

ACTIVE FILTERING CAPABILITY FOR WECS WITH DOUBLY FED INDUCTION GENERATOR BY USING GSC

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I. ABSTRACT

This paper deals with the operation of Doubly Fed Induction Generator (DFIG) with an integrated active filter capabilities using Grid Side Converter (GSC). The main contribution of this work lies in the control of GSC for supplying harmonics in addition to its slip power transfer. The Rotor Side Converter (RSC) is used for attaining maximum power extraction and to supply required reactive power to DFIG. This Wind Energy Conversion System (WECS) works as a Static Compensator (STATCOM) for supplying harmonics even when the wind turbine is in shut down condition. Control algorithms of both GSC and RSC are presented in detail. Proposed DFIG based WECS is simulated using MATLAB / Simulink. A prototype of a proposed DFIG based WECS is developed using a DSP (Digital Signal Processor). Simulated results are validated with test results of the developed DFIG for different practical conditions such as variable wind speed and unbalanced/single phase loads.

Keywords: DFIG, WECS, Nonlinear load, Integrated Active Filter, Power Quality.

II. INTRODUCTION

With the increase in population and industrialization, the energy demand has increased significantly. However, the conventional energy sources such as coal, oil and gas are limited in nature. Now there is a need for renewable energy sources for the future energy demand [1]. The other main advantages of this renewable source are eco-friendliness and unlimited in nature [2]. Due to the technical advancements, the cost of the wind power produced is comparable with that of conventional power plants. So the wind energy is the most preferred out of all renewable energy sources [3]. In the initial days, wind turbines have been used as fixed speed wind turbines with squirrel cage induction generator and capacitor banks. Most of the wind turbines are fixed speed because of their simplicity and low cost [4]. By observing wind turbine characteristics, one can clearly identify that for extracting maximum power, the machine should run at varying rotor speeds at different wind speeds.

By using modern power electronic converters, the machine is able to run at adjustable

speeds [5]. So these variable speed wind turbines are able to improve the wind energy production [6]. Out of all variable speed wind turbines, Doubly Fed Induction Generators (DFIGs) are preferred because of their low cost [7]. The other advantages of this DFIG are the higher energy output, lower converter rating and better utilization of generators [8]. These DFIGs also provide good damping performance for the weak grid [9]. Independent control of active and reactive power is achieved by the decoupled vector control algorithm presented in [10-11]. This vector control of such system is usually realized in synchronously rotating reference frame oriented in either voltage axis or flux axis. In this work, the control of Rotor Side Converter (RSC) is implemented in voltage oriented reference frame.

Grid code requirements for the grid connection and operation of wind farms are discussed in [12]. Response of DFIG based WECS to grid disturbance is compared with the fixed speed WECS in [13]. As the wind penetration in the grid becoming significant, the use of variable speed WECS for supplementary jobs such as power smoothening and harmonic mitigation are compulsory in addition to its power generation. This power smoothening is achieved by including super magnetic energy storage systems is proposed in [14].

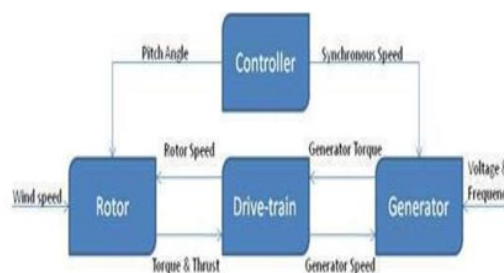


Figure: 2.1.wind energy conversion

The other auxiliary services such as reactive power requirement and transient stability limit are achieved by including Static Compensator (STATCOM) in [15]. A DSTATCOM (Distribution Static Compensator) coupled with fly-wheel energy storage system is used at the wind farm for mitigating harmonics and frequency disturbances [16]. However, the authors have used two more extra converters for this purpose. A super

capacitor energy storage system at the DC link of unified power quality conditioner (UPQC) is proposed in [17] for improving power quality and reliability. In all above methods [15-17], authors have used separate converters for compensating the harmonics and also for controlling the reactive power. But in later stages, some of the researchers have modified the control algorithms of already existed DFIG converters for mitigating the power quality problems and reactive power compensation [18-26].

The harmonics compensation and reactive power control are achieved with the help of existing rotor side converter (RSC) [18-23]. Therefore, harmonics are injected from the RSC into the rotor windings. This creates losses and noise in the machine. These different harmonics in rotating part may also create mechanical unbalance. Moreover, both reactive power compensation and harmonic compensation are achieved in all these methods by using RSC control. These methods increase the RSC rating. In [24-25], harmonic compensation and reactive power control are done by using GSC.

So the harmonics are not passing through machine windings in all these cases. Todeschini et al. [26] have compared three different control algorithms and finally concluded that combined modulation of both RSC and GSC are needed for compensating the harmonics and controlling the reactive power.

However, authors have used direct current control of GSC. So harmonic compensation is not so effective and Total Harmonic Distortion (THD) is not less than 5% as per IEEE- 519 standard given in Table-I. Authors have also not verified simulation results experimentally. An indirect current control technique is simple and shows better performance for eliminating harmonics as compared to direct current control [27-30]. In this work, a new control algorithm for GSC is proposed for compensating harmonics produced by nonlinear loads by using an indirect current control. RSC is used for controlling the reactive power of DFIG. The other main advantage of proposed DFIG is that it works as an active filter even when the wind turbine is in shut down condition.

So it compensates load reactive power and harmonics at wind turbine stalling case. Both simulation and experimental performances of proposed integrated active filter based DFIG are presented in this work. The dynamic performance of proposed DFIG is also demonstrated for varying wind speeds and changes in unbalanced nonlinear loads at PCC (Point of Common Coupling).

III. EXISTING AND PROPOSED SYSTEMS

3.1. EXISTING SYSTEMS

Doubly-Fed Induction Generator (DFIG) based wind turbine with is gaining laurels in the growing wind market. By means of a bidirectional converter in the rotor circuit the DFIG is able to work as a generator in both sub-synchronous and super-synchronous modes. DFIG is connected with back-to-back converters. In general, VAR compensation is a major problem in WECS. Capacitors banks are to be added in parallel to the machine which leads to many problems such as over voltages etc. In this project, the grid side converter itself compensates for the reactive power rather than providing an additional compensating device. Additional power is also extracted from the rotor side. The machine-side converter controls the rotor speed by using the v/f control technique while the grid-side converter controls the dc-link voltage and ensures the operation by making the reactive power drawn by the system from the utility to zero by using the voltage-oriented control technique. The grid-side current is controlled by using reference current generation in p-q theory.

The mainstream high-power wind-energy conversion systems (WECSs) are based on doubly-fed induction generators (DFIGs). The stator windings of DFIGs are directly connected to the grids, and rotor windings are connected to the grids through back-to-back power electronic converters. The back-to-back converter consists of two converters, i.e., rotor side converter (RSC) and grid side converter (GSC) that are connected "back-to back." Between the two converters a dc-link capacitor is placed, as energy storage, in order to keep the voltage variations in the dc-link voltage small. Control of the DFIG is more complicated than the control of a standard induction machine. In order to control the DFIG the rotor current is controlled by a power electronic converter.

Wind turbines use a DFIG consisting of a WRIG and an AC/DC/AC power electronic converter. The stator winding is connected directly to a 3-phase, 50Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter via slip-rings to allow DFIG to operate at variable speeds in response to changing wind speeds as shown in Fig.3.1.

A typical application, for DFIG is wind turbines, since they operate in a limited speed range of approximately 20-25%. Other applications for DFIG system are flywheel energy storage system, pumped storage power plants and so on.

The total system is that the machine-side converter controls the speed, while the grid-side converter controls the dc-link voltage and ensures

the operation at unity power factor (i.e. zero reactive power). By means of a bidirectional converter in the rotor circuit the DFIG is able to work as a generator in both sub-synchronous and super-synchronous modes. Depending upon the operating condition, power is fed in to or out of the rotor (which is the case of super synchronous mode), then it flows from the rotor via the converter to the grid.

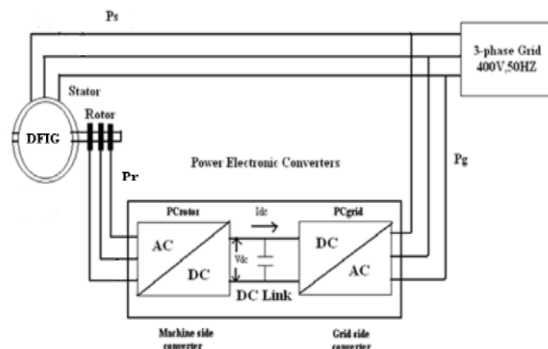


Figure: 3.1. DFIG system with power electronic converters

$P_{C_{rotor}}$ is used to generate or absorb the power P_g in order to keep the dc voltage constant as shown in Figure.3.1. In steady-state for a lossless AC/DC/AC converter, P_g is equal to P_r and the speed of the wind turbine is determined by the power P_r absorbed or generated by $P_{C_{rotor}}$. The phase-sequence of the ac voltage generated by $P_{C_{rotor}}$ is positive for sub-synchronous speed and negative for super-synchronous speed. The frequency of this voltage is equal to the product of the grid frequency and the absolute value of the slip. $P_{C_{rotor}}$ and $P_{C_{grid}}$ have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals. Figure.3.1 Shows the DFIG System with Power Electronic Converters.

3.2. PROPOSED SYSTEM CONFIGURATION AND OPERATING PRINCIPLE

Fig. 3.2 shows a schematic diagram of proposed DFIG based WECS with integrated active filter capabilities. In DFIG, the stator is directly connected to the grid as shown in Fig. 3.2. Two back to back connected Voltage Source Converters (VSCs) are placed between the rotor and the grid. Nonlinear loads are connected at PCC as shown in Fig. 3.2.

The proposed DFIG works as an active filter in addition to the active power generation similar to normal DFIG. Harmonics generated by the nonlinear load connected at the PCC distort the PCC voltage. These nonlinear load harmonic currents are mitigated by GSC control, so that the stator and grid currents are harmonic free. RSC is

controlled for achieving MPPT and also for making unity power factor at the stator side by using voltage oriented reference frame. Synchronous reference frame (SRF) control method is used for extracting the fundamental component of load currents for the GSC control.

3.3. DESIGN OF DFIG BASED WECS

Selection of ratings of VSCs and DC link voltage is very much important for the successful operation of WECS. The ratings of DFIG and DC machine used in this experimental system are given in Appendix. In this section, detailed design of VSCs and DC link voltage is discussed for the experimental system used in the laboratory.

3.3.1. Selection of DC Link Voltage

Normally, the DC link voltage of VSC must be greater than twice the peak of maximum phase voltage. The selection of DC link voltage depends on both rotor voltage and PCC voltage. While considering from the rotor side, the rotor voltage is slip times the stator voltage. DFIG used in this prototype has stator to rotor turns ratio as 2:1. Normally, the DFIG operating slip is ± 0.3 . So the rotor voltage is always less than the PCC voltage.

So the design criteria for the selection of DC link voltage can be achieved by considering only PCC voltage. While considering from the GSC side, the PCC line voltage (V_{ab}) is 230 V as the machine is connected in delta mode.

So the DC link voltage is estimated as [31],

$$V_{dc} \geq \frac{2\sqrt{2}}{\sqrt{3} \cdot m} V_{ab}$$

Where V_{ab} is the line voltage at the PCC. Maximum modulation index is selected as 1 for linear range. The value of DC link voltage (V_{dc}) by (1) is estimated as 375 V. Hence, it is selected as 375 V.

3.3.2. Selection of VSC Rating

The DFIG draws a lagging volt-ampere reactive (VAR) for its excitation to build the rated air gap voltage. It is calculated from the machine parameters that the lagging VAR of 2 kVAR is needed when it is running as a motor.

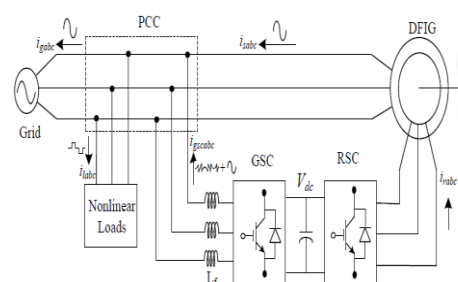


Figure.3.2. Proposed System Configuration.

In DFIG case, the operating speed range is 0.7 p.u to 1.3 p.u. So the maximum slip (S_{max}) is 0.3. For making unity power factor at the stator side, reactive power of 600 VAR ($S_{max} * Q_s = 0.3 * 2 \text{ kVAR}$) is needed from the rotor side (Q_{rmax}). The maximum rotor active power is ($S_{max} * P$). The power rating of the DFIG is 5 kW. So the maximum rotor active power (P_{rmax}) is 1.5kW ($0.3 * 5 \text{ kW} = 1.5 \text{ kW}$). So the rating of the VSC used as RSC, S_{rated} is given as,

$$S_{\text{rated}} = \sqrt{P_{\text{rmax}}^2 + Q_{\text{rmax}}^2}$$

Thus kVA rating of RSC S_{rated} is calculated as 1.615 kVA.

3.3.3. Design of Interfacing Inductor

The design of interfacing inductors between GSC and PCC depends upon allowable GSC current limit (i_{gscpp}), DC link voltage and switching frequency of GSC. Maximum possible GSC line currents are used for the calculation. Maximum line current depends upon the maximum power and the line voltage at GSC. The maximum possible power in the GSC is the slip power. In this case, the slip power is 1.5 kW. Line voltage (V_L) at the GSC is 230 V (the machine is connected in delta mode). So the line current is obtained as, $I_{gsc} = 1.5kW / (\sqrt{3} \cdot 230) = 3.765$ A. Considering the peak ripple current as 25% of rated GSC current. The inductor value is calculated as,

$$L_i = \frac{\sqrt{3}mv_{dc}}{12af_m\Delta i_{gsc}}$$

$$= \frac{\sqrt{3} \times 1 \times 375}{12 \times 1.5 \times 10000 \times 0.25 \times 3.76} = 3.8\text{mH}$$

Interfacing inductor between PCC and GSC is selected as 4 mH.

3.4. CONTROL STRATEGY

Control algorithms for both GSC and RSC are presented in this section. Complete control schematic is given in Fig.3.3. The control algorithm for emulating wind turbine characteristics using DC machine and Type A chopper is also shown in Fig.3.3.

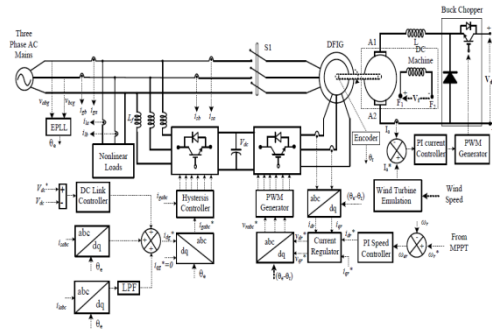


Fig.3.3. Control Algorithm of the proposed WECS.

3.4.1. Control of RSC

The main purpose of RSC is to extract maximum power with independent control of active and reactive powers. Here, the RSC is controlled in voltage oriented reference frame. So the active and reactive powers are controlled by controlling direct and quadrature axis rotor currents (i_{dr} and i_{qr}) respectively. Direct axis reference rotor current is selected such that maximum power is extracted for a particular wind speed. This can be achieved by running the DFIG at a rotor speed for a particular wind speed. So the outer loop is selected as a speed controller for achieving direct axis reference rotor current (i_{dr}^*) as,

$$i_{dr}^*(k) = i_{dr}^*(K-1) + K_{pd}\{\omega_{er}(K) - \omega_{er}(K-1)\} \\ + K_{id}\omega_{er}(K)$$

where the speed error (ω_{er}) is obtained by subtracting sensed speed (ω_r) from the reference speed (ω_r^*). K_{pd} and K_{id} are the proportional and integral constants of the speed controller. $\omega_{er}(K)$ and $\omega_{er}(K-1)$ are the speed errors at K^{th} and $(k-1)^{th}$ instants. $i_{dr}^*(K)$ and $i_{dr}^*(K-1)$ are the direct axis rotor reference current at K^{th} and $(k-1)^{th}$ instants. Reference rotor speed (ω_r^*) is estimated by optimal tip speed ratio control for a particular wind speed.

The tuning of PI controllers used in both RSC and GSC are achieved by using Ziegler Nichols method. Initially K_{id} value is set to zero and increase the value of K_{pd} until the response starts oscillating with a period of T_i . Now the value of K_{pd} is taken as $0.45 K_{pd}$ and K_{id} is taken as $1.2K_{pd}/T_i$.

Normally, the quadrature axis reference rotor current (i_{qr}^*) is selected such that the stator reactive power (Q_s) is made zero. In this DFIG, quadrature axis reference rotor current (i_{qr}^*) is selected for injecting the required reactive power.

Inner current control loops are taken for control of actual direct and quadrature axis rotor currents (i_{dr} and i_{qr}) close to the direct and

quadrature axis reference rotor currents (i_{dr}^* and i_{qr}^*). The rotor currents i_{dr} and i_{qr} are calculated from the sensed rotor currents (i_{ra}, i_{rb} and i_{rc}) as [32],

$$i_{dr} = \frac{2}{3} \begin{bmatrix} i_{ra} \sin \theta_{slip} + i_{rb} \sin(\theta_{slip} - 2\pi/3) \\ + i_{rc} \sin(\theta_{slip} + 2\pi/3) \end{bmatrix}$$

$$i_{qr} = \frac{2}{3} \begin{bmatrix} i_{ra} \cos \theta_{slip} + i_{rb} \cos(\theta_{slip} - 2\pi/3) \\ + i_{rc} \cos(\theta_{slip} + 2\pi/3) \end{bmatrix}$$

Where slip angle (θ_{slip}) is calculated as

$$\theta_{slip} = \theta_e - \theta_r$$

Where, θ_e is calculated from PLL for aligning rotor currents into voltage axis. The rotor position (θ_r) is achieved with an encoder. Direct and quadrature axis rotor voltages (v_{dr} and v_{qr}) are obtained from direct and quadrature axis rotor current errors (i_{der}, i_{qer}) as,

$$\begin{aligned} v_{dr}'(k) &= v_{dr}'(k-1) \\ &+ k_{pdv}\{i_{der}(k) - i_{der}(k-1)\} \\ &+ k_{idv}i_{der}(k) \\ v_{qr}'(k) &= v_{qr}'(k-1) \\ &+ k_{pqv}\{i_{qer}(k) - i_{qer}(k-1)\} \\ &+ k_{iqv}i_{qer}(k) \end{aligned}$$

where, $i_{der} = i_{dr}^* - i_{dr}$ and $i_{qer} = i_{qr}^* - i_{qr}$

where K_{pdv}, k_{idv} are the proportional and integral gains of direct axis current controller.

K_{pqv}, k_{iqv} are the proportional and integral gains of quadrature axis current controller.

Direct and quadrature components are decoupled by adding some compensating terms as

$$\begin{aligned} v_{dr}^* &= v_{dr}' + (\omega_e - \omega_r)\sigma L_r i_{qr} \\ v_{qr}^* &= v_{qr}' + (\omega_e - \omega_r)(L_m i_{ms} + \sigma L_r i_{dr}) \end{aligned}$$

These reference direct and quadrature voltages (v_{dr}^*, v_{qr}^*) are converted into three phase reference rotor voltages ($v_{ra}^*, v_{rb}^*, v_{rc}^*$) as [32],

$$\begin{aligned} v_{ra}^* &= v_{dr}^* \sin \theta_{slip} + v_{qr}^* \cos \theta_{slip} \\ v_{rb}^* &= v_{dr}^* \sin(\theta_{slip} - 2\pi/3) \\ &+ v_{qr}^* \cos(\theta_{slip} - 2\pi/3) \\ v_{rc}^* &= v_{dr}^* \sin(\theta_{slip} + 2\pi/3) \\ &+ v_{qr}^* \cos(\theta_{slip} + 2\pi/3) \end{aligned}$$

These three phase rotor reference voltages ($v_{ra}^*, v_{rb}^*, v_{rc}^*$) are compared with triangular carrier wave of fixed switching frequency for generating Pulse Width Modulation (PWM) signals for the RSC.

3.4.2. Control of GSC

The novelty of this work lies in the control of this GSC for mitigating the harmonics produced by the nonlinear loads. The control block diagram of GSC is shown in Fig. 2. Here an indirect current control is applied on the grid currents for making them sinusoidal and balanced. So this GSC supplies the harmonics for making grid currents sinusoidal and balanced. These grid currents are calculated by subtracting the load currents from the summation of stator currents and GSC currents. Active power component of GSC current is obtained by processing the DC link voltage error (v_{dce}) between reference and estimated DC link voltage (v_{dc}^* and v_{dc}) through PI controller as,

$$\begin{aligned} i_{gsc}^*(k) &= i_{gsc}^*(k-1) \\ &+ k_{pdc}\{v_{dce}(k) - v_{dce}(k-1)\} \\ &+ k_{idc}v_{dce}(k) \end{aligned}$$

Where k_{pdc} and k_{idc} are proportional and integral gains of DC link voltage controller. $v_{dce}(k)$ and $v_{dce}(k-1)$ are DC link voltage errors at K^{th} and $(K-1)^{th}$ instants.

$i_{gsc}^*(k)$ and $i_{gsc}^*(k-1)$ are active power component of GSC current at K^{th} and $(K-1)^{th}$ instants.

Active power component of stator current (i_{ds}) is obtained from the sensed stator currents (i_{sa}, i_{sb} and i_{sc}) using abc to dq transformation as [32],

$$\begin{aligned} i_{ds} &= \frac{2}{3} [i_{sa} \sin \theta_e \\ &+ i_{sb} \sin(\theta_e - 2\pi/3) + i_{sc} \sin(\theta_e + 2\pi/3)] \end{aligned}$$

Fundamental active load current (\bar{i}_{ld}) is obtained using SRF theory [33]. Instantaneous load currents (i_{labc}) and the value of phase angle from EPLL are used for converting the load currents in to synchronously rotating dq frame (\bar{i}_{ld}). In synchronously rotating frames, fundamental frequency currents are converted into DC quantities and all other harmonics are converted into non-DC quantities with a frequency shift of 50 Hz. DC values of load currents in synchronously rotating dq frame (\bar{i}_{ld}) are extracted using low pass filter (LPF). Direct axis component of reference grid current (i_{gq}^*) is obtained from the direct axis current of stator current (i_{ds}) and load current (\bar{i}_{ld}) in synchronously rotating frame and the loss component of GSC current (i_{gsc}^*) as,

$$i_{gd}^* = i_{gsc}^* + i_{ds} - \bar{i}_{ld}$$

Quadrature axis component of reference grid current (i_{gq}^*) is selected as zero for not to draw any reactive power from grid. Reference grid currents (i_{ga}^*, i_{gb}^* and i_{gc}^*) are calculated from the direct and quadrature axis grid currents (i_{gd}^*, i_{gq}^*) [32]. The hysteresis current controller is used to generate switching pulses for the GSC. The hysteresis controller is a feedback current control where sensed current tracks the reference current within a hysteresis band (i_{hb}) [34]. At every

sampling instant, the actual current (i_{gabc}) is compared with the reference current (i_{gabc}^*) as,

$$\Delta i_{gabc} = i_{gabc}^* - i_{gabc}$$

When $\Delta i_{gabc} > i_{hb}$, lower switch is turned on

When $\Delta i_{gabc} < -i_{hb}$, upper switch is turned on

By using these equations, gating pulses for three phases of GSC are generated in the same way.

IV.SIMULATION OUTPUTS

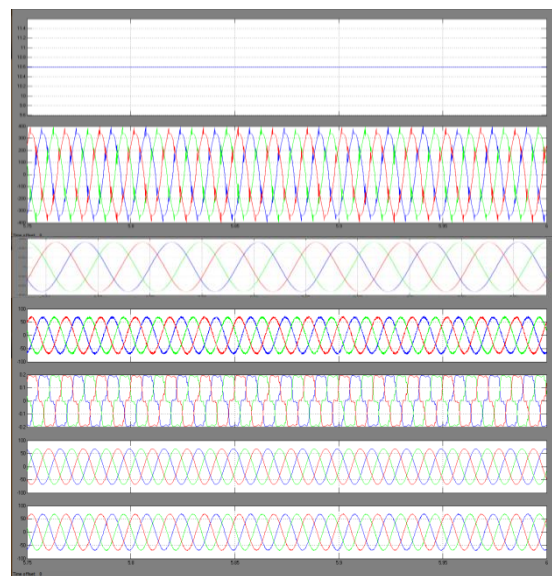
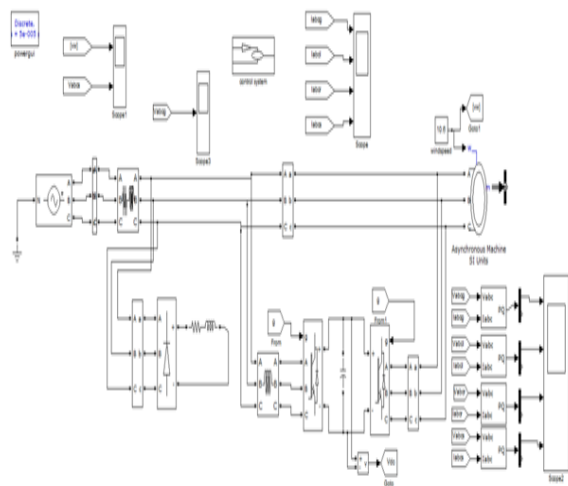


Figure. 4.1. Simulated performance of the proposed DFIG based WECS

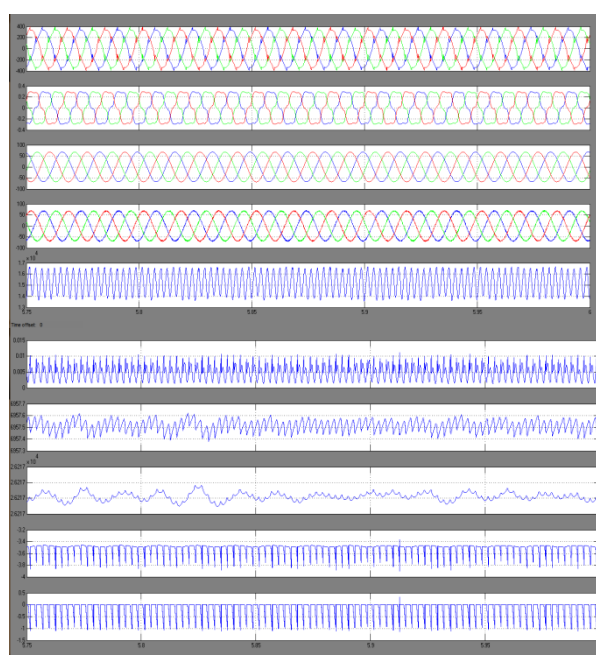
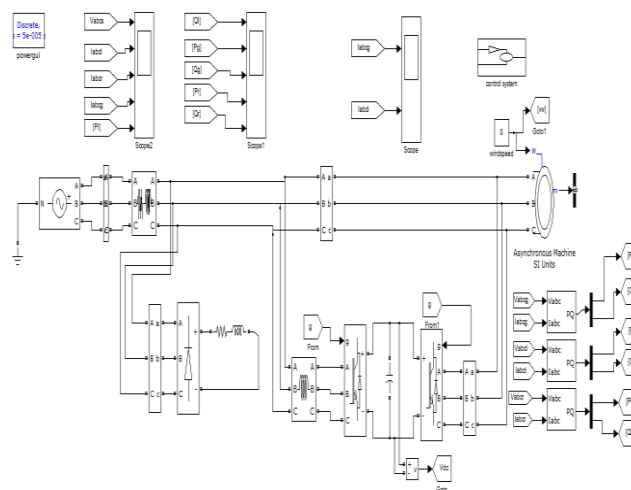
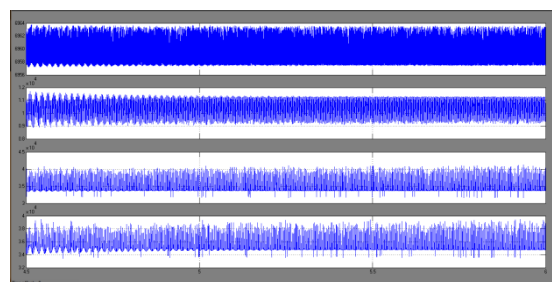
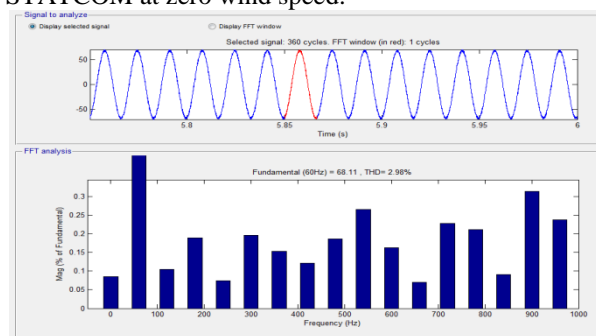


Figure. 4.2. Simulated performance of the proposed DFIG based WECS working as a STATCOM at zero wind speed.



FFT ANALYSIS

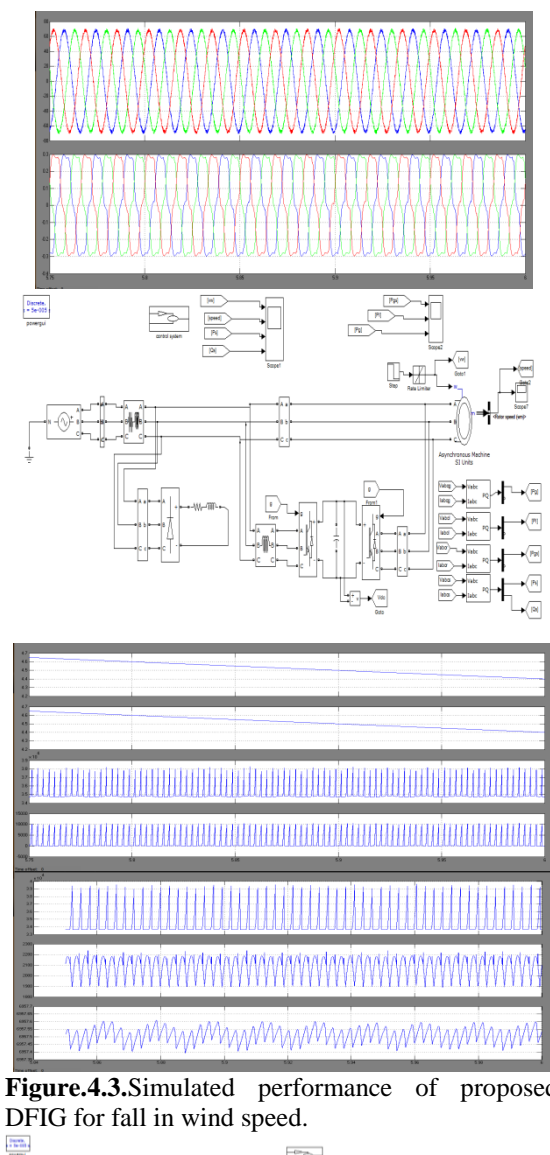
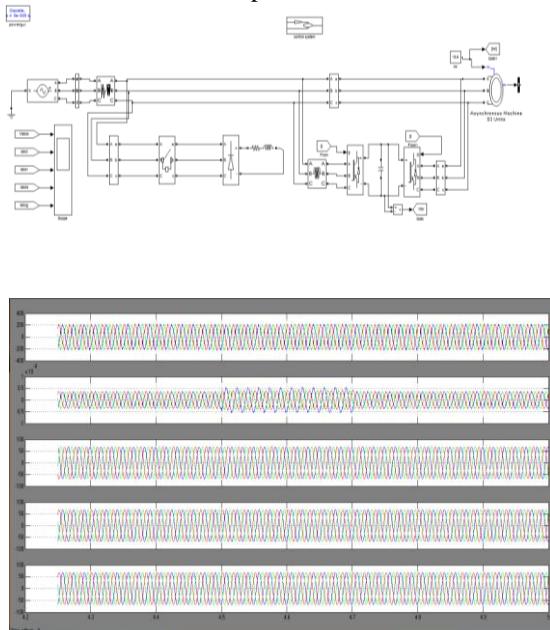


Figure.4.3. Simulated performance of proposed DFIG for fall in wind speed.



V.CONCLUSION AND FUTURE SCOPE

CONCLUSION:

Detailed models of the DFIG have been analyzed with required parameters and their generating mode of operation is explained clearly with help of waveforms obtained from simulation results. The various response of the system is observed in both super and sub-synchronous generating mode of operation. The control scheme of machine-side converter and grid-side converter has been simulated by using MATLAB/SIMULINK.

The GSC control algorithm of proposed DFIG has been modified for supplying the harmonics and reactive power of the local loads. In this proposed DFIG, the reactive power for the induction machine has been supplied from the RSC and the load reactive power has been supplied from the GSC. The decoupled control of both active and reactive powers has been achieved by RSC control. The proposed DFIG has also been verified at wind turbine stalling condition for compensating harmonics and reactive power of local loads. This proposed DFIG based WECS with an integrated active filter has been simulated using MATLAB/Simulink environment and simulated results are verified with test results of developed prototype of this WECS. Steady state performance of proposed DFIG has been demonstrated for a wind speed. Dynamic performance of this proposed GSC control algorithm has also been verified for the variation in the wind speeds and for local nonlinear load.

FUTURE SCOPE:

The controller is modified and implemented in FUZZY LOGIC CONTROLLER. The simulation outputs of FLC is most steady state and fast response when compare to traditional controller.

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