PCC and therefore, reactive power control is required to regulate the system voltage profile. Also, the response of the system following faults in this case is also of great concern and is more dominant in case of weak system. The large value of source impedance results in significant fluctuations in the voltage at the PCC due to changes in power flows. Under the influence of unbalanced voltages/currents at stator terminal, the most DFIG may witness large power flow due to large voltage ripple on the dc link of back-to-back VSC, which may further decrease the lifetime of the dc capacitor also. Further any unbalance in the stator circuit distorts the magnetization of the machine and disturb the operation of generation with distorted generated voltages.

Many different solutions may be adopted to improve wind farm performance and there are, of course, trade-offs between cost and effectiveness of the defined solutions. For Wind farms connected to weak systems, the problem of wind farm operation with low system strength needs to be identified and properly evaluated.

The above stated challenges with existing current/voltage based control methodologies and need for the most effective solution has given motivation for this work. This led to the development of the control scheme which uses reduced number of sensors with easy implementation. The proposed work is based on *direct current control method* that has the capability to offer immunity to the DFIG system despite various power quality problems associated with the wind turbine system. It mainly contributes for dynamic reactive power compensation, negative sequence compensation and harmonic compensation under various operating condition with variety of loads connected at PCC. The proposed control also facilitates active power levelling at stator terminals under fluctuating wind conditions and maintains unity power factor at PCC in order to keep the magnetic circuit balanced and steady.

CHAPTER 3

DFIG WIND TURBINE SYSTEM CONFIGURATION AND MODELLING

3.1 General

To enable the study of DFIG based WECS in distributed power system, an appropriate system configuration is considered and discussed in this chapter along with the transient modelling of the DFIG based WECS and modelling of independent real and reactive power control. Reactive power sources for quenching the reactive power requirement of WECS are presented and a method for allocation of reactive power between the two converters (SSC and RSC) is also discussed. Lastly, the advantages and disadvantages of the DFIG based WECS is also discussed.

3.2 DFIG system configuration

The system configuration of proposed grid connected DFIG wind energy conversion system is shown in Fig. 3.1. The system mainly includes the DFIG which consists of two bi-directional back-to-back voltage source converters with a DC-link, a wound rotor induction machine, and number of wind turbines (WECS) connected in parallel forming a micro grid which in turn supplies a common load. WRIG controlled by low rating back-to-back converters, one of which is connected to the stator of the DFIG while other converter is coupled to the rotor circuit via slip-rings. VSC supported DFIG system is connected in a manner such that the SSC (stator side converter) is connected in shunt with the line through coupling inductor to compensate for the variable reactive power demand of generator.

The compensation through DFIG allows use of converters, with lower power rating as they deals only with fraction of total power delivered to the system. These converters typically employ IGBTs in their design and allow a wide range of variable speed operation of the DFIG. The variable rotor voltage assures variable speed operation of the generator and allows independent control of the generator’s active and reactive power. Thus, DFIG allows operation either in sub-synchronous or super-synchronous mode depending on the rotor voltage’s amplitude and phase. In sub-synchronous operation the converter tends to feed power into the rotor, while in super-synchronous operation the rotor power is fed via the converter back to the grid.

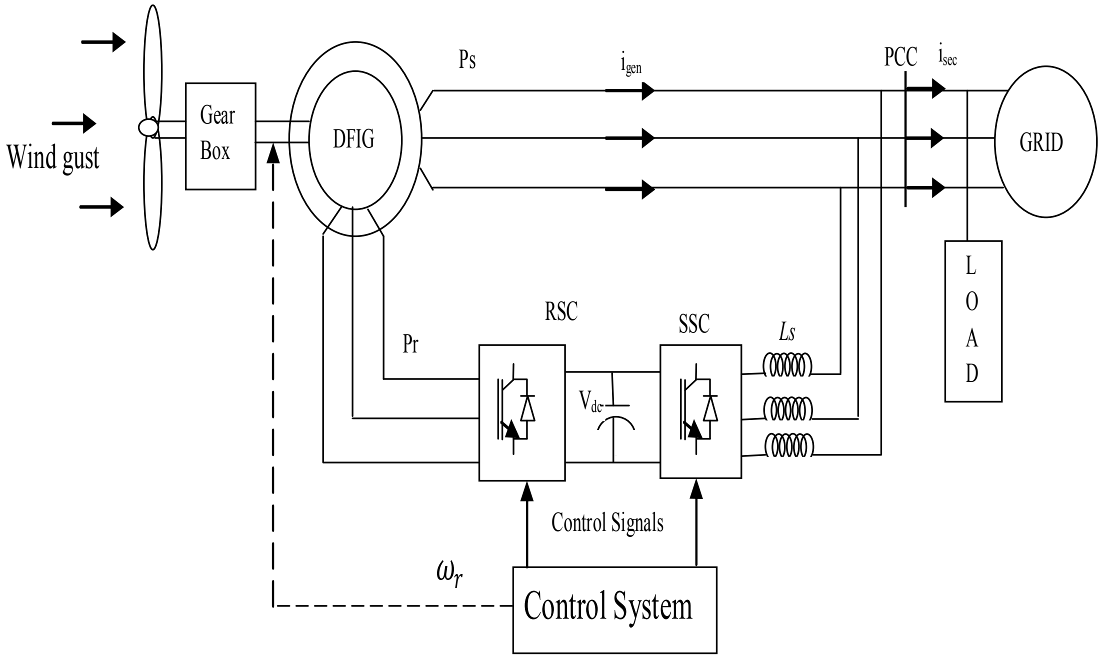

Fig.3.1 Doubly fed induction generator based WECS

Also, if the variation in operating speed is small, then less power has to be handled by the bi-directional power converter connected to the rotor. If the operating speed range is controlled between +/- 30 %, then the converter must have a rating of approximately 30 % of the total generated power. Thus the required converter rating is significantly smaller than the total output power, but it depends on the selected variable speed range and hence the slip power.

As the stator is connected directly to the PCC, any unbalance in feeder current will cause voltage distortion at PCC, which in turn will distort stator flux affecting the generation if not compensated by SSC. Hence, each WECS unit is independently controlled to transact only balanced upf current with the PCC.

The various units of the system (refer Fig. 3.1) are discussed in brief;

(i) Voltage source converter

A voltage source converter is a power electronic device which can generate sinusoidal output voltage with desired magnitude and frequency depending upon its switching control employed. Here, back-to-back VSC's are connected through a dc-link, such that the SSC injects current to compensate for the variable reactive power demand of s the DFIG while RSC allows active power levelling at stator terminal under varying wind conditions. It also mitigates other power quality problems associated with the system.

(ii) Interfacing inductor

An interfacing inductor is usually connected between VSC and PCC to facilitate active power flow between VSC and the system in order to maintain a constant voltage at Dc link by creating a voltage angle difference between the two. It also act as a 2^{nd} order L-C-L filter when coupled with the L-C filter connected with the VSC to mitigate the switching harmonics generated by the converter switching and to smooth the output voltage waveform.

(iii) L-C filter

The voltage ripples are present in the stator voltages primarily due to PWM switching of VSCs. So a low pass capacitor filter (LPF) is usually employed in order to curb the high frequency noise present in the voltages at PCC. The criterion for selection of filter parameters mainly depends upon the value of capacitor, such that a resonant frequency could be achieved in between the operating frequency and the switching frequency of the converter.

(iv) DC link capacitor

The capacitor connected at the DC-link of the back-to-back connected VSCs acts as a constant, ripple free DC voltage source and an energy storage device. Moreover, the DC-link provides requisite exchange of power and stabilization between both the AC systems. This capacitor could be charged by a battery source or by converter itself. And the capacitor is selected such that it is able to maintain a constant voltage which is approximately equal to the twice of the peak of the PCC voltage.

The minimum voltage level of the battery bank is decided by the line voltage of the grid and is given as []

$$V_{Dc} = \sqrt{\frac{2}{3}}\, V_{PCC} \qquad \text{... (3.1)}$$

Where, V_{pcc} is the line voltage on the grid side.

3.3 Control And Analysis

The DFIG stator is coupled to the grid with fixed grid frequency (*fs=50Hz*) at fixed grid voltage (*Vs*) to generate constant frequency AC power during all operating conditions and the rotor is connected to the variable frequency VSC having a frequency ($f_r = s\ .\ f_s$) which varies according to the slip. At constant frequency, the magnetic field produced in the stator rotates at constant angular velocity ($\omega s = 2\,\pi\, fs$), which is the synchronous speed of the machine. The stator rotating magnetic field in stator will induce a voltage between the rotor terminals. This induced rotor voltage produces a rotor current, which in turn produces a rotor magnetic field that rotates at variable angular velocity ($\omega r = 2 \pi fr$).

The control topology is employed such that the stator terminals are connected directly to the grid, the stator field is a function of the grid voltage, with a rotation based on the grid frequency and coinciding with the synchronous speed. The grid voltage can be assumed to be more or less constant during steady state operation, and therefore the stator flux can be considered constant. The rotor flux is dependent on the rotor current, which is controlled directly by the power converter. Therefore, the torque produced in the DFIG can be directly controlled by controlling the magnitude of rotor current and angular position relative to the stator flux [77]. The converters share a DC-link that allows bi-directional flow of power between the machine's rotor circuit and the grid since the converters are IGBT based. Since the DFIG is essentially a rotating transformer, the fundamental frequency of the current and the voltage in the rotor circuit changes with its speed [80]. The DC-link thus provides the decoupling between the two AC sides, which are at different frequencies. The LC filter mitigates the harmonics in the current, due to the switching converter, and provides the impedance over which energy can be transferred [6].

The control of the DFIG consists of two separate control algorithms, which together realize the overall operation of the system. Through appropriate modulation of the RSC and GSC, decoupled control of Ps and Qs is possible. The stator side control is responsible for regulating the dc bus voltage and to provide dynamically varying reactive power demand of the generator thereby facilitates the flow of rotor power either to or from the machine [48]. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. To achieve full control of grid current, the DC-link voltage must be maintained to a level higher than the amplitude of grid line-to-line voltage [3]. The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. Control of both the converters has been discussed in the next chapter.

a) GSC Control Theory

The power rating of the GSC is mainly determined by its reactive power control capability. Since it usually operates at a unity power factor, the losses in the converter are minimized [59]. The GSC is normally dedicated to controlling the DC-link voltage only. The converter can also be utilized to support reactive power demand of the generator and sometimes during a fault [60]. The grid-side converter can also be used to mitigate the power quality problems associated with the system [10].

The amount of energy stored in the dc-link capacitor can be written as:

$$E_c = \int P dt = \frac{1}{2} C V_{DC}^2 \qquad \text{... (3.2)}$$

Where P is the net power flow into the capacitor, C is the DC-link capacitor value and V_{DC} is the voltage across capacitor. P is equal to Pr - Pg, where Pr is the rotor power inflow and Pg is the grid power outflow.

GSC also facilitates a control scheme for compensating the effects due to unbalanced load condition. Here, compensation is achieved by regulating the negative sequence current supplied from the grid side voltage source converter. This drives the negative sequence currents in the DFIG stator to zero, thereby, eliminating the torque pulsations.

b) RSC Control Theory

In general, the power rating of the RSC is determined by maximum slip power. The rotor-side converter can be seen as a current controlled voltage source converter. The control objective of the RSC is to eliminate the rotor current harmonics and to offer active power levelling at stator of the DFIG. This can be achieved when converter is designed to supply an additional rotor voltage at slip frequency to the rotor terminals. This variable rotor voltage ensures variable speed operation of the DFIG and allows independent control of the generator’s active and reactive power. DFIG is made to operate in both sub-synchronous and super-synchronous mode depending on the rotor voltage’s amplitude and phase [5], [6]. Thus allows bi-directional power flow through RSC and GSC.

Advantages of DFIG wind energy conversion system:

- It can effectively control reactive power and active power independently through RSC and GSC.
- DFIG is wound rotor induction machine which has simple construction and cheaper than the synchronous machine.

- Converter rating is typically 25-30 % of total rated power which results in reduced converter cost, less harmonics injection to the connected grid which in turn improves overall operation of the WECS.
- In the case of a weak grid, where the voltage may fluctuate, the DFIG can produce or absorb adequate amount of reactive power to or from the grid within its capacity in order to maintain the voltage at PCC.
- It offers high energy conversion efficiency.
- Smaller power rated DFIG can be coupled with higher power rated wind turbine.

Disadvantages of DFIG wind energy conversion system:

- Inevitable need of slip rings and gear box requires frequent maintenance.
- It has limited reactive power capability.

3.4 DFIG based WECS Modelling

In this section, the overall DFIG system with its sub models is depicted in Fig. 3.2 and set of steady state and dynamic equations of the sub models are gathered and discussed in brief. This primarily includes modelling of wind turbine, DFIG and power electronics converter which are discussed in the subsequent sections;

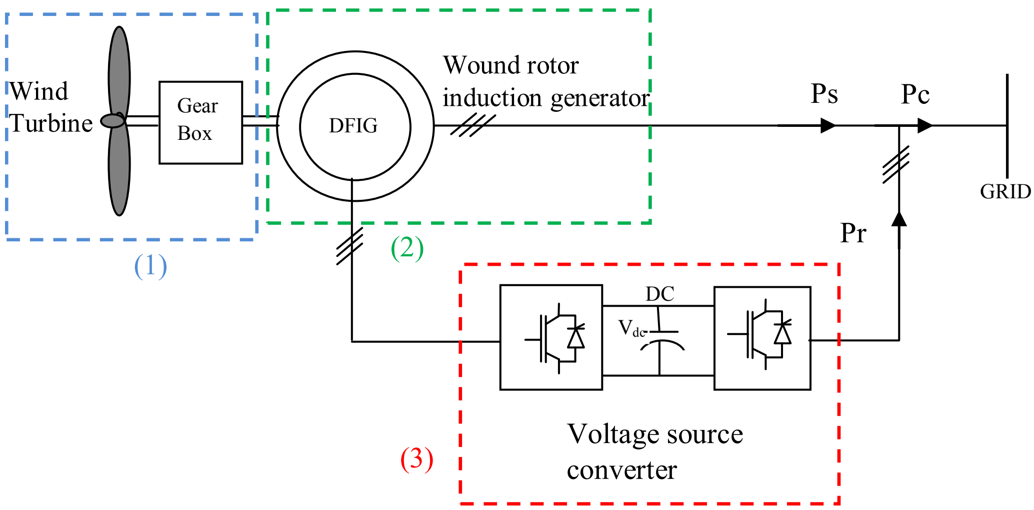

Fig. 3.2 DFIG based WECS with sub models represented as (1), (2) and (3).

3.4.1 Wind turbine modelling

The energy extracted from the wind varies with the cube of wind velocity, so a proper understanding of the wind power characteristics is essential to all aspects of viable wind energy generation [2-4]. The most important attribute of the wind is its randomness and this variability in its nature is mainly due to diverse climatic conditions across the world along with the lean of earth on its axis and its own rotation results in distinct wind distributions across the world. These variations need to be considered carefully because they can largely affect the extraction of energy from wind and may cause variations in the quality of power delivered. Generally more intense wind is witnessed on the tops of hills and mountains than in lower regions which give way to higher power production. Also, offshore wind is steadier and stronger than on land, and offshore farms have less visual impact. However, construction and maintenance costs are considerably higher [5].

Wind energy is considered as the kinetic energy of moving air, also called wind. Total wind energy flowing through an imaginary area *A* during the time *t* is:

$$E = \frac{1}{2} A t \rho {\omega_{wind}}^3 \quad \text{... (3.3)}$$

Where, ρ is the density of air (1.225 kg/rn3), *v* is the wind speed, A is the rotor swept area of the wind turbine [8]. Thus, the wind power characteristics can be expressed as;

$$P_{wind} = E/t \quad \text{... (3.4)}$$

$$P_{wind} = \frac{1}{2} A \rho {\omega_{wind}}^3 \quad \text{... (3.5)}$$

Also, $A = \pi R^2$

Where, R is the rotor radius.

$$P_{wind} = \frac{1}{2} \rho \pi R^2 {\omega_{wind}}^3 \quad \text{... (3.6)}$$

Also it is not feasible to extract all the kinetic energy from the available wind since this would mean that the air would stand still directly in the wake of the wind turbine which is practically not viable. This would not allow the wind gust to flow away from the wind turbine, and thus cannot signify a physical steady-state condition. The wind speed is only reduced by the wind turbine, which thus extracts a fraction of the total power in the wind. This fractional power is expressed as the coefficient of power, C_p of the wind turbine. Therefore the mechanical power output of the wind turbine P_{mech} considering the characterization of C_p can be stated as given by

$$C_P = \frac{P_{mech}}{P_{wind}} < 59.3\% \quad \text{... (3.7)}$$

$$P_{mech} = \frac{1}{2} \rho \pi R^2 {\omega_{wind}}^3 C_P \quad \text{... (3.8)}$$

Thus, the approximate maximum value of C_p is 0.59, which implies the maximum efficiency to be approx 59%.

C_p is a function of tip speed ratio and the blade pitch angle and is defined as;

$$C_P(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{C_5}{\lambda_i}} + C_6\lambda \quad \text{... (3.9)}$$

Where C_1 to C_6 are constant coefficients and λ_i is related to λ and β through the following relationship:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \quad \text{... (3.10)}$$

By knowing the value of λ, it is possible to determine the value of turbine speed that extracts maximum power as below:

$$\omega_t = \frac{\lambda.\omega_{wind}}{R} \quad \text{... (3.11)}$$

Thus, knowing the value of C_P, maximum mechanical power from the wind for a particular value of wind speed (ω_{wind}) and the corresponding value of the turbine speed can be obtained.

Also, in terms of practical wind turbine, the power captured by a DFIG is defined under four different operating conditions. Initially, when wind speed is below its cut-in speed, the power output of the generator is zero as the required driving torque is not available. 2) After crossing the cut-in speed, the turbine operates such that the DFIG may be allowed to control for maximum power extraction. 3) After rated wind speed, the turbine operates in the power control mode wherein the output power generated by the machine is maintained by external control. 4) Beyond cut-out wind speed, the turbine is shut down and no output power is generated (refer Fig. 3.3). Thus, the overall performance of the DFIG wind turbine depends not only on the wind gust but also on the generator employed and aerodynamic control systems which should effectively co-ordinate under variable wind conditions [9].

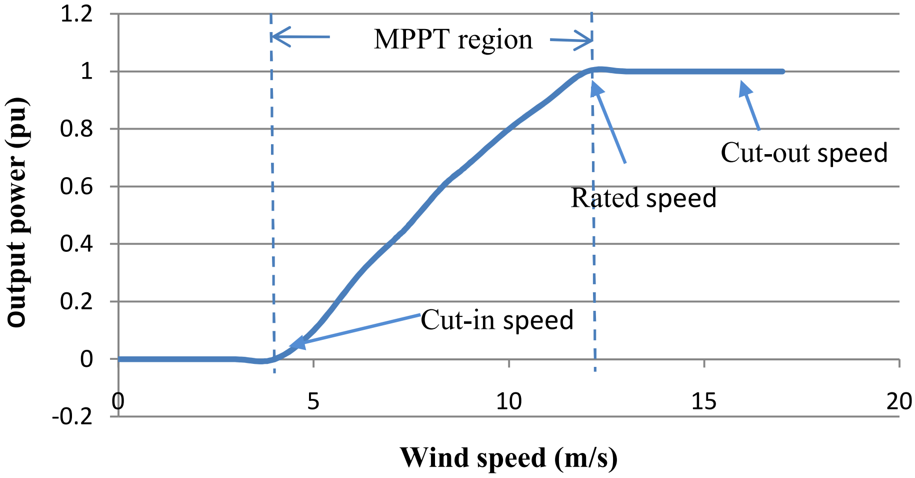

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Fig. 3.3 Operating regions of DFIG based wind turbine

Table 3.1 PARAMETERS OF WIND TURBINE MODEL CONSIDERED

Wind Turbine Model			
Inputs	Wind Speed	ω_{wind}	10m/sec
	Pitch angle	β	0 degree
	Generator speed	ω_r	(rad/sec) from IG
Data	Nominal mechanical output power	P_{nom}	33.3kW
	Base power of the electrical generator	S_b	50HP
	Base wind speed	ω_{wbase}	12m/s
	Maximum power at base wind speed		0.73
	Base rotational speed		1.2

3.4.2 Dynamic Modelling

The dynamic model of the doubly-fed induction generator is based on the dynamic equations of stator and rotor voltage expressed corresponding to the steady state voltage equations.

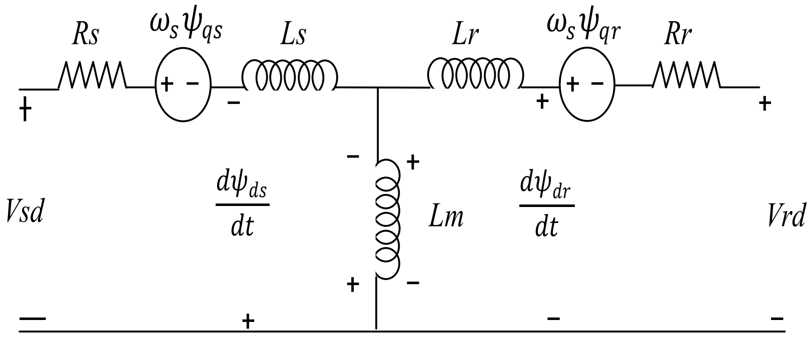


Fig.3.4 Equivalent *d* model for Doubly fed induction generator

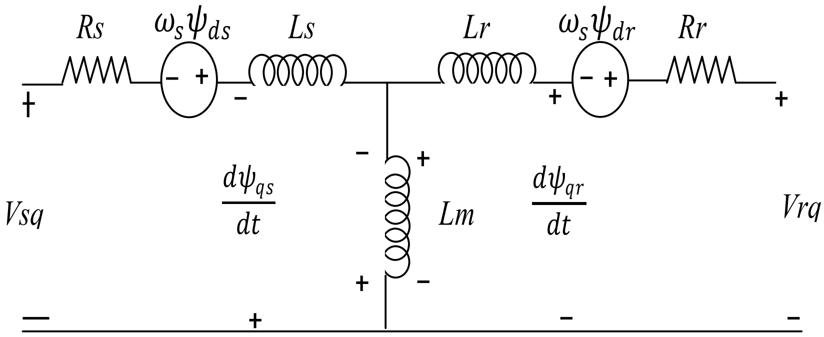


Fig.3.5 Equivalent *q* model doubly Fed Induction generator

Stator voltage equations

$$V_{ds} = R_s i_{ds} + \frac{d\psi_{ds}}{dt} - \omega_s\psi_{qs} \qquad ...\ (3.12)$$

$$V_{qs} = R_s i_{qs} + \frac{d\psi_{qs}}{dt} + \omega_s\psi_{ds} \qquad ...\ (3.13)$$

Rotor voltage

$$V_{dr} = R_r i_{dr} + \frac{d\psi_{dr}}{dt} - \omega_s\psi_{qr} \qquad ...\ (3.14)$$

$$V_{qr} = R_r i_{qr} + \frac{d\psi_{qr}}{dt} + \omega_s\psi_{dr} \qquad ...\ (3.15)$$

Stator and Rotor flux equations

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \qquad ...\ (3.16)$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \qquad ...\ (3.17)$$

$$\psi_{dr} = L_m i_{ds} + L_r i_{dr} \qquad ...\ (3.18)$$

$$\psi_{qr} = L_m i_{qs} + L_r i_{qr} \qquad ...\ (3.19)$$

Where V_{ds}, $V_{qs,}$ V_{dr} , are the d and q-axis stator and rotor voltages, respectively. I_{ds}, I_{qs}, $I_{dr,}$ I_{qr} are the d and q-axis stator and rotor currents, respectively. ψ_{ds}, ψ_{dr} ψ_{qs}, ψ_{qr} , are the q and d-axis stator and rotor fluxes, respectively. ω_s is the angular velocity of the synchronously rotating reference frame. is rotor angular velocity, and are the stator and rotor resistances, respectively [3]-[6]. Assuming negligible power losses in stator and rotor resistances, the active and reactive power outputs from stator and rotor side are given as:

$$P_S = \frac{3}{2}\left[V_{ds}I_{ds} + V_{qs}I_{qs}\right] \quad \text{... (3.20)}$$

$$Q_S = \frac{3}{2}\left[V_{qs}I_{ds} - V_{ds}I_{qs}\right] \quad \text{... (3.21)}$$

$$P_r = \frac{3}{2}\left[V_{dr}I_{dr} + V_{qr}I_{qr}\right] \quad \text{... (3.22)}$$

$$Q_r = \frac{3}{2}\left[V_{qr}I_{dr} - V_{dr}I_{qr}\right] \quad \text{... (3.23)}$$

The total active and reactive power generated by DFIG is:

$$P_{Total} = P_S + P_r \quad \text{... (3.24)}$$

$$Q_{Total} = Q_S + Q_r \quad \text{... (3.25)}$$

Also, the rotor speed dynamics of the DFIG is given as:

$$\frac{d}{dt}\omega_r = \frac{P}{2J}\left(T_m - T_e - K_f\omega_r\right) \quad \text{... (3.26)}$$

Where, P is the number of poles of the machine, K_f is friction coefficient, J is inertia of the rotor, Tm is the mechanical torque generated by wind turbine, and Te is the electromagnetic torque generated by the machine.

3.4.3 Axes Transformation

Reference Frame transformation is the transformation of coordinates, a three-phase *abc* stationery frame system to the *d-q* rotating frame system is known as *Park's Transformation* as shown in Fig. 3.5. It has the property to eliminate all time varyin6g inductances from the voltage equations of three-phase ac machines due to the rotor spinning. This transformation is significant because in $d - q$ reference frame the signal can effectively be controlled to achieve the desired reference signal. Initially three-phase stationery coordinates system to the two-phase $\alpha - \beta$ stationery coordinate system is carried out. If θ is the transformation angle, the transformation is defined by:

$$\begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta - 2\pi/3) & \cos(\theta + 2\pi/3) \\ \sin\theta & \sin(\theta - 2\pi/3) & \sin(\theta + 2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \ldots (3.27)$$

And the inverse transform is given by:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta - 2\pi/3) & \sin(\theta - 2\pi/3) & 1 \\ \cos(\theta + 2\pi/3) & \sin(\theta + 2\pi/3) & 1 \end{bmatrix} \begin{bmatrix} i_q \\ i_d \\ i_0 \end{bmatrix} \quad \ldots (3.28)$$

Phasor representation of the voltage/current vectors in space is defined by:

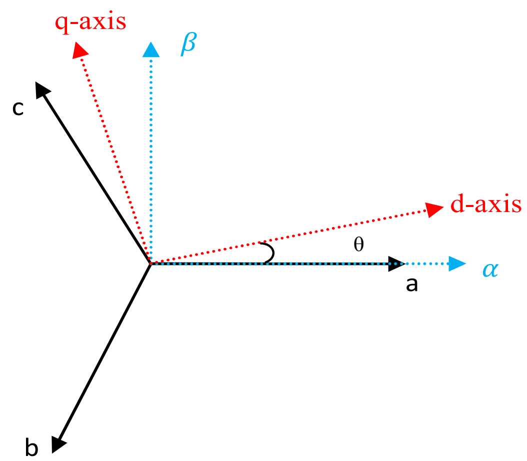


Fig.3.6 Reference frame transformation

In the synchronous reference frame, θ is a time variant angle that represents the angular position of the reference frame. The reference frame is rotating with a constant speed in synchronism with the 3-phase ac voltages. To implement SRF method, phase locked loop (PLL) is used for synchronising the system. The fundamental d-q current is a dc value which allows easier control of the proposed scheme.

3.5 Power Electronics Converter Control

The power electronic converters facilitate control over the generator operating characteristics such reactive power and speed, features which are lacking in squirrel cage induction machine. This allows for variable speed operation for peak power point tracking or generator output power regulation [55]. The frequency converter of a

DFIG system is connected to the rotor circuit of the generator. Since the converter has to guarantee a bi-directional power flow it must consist of active elements. The model uses an IGBT back-to-back voltage source converter as illustrated in Figure.

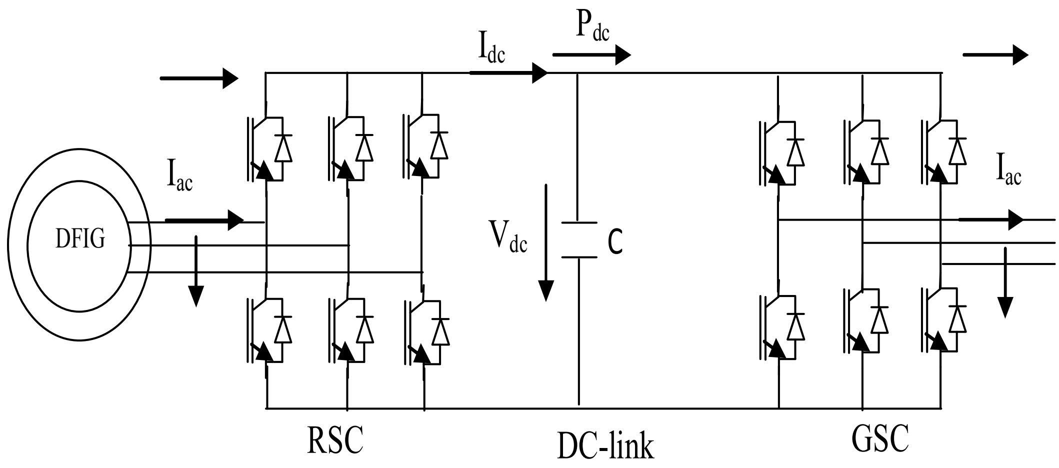


Fig.3.7 Block diagram of Back-to-back voltage source converter

The converters that are connected between the rotor and the stator of the machine are typically back-to-back VSC; however a matrix converter could be used alternatively. The advantages compared with the VSC connected machine is that the converter rating is reduced, since the rating is now based upon rotor voltages which are related to the speed range of the machine [52]. The rotor voltages are related to the stator voltages by:

$$V_r = sV_s \qquad \text{... (3.29)}$$

where s is the machine slip.

The converter rating is then defined by the maximum speed and the maximum stator current and voltage at that speed. If the upper speed limit is taken to be 1.2 of synchronous speed then the minimum converter rating will be 20% that of the machine's rating. However, for practical purposes a rating of 30-50% might be used taking into account transient operation and the ability to deliver reactive power from the stator. The larger the converter size, the more power can be transmitted via the converter and the larger the slip, which can be provided. However, a larger converter size means higher costs. Thus, there is a trade-off between financial benefits using a cheaper, smaller converter and the speed range, which can be provided. The switching of VSC may be carried out in either of the two ways: Pulse width modulation based control and hysteresis current control techniques [22].

3.5.1 PWM current control

The current control strategy for PWM-VSI system is one of the most important aspects of the modern power electronics converters. There are two main categories of current controllers: nonlinear controllers based on closed loop current type PWM, and linear controllers based on open loop voltage type PWM. Both categories of controllers utilize the inner current feedback loop.

In this control method, the three phase currents are decomposed into their direct axis (*d-axis)* and quadrature axis (*q-axis)* components. These components are compared with the reference signal to generate error signal, the error in the quantities is then passed through a proportional integral (PI) controller, whose output generates the d and q components of the modulating signals. Also, a feed-forward signal may be included which in some cases can improve the transient response [72]. AC and DC voltages results from PWM control are related by the following equations:

$$V_{AC} = K_o m_a V_{DC} \qquad \text{... (3.30)}$$

The modulation factor m_a should lay in the range 1 and -1 in order to avoid saturation effects. The factor K_o depends on the modulation method, this means it will vary for sinusoidal and rectangular PWM. However, sinusoidal modulation is dominant in power applications resulting in lower amount of harmonics produced. And the factor K_o in case of sinusoidal PWM is defined as:

$$K_o = \frac{\sqrt{3}}{2\sqrt{2}} \qquad \text{... (3.31)}$$

And if the power conversion through IGBT is considered loss-less, then it results in equal power at AC and DC side of the converter, which can be further expressed by the following equation:

$$P_{AC} = R_e\{V_{AC}.I_{AC}^*\} = V_{DC}I_{DC} = P_{DC} \qquad \text{... (3.32)}$$

Thus, the above equation can be solved in order to determine the converter currents. Thus, by implementing pulse width modulation technique, it is possible to control the VSCs in order to generate an output waveform with controlled voltage magnitude and phase angle and also reduces the lower order harmonics.

3.5.2 Hysteresis current control (HCC)

In the nonlinear controller, hysteresis current control (HCC) is commonly used for three-phase grid-connected VSI systems. The HCC compensates the current error and generates PWM signals with acceptable dynamic response while the current is controlled independently with a control delay resulting in a large current ripple with high total harmonic distortion (THD).

In HCC, a small hysteresis band is included to the reference signal. Further the gating signals are chosen based upon the required slope of the instantaneous line currents. This allows the current to remain within the specified band. The method includes certain drawbacks i.e unpredictable switching frequency which makes tuning of filtering components difficult and increased switch stresses, however, the control offers very precise and adequate results.

Moreover, the linear current controller based space vector PWM (SVPWM) is an adequate controller, which compensates the current error either by the proportional-integral (PI) regulator or predictive control algorithm while the compensation and PWM generation can be done separately. This controller yields an excellent steady-state response, low current ripple, and a high quality sinusoidal waveform. In addition, the SVPWM can help to improve the controller behaviour because it has favourable features such as constant switching frequency, optimum switching pattern and excellent DC-link voltage utilization. However, HCC based controller is used for modelling and simulation of proposed control.

3.6 Real and Reactive Power Capabilities Of DFIG WECS

A majority of the newly installed wind generation primarily consists of doubly fed induction generators (DFIG's). As more units start coming online, increasing levels of wind penetration has shown a widespread concern over its impact on wind farm performance. There are two main reasons for such a concern, the variability of wind and the type of the generator [58].

The precise modelling of DFIG is vital for both static and dynamic analysis of power system performance. Thus, accurate assessment to prevent voltage violations incorporates computation of adequate reactive power requirement in the system [71], [59]. Reactive power is essential for the stable operation of the system as it facilitates active power flow from generation sources to load [58]-[60] and maintains bus voltages within prescribed limits [61].

Now wind parks consisting of DFIG units have reactive power capability [63]. The presence of power electronic controls in DFIGs makes them a fast acting dynamic reactive resource as compared to direct grid connected synchronous generators used in conventional wind farm applications. This allows for voltage control and reactive power regulation of the wind park [59], [64].

Also, reactive power control is an important issue, particularly in DFIG supported WECS which are connected to weak grids. Voltage support capability is often required to maintain the ac voltage within the limits of operation and improve recovery following disturbances or faults in the system. The DFIG is one of the most suited wind generators which have the ability to at the very least compensate for the reactive power required by the induction machine. Various studies have shown that this and other wind generators capable of reactive power control can improve the stability of the system and its tolerance to disturbances [66], [67], [73].

The three limiting parameters for the reactive power capability of the DFIG are stator current, rotor current and rotor voltage [60]. The stator voltage is decided by the grid, and is not influenced by the wind turbine design. The stator current limit depends on the generator design, whereas the rotor voltage and rotor current limits depend on generator as well as power converter designs. The rotor voltage limitation is essential for the rotor speed interval, because the required rotor voltage to provide a certain field is directly proportional to the slip. Thus, the possible rotor speed is limited by the possible rotor voltage.

CHAPTER 4

PROPOSED CONTROL SCHEME FOR DFIG BASED WECS

4.1 General

This chapter presents a DFIG wind turbine control study using a direct current control technique. The chapter compares the proposed control scheme with the conventional standard DFIG control methods. This also shows under the direct-current control configuration, how the integrated SSC and RSC control is used to implement the maximum power extraction, dc-link regulation, reactive power, and grid voltage support control functions.

It has also been discussed in the previous section that the reactive power capability of wind generator is not enough to maintain required power factor at the PCC when the DFIG is operating at higher rotor speed (more than 1.1 pu). According to grid code requirement, WECS should be operating up to 0.9 lagging pf to enhance the stability of the connected power system. So to meet this requirement, we need extra reactive power source. Here shunt connected device is proposed as a dynamic reactive power source for the generator because of its many advantages compared to other reactive power sources while the series connected RSC controller allows real power levelling at stator of the DFIG thereby preventing the DFIG generator from deep saturation in case of variable output by the wind turbine.

Furthermore, because of the increased penetration level of wind farms in the power system certain grid codes have to be fulfilled for their adequate interconnection to the power network such that wind turbines remain connected to the network even during temporary disturbances in the system like voltage swelling and sagging, and sudden change in load. For this they must be able to provide adequate reactive power and adjust their control according to the necessity of the system. To meet this requirement, the DFIG based WECS should be able to respond fast by supplying or absorbing reactive power whenever there is a disturbance in the system. Hence, the added reactive power source should have good dynamic response. Thus depending upon the various control specifications involved, a control topology has been proposed and is discussed in this chapter.

4.2 Broad Control Specifications of the System

Various control specifications have been considered in the proposed control scheme in order to provide flexible control of DFIG based WECS under fluctuating wind speed conditions. The following are discussed here;

4.2.1 Generator Speed Control

DFIG allows operation in variable speed by modulating the stator real power, thus the control is capable of regulating the speed of the machine at desired slip. This can be explained by considering the following equation which describes the mechanical state variables of the system

$$J\frac{d\omega_m}{dt} = P_m - P_e \qquad \text{... (4.3)}$$

Here, it can be noted that if there is an imbalance between generated power (Pm) and the power output from the wind (i.e shaft power Pe) then the control employed should either accelerate or decelerate the generator speed in order to have rated power at the stator terminals which is seen as the balanced rated operation of the generator. Thus, allows power levelling at stator terminals of DFIG either by injecting or absorbing real power through RSC control.

4.2.2 Voltage Regulation

Due to increased penetration of WTs for electricity generation makes reactive control more challenging; due to the unpredictable nature of available wind. Voltage instability problems occur in a power system that cannot supply the adequate reactive power during disturbances like faults, heavy loading, and voltage swelling/sagging. In case of WECS the aerodynamic behaviour of the wind turbine and variable nature of wind also causes fluctuation in its output voltage. Thus, voltage regulation refers to the task of keeping bus voltages in the system within the tolerable bandwidth (normally 5% to 10%) in the system [61].

The fluctuations in the line voltage at the PCC depend on the active (P) and reactive power (Q) flow along the line. However, in cases where the *X/R* ratio has larger value, the terminal voltage can be controlled through adequate reactive power support at the PCC. Not only are the voltages at various locations affected, but also the power flow, power system dynamic, transient stability, and reliability of the system [60], [64].. Although, the DFIG-based wind turbines are able to control active and reactive power independently, though the reactive power capability of those generators is limited. This problem is more severe in the case of DFIG wind turbines connected to weak power grids having under voltage condition as the reactive power capability gets even more degraded. Hence an additional local reactive power source is needed [59].

4.2.3 Reactive power compensation

Stable operation of power systems requires the availability of sufficient reactive power support. Hence accurate assessment of the reactive power capability of wind turbines is very crucial to prevent the voltage violations in the system. A DFIG being the most dominant wind generator installed in current wind farms has significant impacts on the current power system stability and control.

Thus, dynamically varying reactive power support is required for DFIG to enhance the stability and reliability of the system [65]. In the proposed control grid side converter (GSC) is controlled to provide reactive power irrespective of the wind speed variations. This allows the provision for reactive power compensation, to improve the voltage profile during various load conditions. The GSC in this case, works similar to a STATCOM, with indirect regulation of the voltage at PCC. The action of the reactive power compensation is limited by the power capability of the converter [63].

4.2.4 Negative sequence compensation

Unbalanced conditions at stator terminal in DFIGs give rise to rotor current harmonics and torque pulsations which can cause excessive shaft stress and winding losses. Since it is the negative sequence current this will establish oppositely rotating magnetic field which in turn induce high frequency harmonics in the rotor current and electromagnetic torque that results in serious damage to DFIG wind turbine including overheating or high stress on mechanical or active components which then degrades the quality of power. Thus, another main objective of the SSC controller is to provide the immunity against negative sequence currents and allows balanced transaction of currents to the generator [22].

Table 4.1: Comparison of control specifications for several DFIG control topologies developed so far

Control topology	Reactive Var compensation	Negative sequence compensation	DC-link regulation	Real power control	Voltage regulation
Direct current vector control (field oriented control) [52]	By GSC	No	By GSC	By RSC	Allows upf operation at stator
Direct power control (DPC) [51]	By RSC	No	By GSC	By RSC	No
NEW direct torque control (DTC) by scalar control method) [53]	Through GSC	Yes	By GSC	RSC	Allows upf operation at stator
Constant power control (CPC) with super capacitor energy storage [79]	Through RSC	No	BY GSC	By RSC	No
Improved direct power control (space vector modulation) [80]	RSC	Yes	GSC	RSC	Yes

4.3 Proposed Control Scheme for DFIG Based WECS

This thesis aims at providing solutions to major problems associated with DFIG supported wind farm under unbalance condition on the feeder. A control strategy is proposed to prevent the system from cascade tripping due to unbalance in a single generating unit or occurrence of fault. The proposed control topology is based on the computation of reactive component of positive sequence fundamental component and negative sequence component in the current for realizing *direct control* of stator side converter (SSC) and controlling the rotor side converter (RSC) under current control for fast stabilizing the power fluctuations arising from fluctuation in wind power input[7],[5]. The considered system is depicted in Fig 4.1

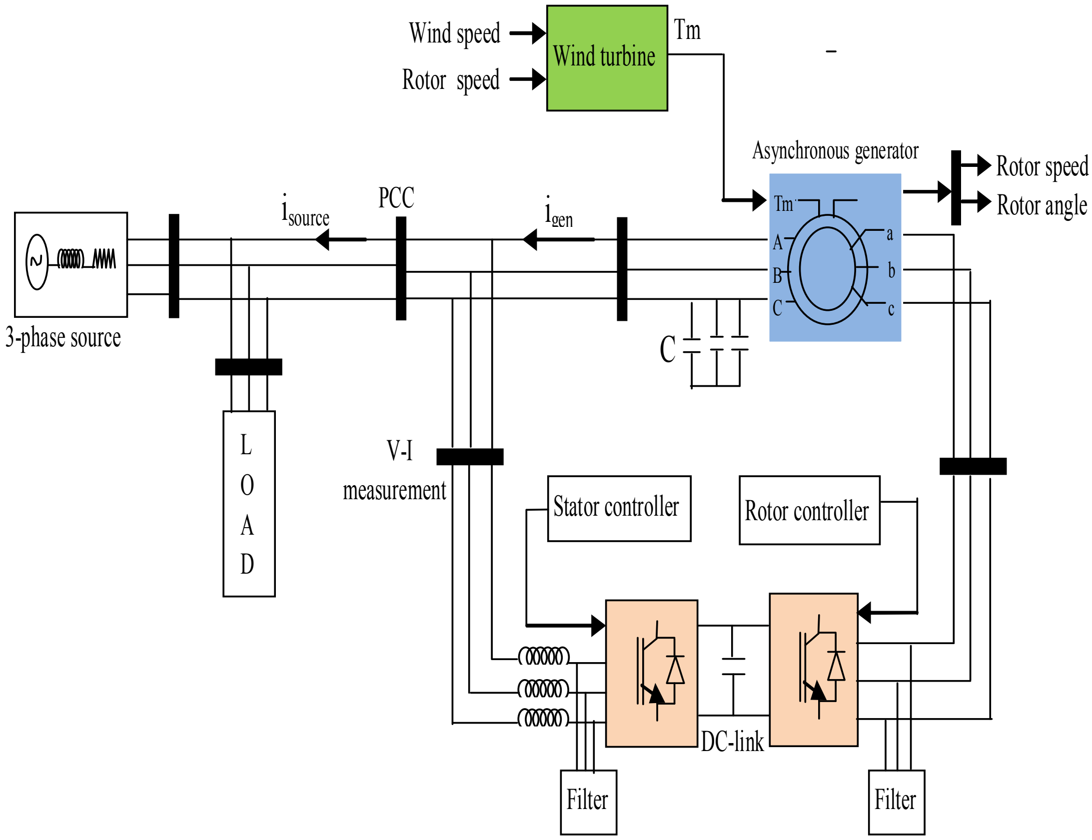


Fig.4.1 Block diagram representing overall DFIG wind turbine system considered.

For unbalanced conditions on the feeder it is required to and compensates for the negative sequence currents to keep the magnetic circuit balanced and steady. Under the influence of unbalanced voltages/currents at stator terminal, most DFIG's may witness large power due to large voltage ripple in the dc link of back-to-back VSC, which may decrease the lifetime of the dc capacitor also. Further any unbalance in the stator circuit distorts the magnetization of the DFIG and affect operation of generation with distorted generated voltages [1]. So it is vital to ensure balanced transaction of currents, by proper control over currents at PCC by stator side converter. It is necessary to point out that a fast current-loop controller is critical to assure the highest power quality in terms of harmonics and unbalance for the GSC.

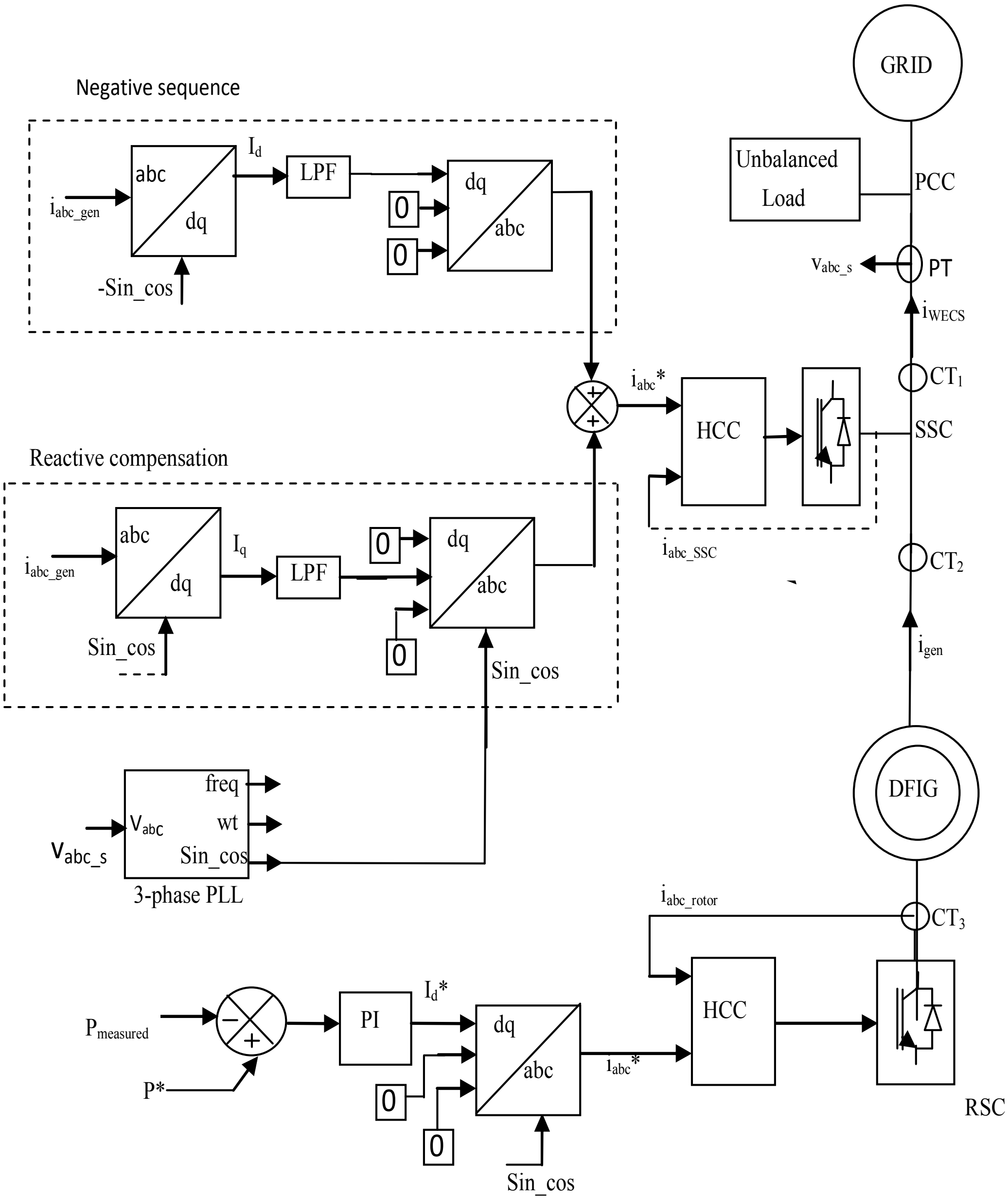


Fig. 4.2 Block diagram of overall proposed control scheme for grid connected DFIG WECS

The main aim of the proposed control scheme is to provide ***compensation for negative sequence, harmonics in current*** and ***variable reactive power demand*** during unbalanced conditions on the feeder as well as during normal operating conditions. A direct current control scheme employed to SSC for compensation of requisite problems [5],[12]. The control technique for SSC and RSC are described in Fig. for grid connected operations. It involves synchronous reference (dq) frame approach for estimation of various parameters. The proposed scheme operates such that RSC maintains requisite frequency at the stator terminals by levelling the power at rotor while SSC injects the desired current on the stator side to have purely balanced and undistorted currents transacted by the stator of the DFIG from the feeder, which ascertains the unity power factor operation at the connection point of DFIG with the PCC [11]. The detailed block diagram is depicted in Fig 4.2.

A) Proposed Stator Side Control

This scheme is designed to compensate for *negative sequence component* of current due to unbalance in current/voltage at PCC on feeder and provides either *voltage regulation* at PCC by requisite reactive power insertion at PCC or to have upf operation. It involves computation of reference converter currents to be injected into the system at fundamental frequency using Synchronous Reference Frame (SRF) theory. The stator side converter control involves generation of *d* and *q* current references using the dc voltage error and the reactive power references, followed by a hysteresis current control block for generation of the gating signals. Again a PLL is required for synchronization to the grid voltage and proper transformation to *dq* components.

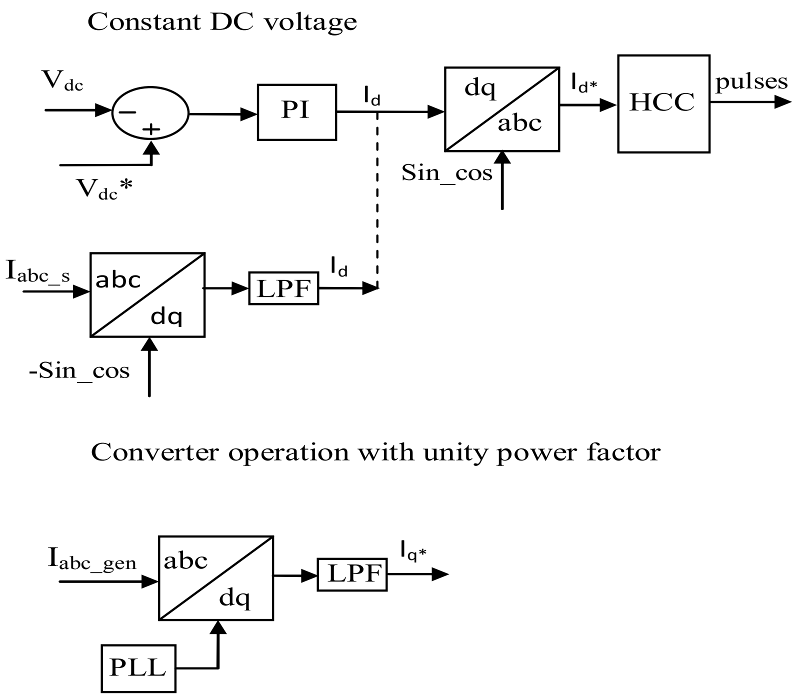


Fig.4.3 Control loops for stator Side converter control

In the Fig q-axis component provide the estimate of desired reactive power compensation to be provided in order to have upf operation of WECS at PCC. Whereas, the reference negative sequence component of current can be extracted by rotating synchronous reference frame in opposite direction pertaining to the sensed current. The compensation of such negative sequence currents prohibit any ill effect of unbalance at PCC entering into the generator terminal. The current control is achieved through hysteresis controller which in turn generates pulses to shape the current close to reference value. The injected current through coupling transformer provides adequate reactive power and negative sequence compensation.

B) Proposed Rotor Side Control

RSC is employed to provide active power leveling at rotor side to invoke grid frequency at stator terminals even under fluctuating wind condition avoiding stress on the magnetic circuits [5]. This can be achieved by injecting/absorbing real power into/out from the rotor circuit through RSC. The control philosophy of proposed scheme also utilizes SRF theory for extraction of real power component of current from rotor side at slip frequency [7],[12]. Here the rated power is compared with the measured instantaneous power at stator terminals. The generated error is then fed to PI Controller which estimates the reference rotor current as d-axis component responsible for power leveling at stator terminals. The reference current generated and the sensed value of instantaneous current are fed to hysteresis controller (HCC) to implement the requisite current control. Fig 4.4 present the block diagram of the proposed RSC control.

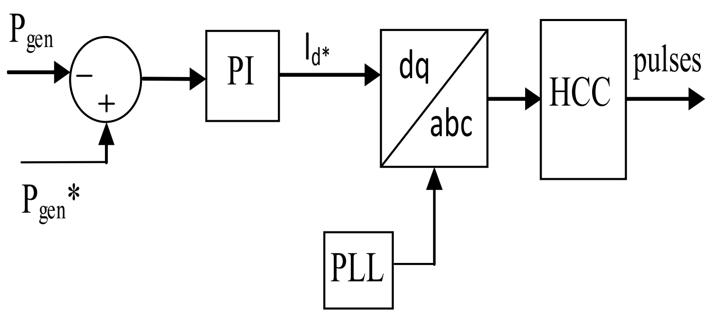


Fig.4.4 Control loop for rotor side converter controller

4.4 Conclusion

A dedicated control scheme of DFIG wind turbine system is designed. The control is realized by Direct Current Control technique using synchronous (dq) reference frame method. The proposed control allows coordinated control for power from the wind and generator speed. The overall control is subdivided into rotor side control and stator side converter control. The RSC controls the generator active power while SSC maintains constant DC-link and assures adequate support of dynamically varying reactive power to the generator under fluctuating wind condition. The control parameters for PI-controller (K_P and K_I) are optimized based on the desired simulation results. Comprehensive simulation studies demonstrate that the proposed DFIG wind turbine control structure can effectively accomplish the desired control objectives with superior performance under both steady and variable wind conditions within physical constraints of a DFIG system. The proposed control approach operates the system by regulating the RSC for stator power levelling and by controlling the GSC to stabilize the dc-link voltage and dynamic reactive power compensation as the main concern. But, for high PCC bus voltage or under sag conditions, it may be impossible to boost the PCC voltage to the rated voltage.

The control methodology also facilitates improvement of various power quality issues, like negative sequence and harmonic compensation which may be injected into the system when operating with highly non-linear loads. Nevertheless, it can be concluded that the proposed control offers immunity to DFIG based WECS under steady as well as dynamic conditions.

CHAPTER 5

PERFORMANCE ANALYSIS

5.1 MATLAB Implementation of DFIG based WECS

In this chapter, a DFIG wind turbine system is built in order to quantitatively investigate the several control capabilities of the DFIG based WECS. The considered system consists of a DFIG wind turbine which is connected to a weak grid represented by an AC voltage source with finite source impedance. A capacitor bank is connected at the stator terminal of the DFIG to filter the harmonics and stabilize the wind turbine terminal voltage by providing the requisite reactive power.

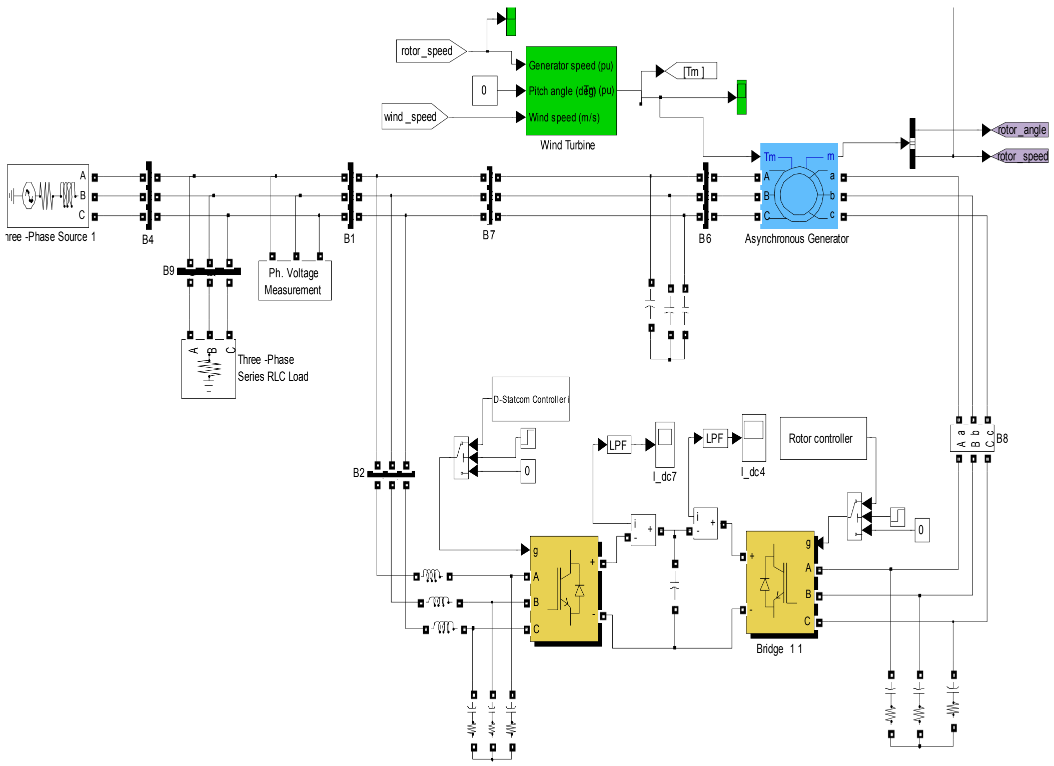


Fig. 5.1 MATLAB Simulation model of DFIG based WECS

The grid source, three phase load, LC filter, DFIG Model and control unit are modelled in MATLAB using Power System Block set. Fig. 5.1 depicts the MATLAB model of the DFIG based WECS for evaluating the performance of proposed scheme under different operational conditions on the feeder: *Balanced and unbalanced condition of voltage and currents*. The AC grid is presented as three-phase voltage source with finite line impedance and connected to the DFIG system with balanced/unbalanced static R-L load. The considered loads on the ac bus are star connected 15.8kW and 31.7kW resistive load. A PLL block is used to generate sine and cosine synchronizing signals. Assuming constant balanced source, DFIG operates under variable load condition by a varying resistor connected as load. Whereas, the unbalance is introduced by single phasing the resistive load at 0.3sec. The rated capacity of DFIG under consideration is 37kW at 400V/50Hz with the variable wind speed of 10m/sec with ±10% variations. DFIG based WECS incorporates SSC and RSC of approximately10kW rating, the switching frequency is kept at near 10kHz by digital processing of hysteresis current controller (HCC) and depending on the switching frequency of VSC, LC ripple filter is tuned to cut-off frequency of nearly 6kHz, with 4.2mH inductor and 1μF capacitor to filter out the switching ripples. The voltage across Dc-link is maintained at 700V through SSC to provide bi-directional power flow through RSC. The proportional integral (PI) controller is used in the proposed scheme which is coarsely tuned by Ziggler Nicholas method. As the system is highly nonlinear, fine tuning is done next by hit and trial method. Three CTs are deployed to estimate instantaneous values of currents at rotor and stator ends and a PT is deployed to estimate voltage at PCC. Table I depicts parameters of the considered system.

Voltage waveform across DC-link capacitor

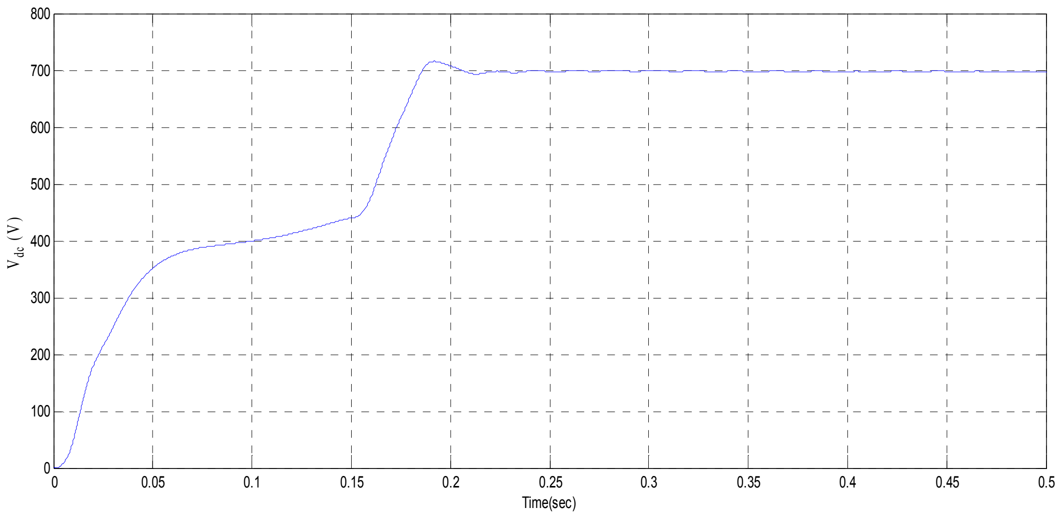


Fig. 5.2 waveform representing constant voltage of 700V across dc-link capacitor

Table 5.1 PARAMETERS OF DFIG SYSTEM CONSIDERED

DFIG SPECIFICATIONS	VALUE
Rated mechanical output	37 kW/50 HP
Rated stator voltage	400V
Rotor to stator turns ratio	1
Machine inertia	0.1234 pu
Inductance: mutual, stator, rotor	0.0526 pu
Resistance: stator, rotor	0.1904 & 0.01163 pu
Number of poles	4
Grid frequency	50Hz
Rotor speed	1500rpm
Maximum slip range	20-30%

Fig. 5.1 shows the results of the steady state analysis of the DFIG wind turbine system. The SSC controls the terminal voltage to exactly 1 p.u. despite of the active power output variation from 0 to 1 p.u. by supplying adequate amount of reactive power as discussed in this chapter. The power rating of SSC is not limited for the present simulation study, but in practice it has to be limited and would limit the control upto its capacity (30% of total wind turbine MVA) so that reactive power feeding capability requisite by wind turbine is catered.

5.2 Performance Evaluation

This chapter focus on the detailed analysis of DFIG wind generator under various operating conditions witnessed at the PCC under steady and varying wind conditions. The performance of 37kW grid connected DFIG system is studied under normal and balanced voltage level and unbalanced voltage conditions at PCC. The present control of the converter ensures balanced current transaction of DFIG with feeder at PCC having any conditions of voltage and upf operation of WECS under fluctuating wind conditions. The performance of the proposed scheme is evaluated under different sets of loading conditions: Balanced loading condition to evaluate upf operation of WECS under varying load levels, unbalanced loading together with voltage unbalance at PCC to verify balanced current transaction by DFIG with PCC.

A. *Performance of the DFIG WECS for unity power factor (upf) operation under balanced linear load.*

(i) Dynamics of current and voltages at stator terminal of DFIG

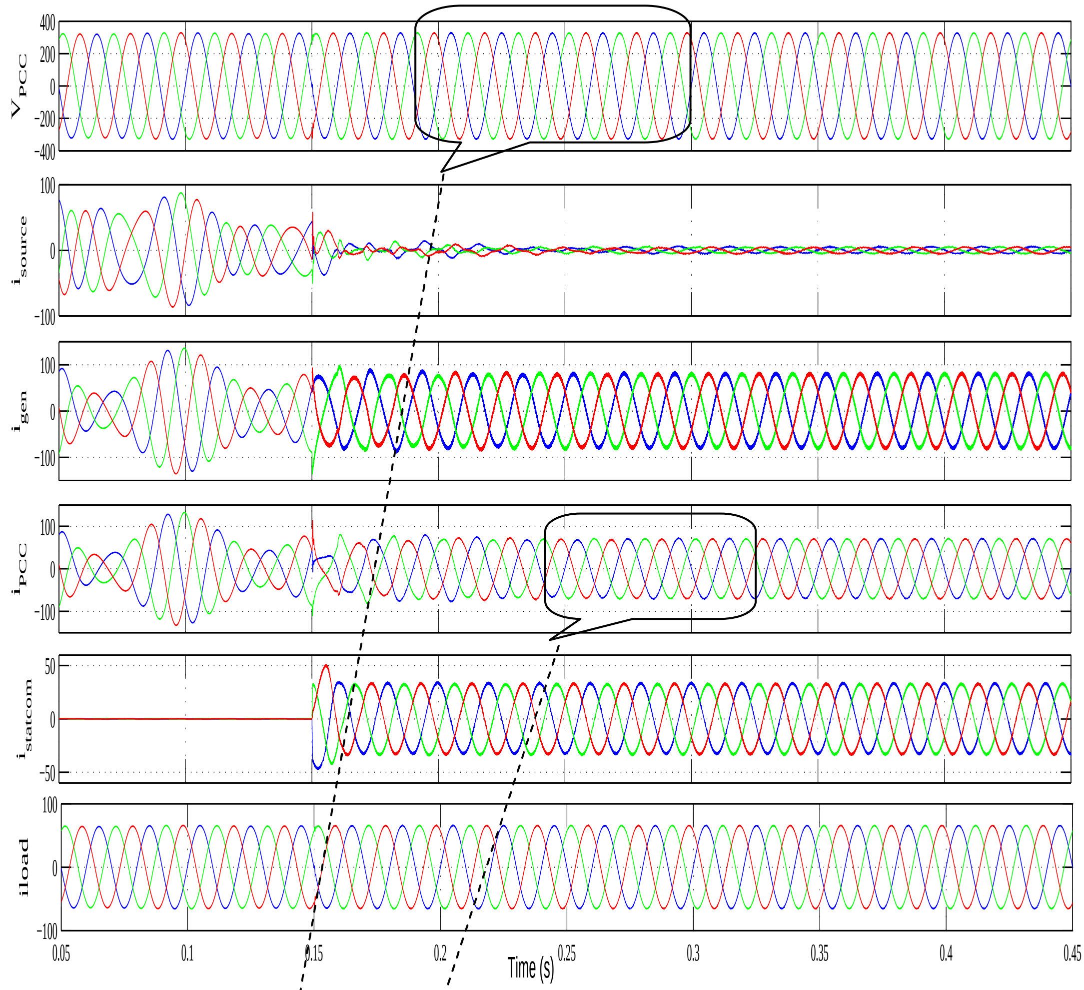
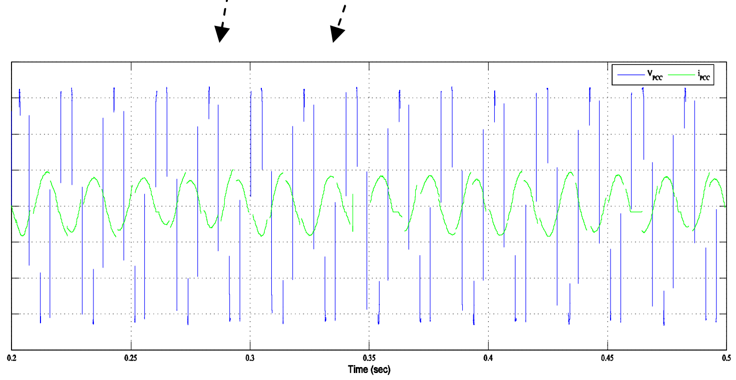


Fig. 5.3 Dynamic response of WECS transacting power at unity pf for balanced conditions when DFIG is supplying rated load.



Waveforms representing unity power factor operation at PCC

The point of observation may be referred from t=0.15sec when the SSC is switched into the circuit to act as STATCOM. The system is tested under balanced load conditions for validating the performance of DFIG wind energy system and its dynamics, supplying constant active power of 37kW, where19KVAr (i.e reactive power) is fed by SSC such that WECS supply only balance power to the grid (refer Fig. 5.3). The results in the Fig. 5.3 (a) demonstrates that voltage at PCC remain unperturbed maintaining approx 326V rms. The sooner SSC is switched in the DFIG supplies rated load of approx. 36kW drawing almost zero current from source (refer Fig. 5.3(b)). It may also be referred from Fig. 5.3(d) and Fig. 5.3(f) that exactly equal amount of current is transacted from DFIG fed through SSC. Whereas, Fig. 5.3(c) and Fig. 5.3(a) clearly show that requisite amount of reactive power is fed by SSC to keep DFIG in steady state operation.

(ii) Dynamics of the system when there is step change in the load connected to the system.

The performance of DFIG wind turbine system under load perturbations but balanced conditions at PCC can be examined from Fig. 5.4. To test the effectiveness and capability of WECS, load is considered lesser than the generation capacity (31.75kW), so that part of power is always pushed into the grid, demonstrating the capability of DFIG system under proposed control.

The result in Fig 5.4 clearly demonstrates that scheme is able to keep upf operation of DFIG based WECS even with varying loading conditions under balanced operating conditions when load is switched from low load (15.87kw) to high load (31.74kw) at t=0.3sec. Since the direction of voltage/current measurement is taken positive from grid source to load/WECS (Refer Fig. 5.4), the i_{WECS} which depicts the actual current emanating from the generator is shown negative (refer Fig 5.4(d)). Similar conditions exist for i_{source} (Fig 5.4(b)) which is also negative since the power is being pushed into the mains. It may also be observed from Fig 5.4(c) that i_{gen} is slightly leading representing consumption of equivalent reactive VAr by DFIG in order to keep the i_{WECS} in phase with the phase voltages at PCC. Whereas, in Fig 5.4(e) it is clear that current supplied by the SSC is in quadrature with the phase voltages at PCC representing supply of requisite reactive VAr are pushed into the system.

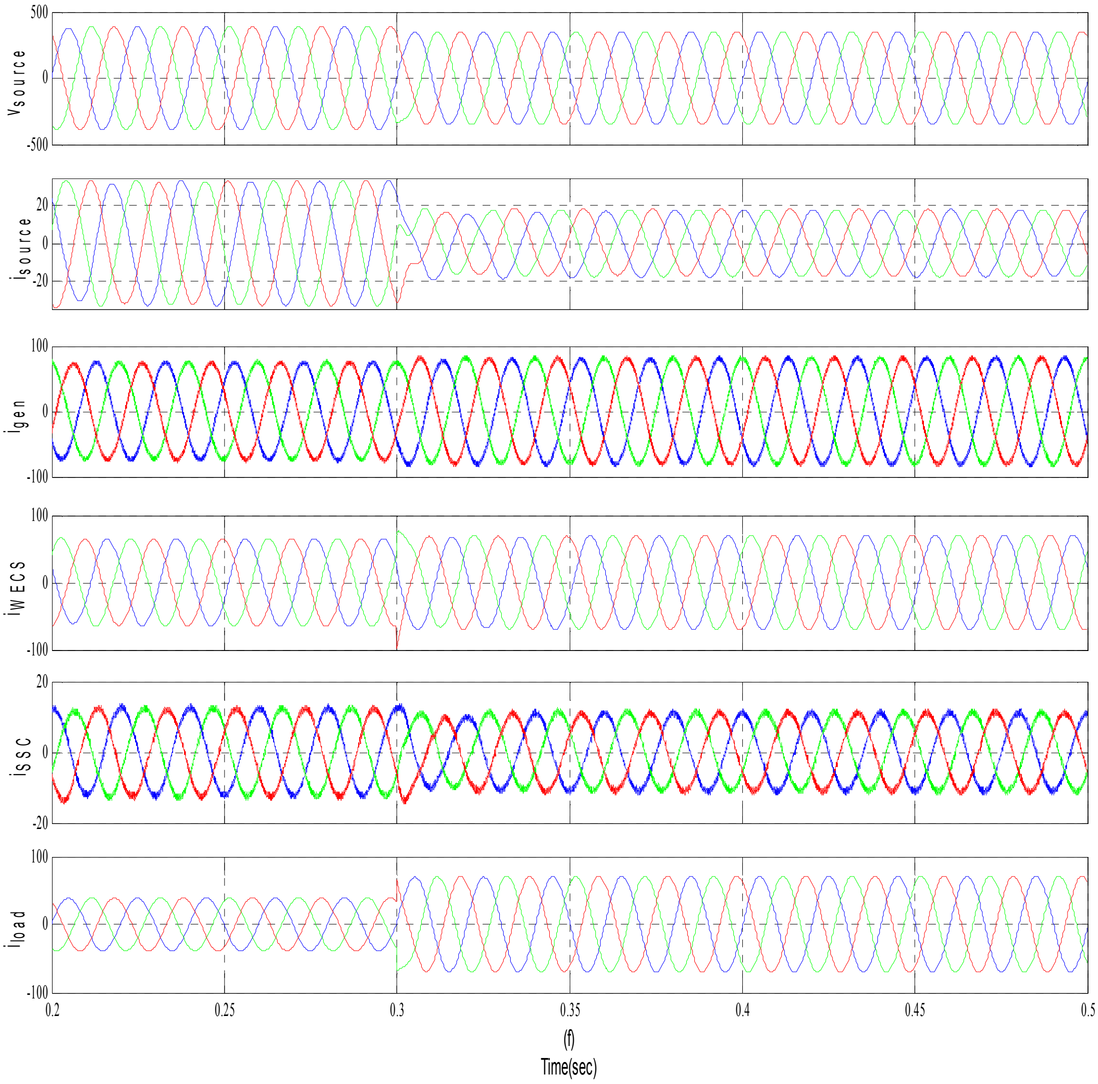


Fig. 5.4 Dynamic response of WECS transacting power at unity pf for balanced conditions on the feeder with varying loading condition when load is changed from 15.87kw to 31.74kw.

It can also be observed in the simulations results that even though there is a real power transition at t= 0.3s when balanced load connected to the system changes, there are no transients in the stator current and the quality of current is still maintained. Also the controller's response to the changing conditions has been very good as no significantly high overshoot is observed in the response. As the load is changed from 15.87kw to 31.74kw at 0.3 sec depicted in Fig 5.4(f), almost instantaneously current going to grid (i_{source}) is reduced from 24.75A to 14.14 A, and the transients is subsided within 1/10th of a cycle, and upf operation is sustained.

(iii) Dynamics of Rotor side converter

To ensure the stabilized performance of DFIG based WECS under fluctuating wind conditions. The considered system is tested under varying wind condition. Fig. 5.5

shows simulation result of the *rotor circuit dynamics* of DFIG system under variable wind condition. The transient response to per unit power from wind (P_{wind}), rotor speed (w_r), power transacted by RSC (P_{RSC}), total power generated (P_{gen}) and RSC current is observed to evaluate the performance of RSC for levelling of power generated by WECS. The simulated result demonstrates that control scheme is capable of balancing the power under fluctuating wind speed input.

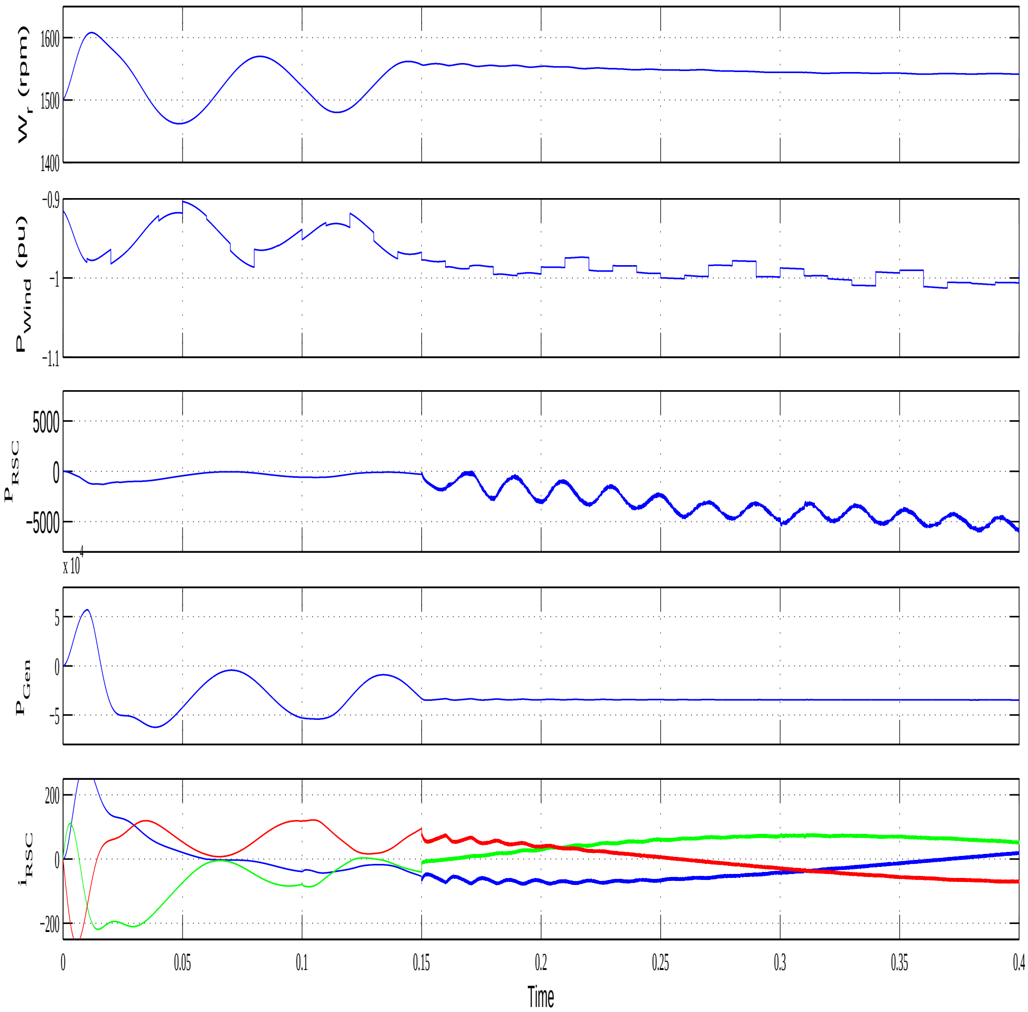


Fig. 5.5 Dynamic response of WECS on rotor side under varying wind conditions

In Fig. 5.5(a), it is clear that rotor is maintaining a constant speed of 1540rpm (refer Fig. 5.5(b)) even with variable shaft power shown in Fig 5.5(b). Fig 5.5(c) depicts the variable power which is being transacted by RSC in order to maintain constant power of output of approx. 36kw at generator terminals (refer Fig 5.5(e)).

(iv) *Active and reactive power at stator terminals*

It s to be noted that active power generated by DFIG wind system and reactive power supplied to it can be examined through Fig. 5.6. At t= 0.15 sec in Fig. 5.6(a) when RSC controller is switched, generator starts to maintain rated power i.e 36kW at its terminals even under fluctuating wind conditions by supplying/absorbing balance power to/from the rotor terminals while Fig. 5.6(b) demonstrates the requisite reactive power which is to be feed to DFIG in order to have stable operation. This action has been accomplished by stator side converter which dynamically fullfils the variable reactive power demand of the generator.

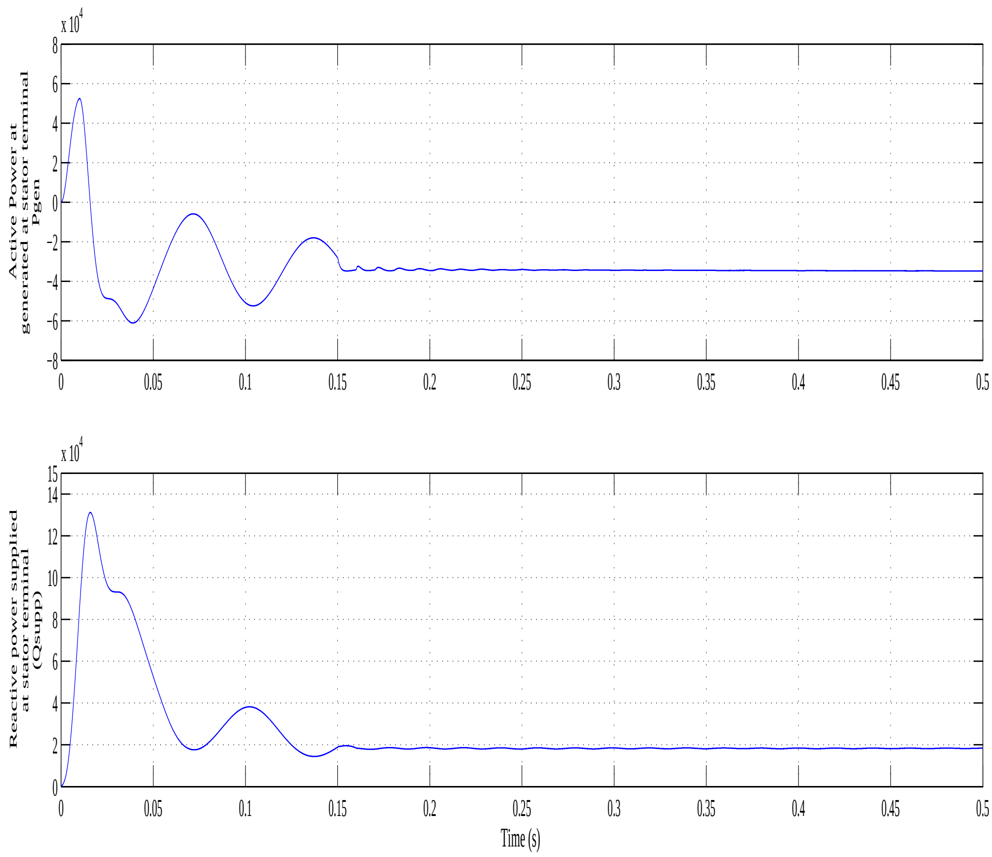


Fig. 5.6 Active and reactive power curves at stator terminal

B. Dynamics of system under Unbalanced load

To test the performance of DFIG system under unbalanced load condition, the system is subjected to unbalanced at t=0.3sec. It is observed that the control employed for SSC is capable of providing compensation against unbalanced in the load current by allowing balanced transaction of current to the generator.

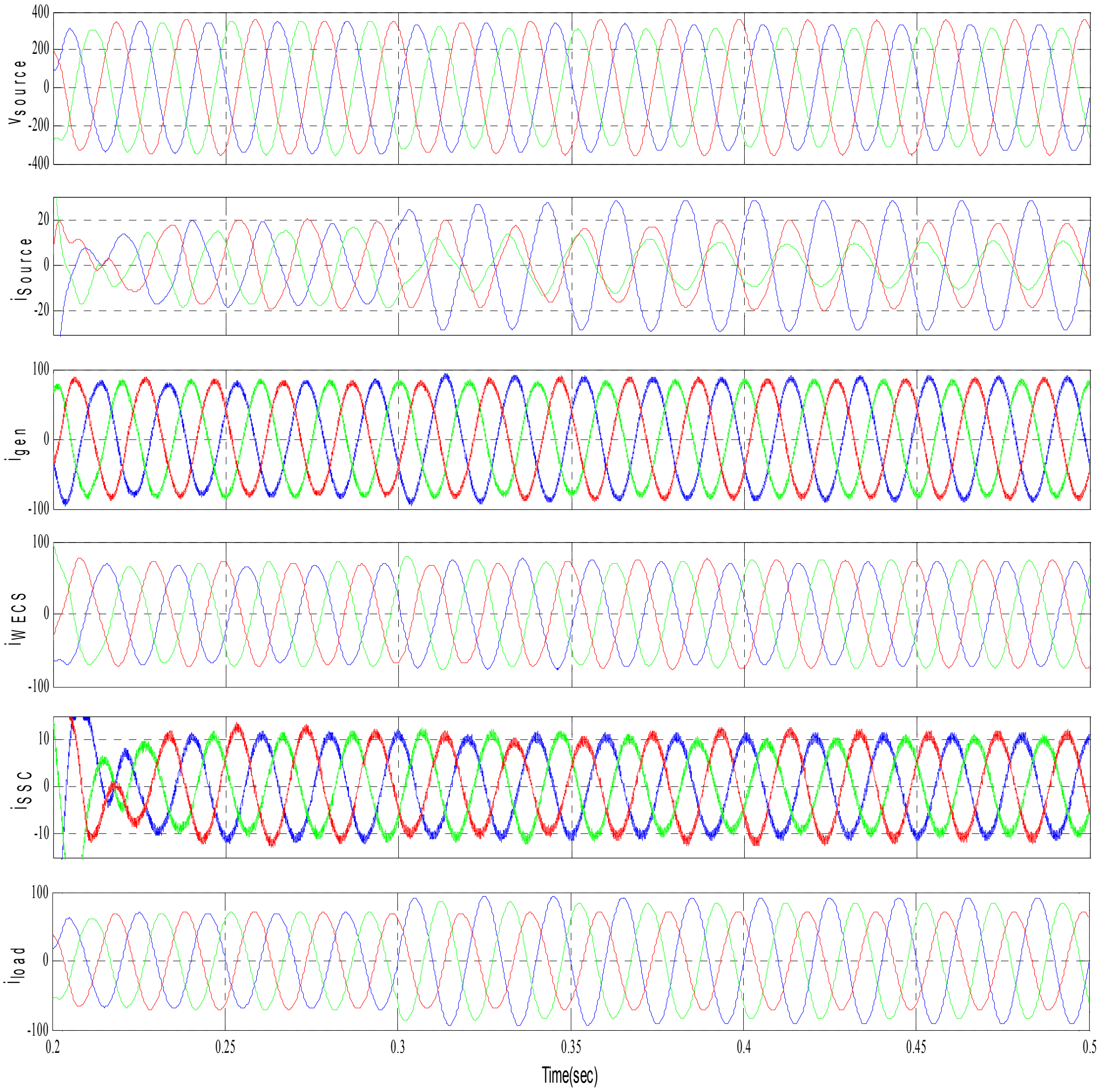


Fig. 5.7 Dynamic response of DFIG based WECS operating at upf for unbalanced conditions on the feeder.

Initially DFIG system is operating under balanced loading condition supplying a constant load of 15.87kW. To evaluate the performance of DFIG based WECS, the underlying system is subjected to highest degree of unbalance by opening a phase of one of the load terminals at t=0.3sec, which causes immediate distortion in voltages at PCC (refer Fig 5.7(a)) in turn the unbalanced voltages tries to induce negative sequence current in the WECS and connected source (refer Fig 5.7(b)). The negative sequence would cause higher heat losses and leads to saturation of generator which may often result in shut down of the system. The unbalance if allowed to pass through the DFIG would distorted the magnetising flux and in turn have produced more serious distortion at PCC and damage to the machine.

The simulation result shown in Fig. 5.7 demonstrates the effectiveness of control scheme to keep the balanced operation of DFIG system under the influence of unbalanced load. The result in Fig 5.7 demonstrates that proposed scheme is capable of providing immunity to the DFIG by sustaining balanced unity pf operation of WECS system even under unbalanced loading condition. It may be clearly seen from Fig. 5.7(c) that generator current is purely sinusoidal and generator is drawing requisite reactive VAr from SSC, thus maintaining i_{WECS} at upf which is in phase with the phase voltages at PCC as shown in Fig 5.7(d). It is observed from the Fig 5.7(e) that the current supplied by SSC is having negative sequence component and it is in quadrature with the phase voltages allowing reactive and negative sequence compensation at generator terminal. The unbalanced load when introduced at t = 0.3sec, the load demand is also changed from 15.87kW to 31.74kW (Fig 5.7(f)) which is met from generator.

C. Performance of system under balanced Non-linear Load

The dynamic behaviour of the DFIG based WECS when connected to non-linear load is depicted in Fig. 5.8. Initially DFIG system is operating under balanced loading condition supplying a constant load of approx. 15kW. To evaluate the performance of DFIG based WECS operates in the proposed control for harnessing immunity. The underlying system is switched to a diode rectifier type non-linear load through a circuit breaker, at t=0.3sec, which causes immediate injection of harmonic current into the system at PCC, causing distortion in voltages at PCC (refer Fig 5.8(a)). At this instant, the DFIG under influence of the proposed controller remains immunity amidst harmonics on the Ac bus. The controller immediately responds and protects DFIG from the onslaught. Thus, current at the generator terminal is purely balanced (refer Fig 5.8(c)).

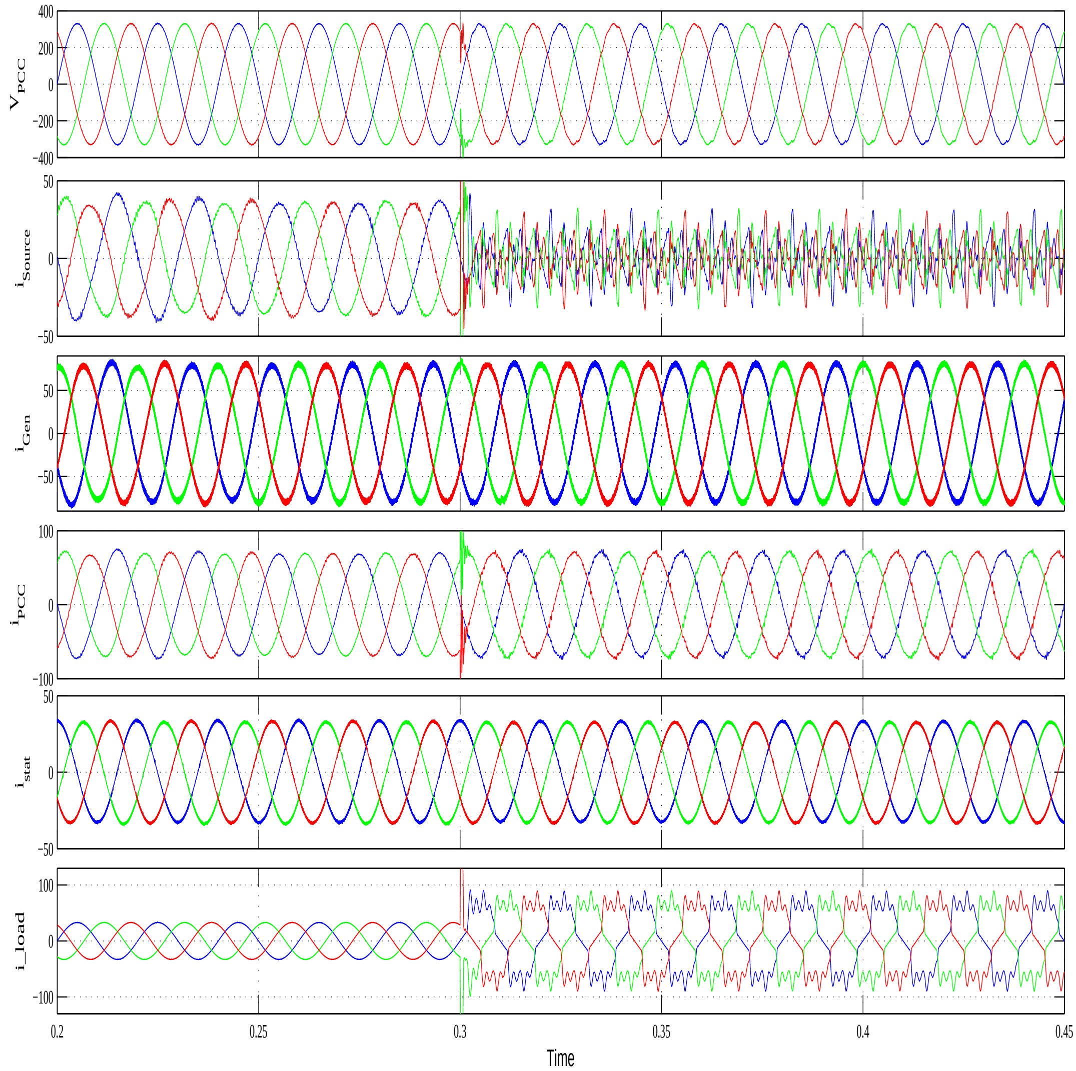


Fig. 5.8 Dynamic response of DFIG based WECS operating for balanced non-linear loading conditions on the feeder.

It may be observed from Fig. 5.8(b) that due to rated loading at t=0.3sec, only the harmonics are flowing towards the mains and does not affect the DFIG.

Thus, generator current and voltage (i_{gen} and V_{PCC}) remained immune and at initial conditions and THD is in compliance with IEEE 519 as depicted in Fig. 5.9.

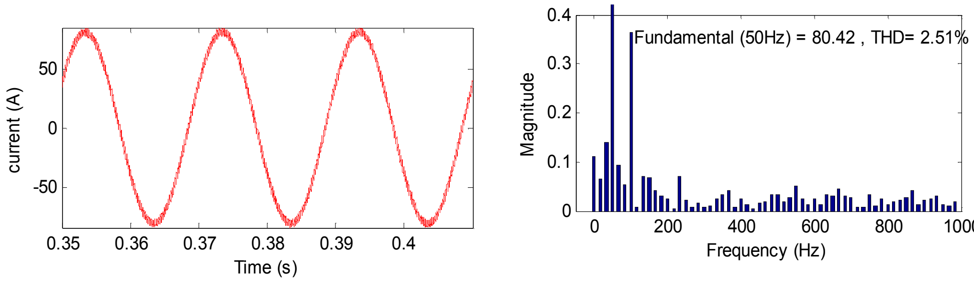


Fig.5.9 FFT analysis of generator current with balanced non-linear load connected to the DFIG system.

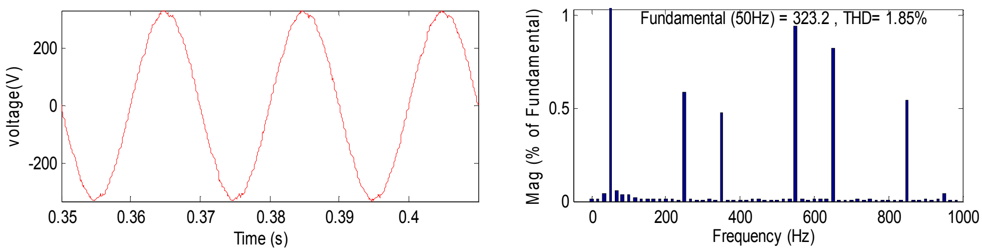


Fig.5.10 FFT analysis of PCC voltage with balanced non-linear load connected to the DFIG system.

The results in Fig.5.9 and in Fig. 5.10 demonstrate the FFT analysis depicting total harmonic distortion (THD) in current is 2.51% and in voltage is 1.85%. Thereby, allowing purely sinusoidal transaction of current at generator terminal even when diode rectifier type non-linear load is coupled to the system.

5.3 Conclusion:

The results presented in this chapter demonstrates the ability and effectiveness of the proposed control scheme to provide the immunity towards disturbances from the grid/micro grid side reflected at PCC, in addition to load dynamics and power quality issues possessed by the types of loads. The proposed control is simple, fast, and easily implementable with minimum number of sensors. The results also demonstrate that both RSC and SSC operate in cohesion with each other and contribute to steady and stable operation of DFIG.

CHAPTER 6
MAIN CONCLUSION AND FUTURE SCOPE OF WORK

6.1 Conclusion

The aim of the work are to develop dynamic simulation models of DFIG based variable speed wind turbines with the propose control scheme enabling the WECS to act as a stabilizing agent in the system to support for various control specifications as discussed in the previous chapter. The design and operation of the proposed control is justified by the manner in which active and reactive components are controlled for extracting rated power from the wind under different wind speeds and avoids the stresses on voltage and frequency of the system.

A proposed *direct current control* method has been investigated for leveling of real power at generator terminal and compensation of reactive power and unbalanced in current in stator circuit of DFIG based WECS. The observed performance of the DFIG wind turbine system has demonstrated the capability of proposed control scheme to transact balanced current even amidst unbalanced condition at PCC, upf operation and supply of rated power by WECS from disturbances in power system and varying wind condition. It has also been observed that the proposed scheme has a fast response. The simulated results has been successfully validated the effectiveness of the proposed scheme for SSC and RSC under different sets of condition i.e with balanced linear load, balanced non-linear load and unbalanced load which ensures the sustenance of WECS against odd conditions on PCC and thus prevent cascade tripping of generators, which is more dominant in weak systems. The scheme is simple and easily implementable.

6.2 Future scope of the proposed work

The economic and technical advantages of the DFIG based wind farms and the promise of wide applications in wind power have stimulated researches which require control scheme with minimum sensor, together with most effective and reliable solution suggesting the need for current based control that can provide absolute protection to the system under odd conditions.

The proposed work in this thesis has significantly enhanced the DFIG system performance under balanced as well as unbalanced conditions on the feeder but there is still a deep research scope exist which may lead to the most efficient way out that could provide high degree of immunity to the system. The proposed control scheme could be modified in a way that allows indirect control of generator current which allows purely sinusoidal transaction of current under odd conditions. Thus, number of current/voltage sensors utilised could be significantly reduced resulting in a cost-effective solution. Further, hardware implementation of the proposed work will lead to more precise view of the problems incurred in the system and their respective solutions.

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