Harmonic Mitigation in Doubly Fed Induction Generator for Wind Conversion Systems by Using Integrated Active Filter Capabilities

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Abstract: This paper presents the control of WECS (Wind Energy Conversion System),equipped with a DFIG (Doubly Fed Induction Generator ,for maximum power generation and power quality improvement simultaneously. The proposed control algorithm is applied to a DFIG whose stator is directly connected to the grid and the rotor is connected to the grid through a back –to-back AC-DC-AC PWM(Pulse Width Modulation) converter .the RSC (Rotor Side Converter) is controlled in such a way to extract a maximum power for a wide range of wind speed. The GSC (Grid Side Converter) controlled in order to filter harmonic currents of a nonlinear load coupled at the PCC (Point Of Common Coupling) and ensure smooth DC bus voltage .Simulation results show that the wind turbine can operate at its turbine can operate at its optimum energy for a wide range of wind speed and power quality improvement is achived.

Key words: Variable speed DFIG, MPPT, wind energy, power quality, active filtering, GSC.

NOMENCLATURE

v_{ab},v_{bc} ,v_{ca}	Three phase stator voltages
i_{sa}, i_{sb} , i_{sc}	Three phase stator currents
i_{ra} , i_{rb} , i_{rb}	Three phase rotor currents
i_{ga}, i_{gb}, i_{gc}	Three phase grid currents
i_{la}, i_{lb}, i_{lc}	Three phase load currents
i_{dr}	Direct axis rotor current
i_{qr}	Quadrature axis rotor current
i_{ld}	Direct axis load current
P_g	Active power fed to the grid
$Q_{g,}$	Reactive power fed to the grid
$P_{s,}$	Stator active power
Q_s	Stator reactive power
$P_{l,}$	Load active power
Q_l	Load reactive power
P_{gsc}	GSC active power
$Q_{gsc,}$	GSC reactive power
V_w	Wind speed in m/sec
θ_e	Angle of grid voltage vector
v_{dc}	DC link voltage

I. Introduction

With the increase in population and industrialization, the energy demand has increased significantly. During the last decade, and to reduce the pollution problem, much effort have been focused on the development of environmentally friendly sources of energies such as wind and solar. WECS (wind energy conversion system) equipped with DFIG (Doubly Fed Induction Generator) has received increasing attention due to its noticeable advantages over other WT (Wind Turbine) systems. Compared to the fixed speed wind turbine, the variable speed wind turbine can provide decoupled control of active and reactive power of the generator and improve power quality. Due to several integration of nonlinear loads, such as power electronics converters and large alternating current drives, which are polluting sources of the grid, the modern WECS is not only controlled to product active power to the customers but also to improve the power quality and support the grid during any kind of faults. Ref.[2]

One can profit of the power electronic converters to provide some of the ancillary services (reactive power absorption or injection to achieve voltage control, harmonic currents compensation). Recently, many groups of researchers have addressed the issue of making use of the WECS converters, connected between The generator and the grid, to improve grid power quality and achieve harmonic currents mitigation. In Ref. [5], Singh et al. have studied the grid synchronization with harmonics and reactive power compensation capability of a permanent magnet synchronous generator-based variable speed wind energy conversion system. In Ref.[6] this work, the GSC (Grid Side Converter) is actively controlled to feed generated power as well as to supply the harmonics and reactive power demanded by the non-linear load at the PCC (Point of Common Coupling). In Gaillard et al. have controlled the RSC (Rotor Side Converter) for reactive power compensation and active filtering capability of a WECS equipped by a DFIG without any over-rating.

This paper presents the control of a WECS, equipped by a doubly fed induction generator, for maximum power generation and power quality improvement simultaneously. A speed PI controller is used for MPPT (Maximum Power Point Tracking) and ensures maximum power generation. This control strategy is applied to the rotor side converter by using a stator flux oriented strategy and an optimal speed reference which is estimated from the wind speed. Elsewhere, another speed Hysteris controller is used to control the GSC (Grid Side Converter) by using the oriented voltage control strategy in order to ensure a smooth DC voltage and compensate the harmonic currents of a non linear load connected at the PCC. The feasibility and effectiveness of these controls strategies, in terms of active power production and active filtering, have been tested by simulation.

II. SYSTEM CONFIGURATION AND OPERATING PRINCIPLE

Shows Fig.1 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. 1. 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. 1. 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. In Ref.[5] 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.

III. 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 section, detailed design of VSCs and DC link voltage is discussed for the experimental system used in the laboratory.

A. 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. In Ref.[2] 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 [1],

$$\mathrm{vdc} \geq \frac{2\sqrt{2}}{\sqrt{3}*\mathrm{m}}\mathrm{vab} \qquad (1)$$

Here 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.

B. 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 2kVAR is needed when it is running as a motor.

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 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 kW=1.5 kW). So the rating of the VSC used as RSC,S_{rated} is given as,

The rating of the VSC used as RSC, Srated is given as,

$$S_{rated} = \sqrt{P_{rmax}^2 + Q_{rmax}^2} \qquad (2)$$

Thus kVA rating of RSC, S_{rated} (2)is calculated as 1.615 kVA.

C. 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,1.5kW/(√3*230) =3.765 A.

$$L_i = \frac{\sqrt{3} m v_{dc}}{12 a f_m \Delta i_{gsc}} \qquad (3)$$

$$= \frac{\sqrt{3} * 1 * 375}{12 * 1.5 * 1000 * 0.25 * 3.76}$$

= 3.8m

Out of all variable speed wind turbines, Doubly Fed Induction Generators (DFIGs) are preferred because of their low cost. The other advantages of this DFIG are the higher energy output, lower converter rating and better utilization of generators. These DFIGs also provide good damping performance for the weak grid. Independent control of active and reactive power is achieved by the decoupled vector control algorithm presented in Ref[2]. The dynamic performance of proposed DFIG is also demonstrated for varying wind speeds and changes in unbalanced nonlinear loads at PCC . This vector control of such system is considering the peak ripple current as 25% of rated GSC current.Interfacing inductor between PCC and GSC is selected as 4 mH.

V. CONTROL STRATEGY

Control algorithms for both GSC and RSC are presented in this section. Complete control schematic is given in Fig. 3. The control algorithm for emulating wind turbine characteristics using DC machine and Type A chopper are given below.

1 . Turbine modeling

The mechanical power captured by the turbine from the wind is given by (4) the following expression:

$$p_t = \frac{1}{2} \rho c_p(\lambda, \beta) s v^3 \qquad (4)$$

Here ρ is the air density (1.225 kg/m3), s is the area of the wind wheel (m²), v is the wind speed (m/s), cp (λ, β) is the power coefficient of the turbine, λ is the tip speed ratio and β is the pitch angle. The tip speed ratio is given by (5) the following equation:

$$\lambda = \frac{R\omega_t}{v} \qquad (5)$$

Here R is the radius of the turbine(m) and ω_t is the speed turbine (rd/s). The turbine blade can capture the maximum of the wind power.

Fig.2 shows the curve of the power coefficient versus λ for a constant value of the pitch angle β.in the case of a variable speed system one can let ω_t changing with the varation of the wind speed v in order to maintain λ at its optimal value λ_{opt}.so the turbine blade can capture the maximum of the wind power. This variable speed turbine design can control reactive power independently of the real power, within a wide range of output levels . In this study, it was assumed that the wind turbines have a power factor range from 0.95 lagging to 0.95 leading.

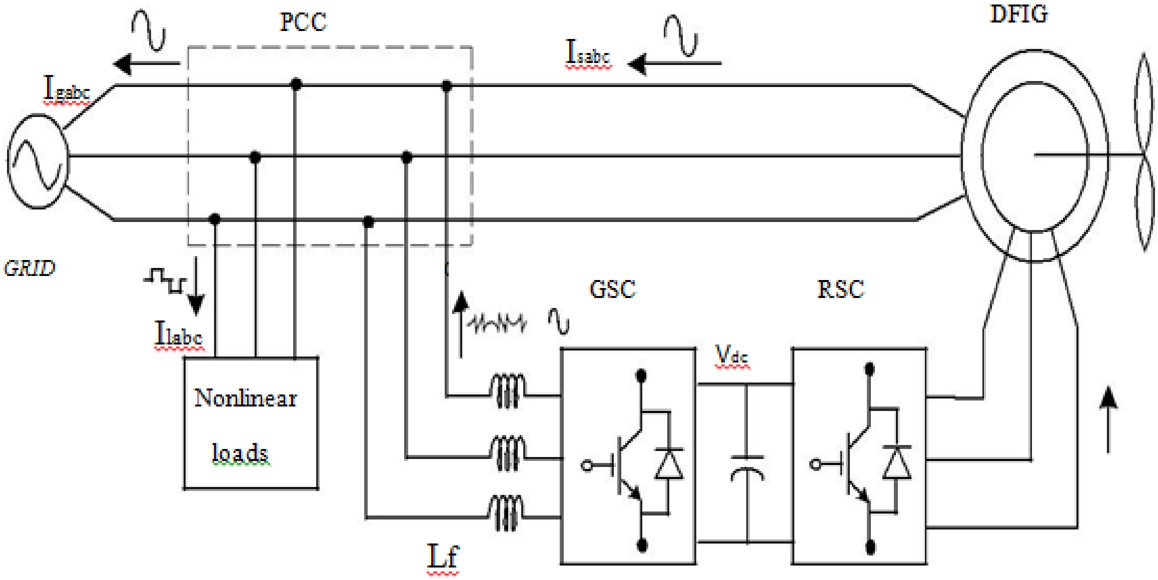

Fig. 1. Proposed System Configuration

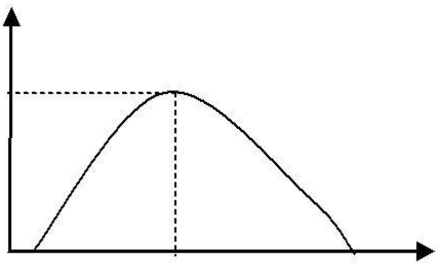

Fig. 2 Power coefficient versus the tip speed

2. Doubly Fed Induction Generator

DFIG base wind energy conversion system with integrated active filter capabilities.In Ref [2] Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter.

The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind.

The electromagnetic torque is expressed by:

$$T_{em} = \frac{3}{2} pm/L_s(i_{dr} i_{qs} - i_{qr} i_{ds}) \qquad (6)$$

The mechanical equation is expressed as follow:

$$T_{em} = J\frac{d\Omega_g}{dt} + f\Omega_g + T_r \quad (7)$$

Here:

J is the total inertia; Ωg is the generator speed; *f* is the total mechanical damping coefficient and *p* is the Number of pole pairs. *Rs* and *Rr* are the stator and rotor phase resistances.

The optimum turbine speed producing maximum mechanical technology is the ability for power electronic converters to generate or absorb reactive power.Thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

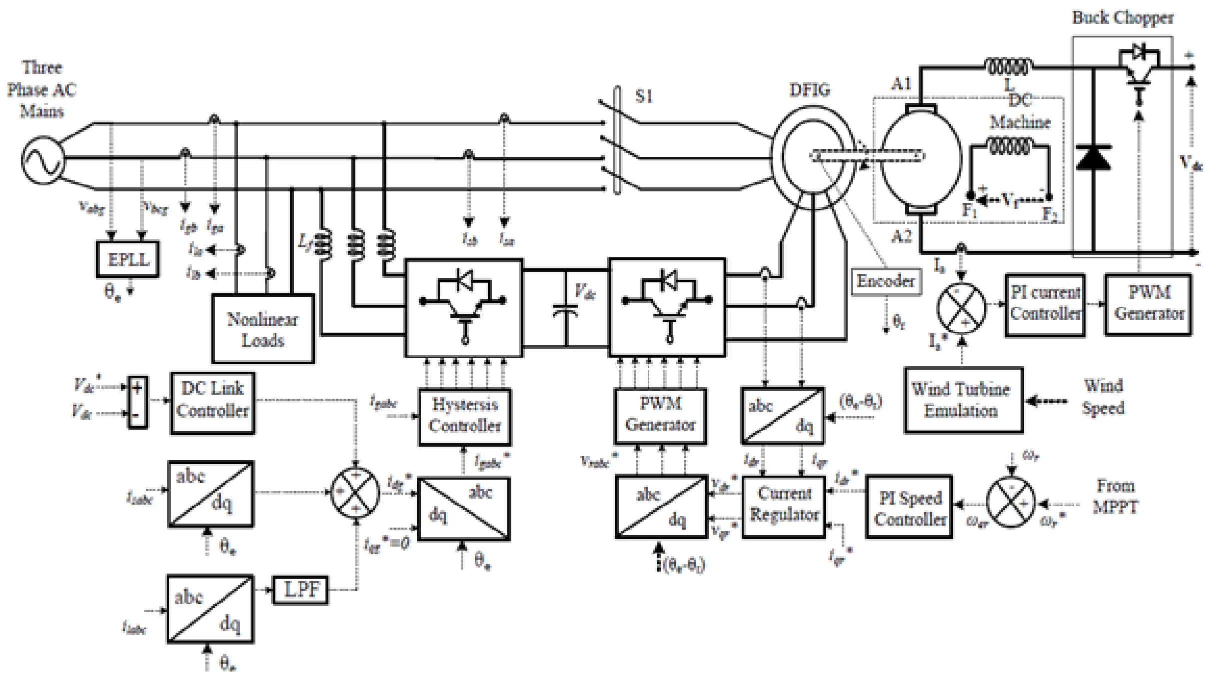

Fig. 3. Control Algorithm of the proposed WECS

3. Control of Rotor Side Converter

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 (9) is selected such that maximum power is extracted for a particular wind speed (8). This can be achieved by running the DFIG at a rotor speed for a particular wind speed.

As,

$$i^*_{dr}(k) = i^*_{dr}(k-1) + k_{pd}\{\omega_{er}(k) - \omega_{er}(k-1)\} + k_{id}\,\omega_{er(k)} \quad (8)$$

The current reference is,

$$i_{qrref} = -\frac{2l_s\omega_s}{3pu_sM}T_{emref} \quad (9)$$

ω_s, ω_r are respectively the synchronous angular speed of the generator and the angular speed of the rotor with $\omega_r = p\Omega_g$.

L_s *and* L_r are respectively the ststor and rotor inductance and M is the magnetizing inductance.

T_r is the turbine speed.

Here the speed error (ω_{er}) is obtained by subtracting sensed speed (ω_r) from the reference speed (ω_r^*). kpd and kid 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 controller used in both RSC and GSC are achieved by using Ziegler nichlos method.initialy k_{id} value is set to zero and increase the value of k_{pd} until the response stars 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 1.2 $k_{pd}/T_{i.}$

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

$$\theta_{slip} = (\theta_e - \theta_r \tag{10}$$

Here θ_e is calculated from PLL for aligning rotor currents into voltage axis. The rotor position (θ_r) Achieved with an encoder.

4. Control of Grid Side Convert

The control block diagram of this converter is presented in Fig. 3.The grid side converter uses direct field oriented vector control. Here no position sensors are required. The orientation of the reference frame is done along the supply voltage vector to obtain decoupled control over active and reactive power.in Ref[6] the grid side converter (GSC) can provide reactive power, and the reactive power is also can be control dependently while the active power generating. The control of this GSC for mitigating the harmonics produced by the nonlinear loads. Here an indirect current control is applied on the grid currents for making them sinusoidal and balanced. These grid currents are calculated by (11) 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

$$i_{gsc}^{*}(k) = i_{gsc}^{*}(k-1) + k_{pdc}\{v_{dce}(k) - v_{dce}(k-1)\} + k_{idc} v_{dce}(k) \tag{11}$$

Here 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.

The grid phase voltage can be expressed as follow:

$$v_{ag} = R_g i_{ag} + L_g \frac{di_{ag}}{dt} + v_{ainv}$$

$$v_{bg} = R_g i_{bg} + L_g \frac{di_{bg}}{dt} + v_{binv} \tag{12}$$

$$v_{cg} = R_g i_{cg} + L_g \frac{di_{cg}}{dt} + v_{cinv}$$

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 (i_{ld}). In synchronously rotating frames, fundamental frequency are converted into DC quantities and all other harmonics are converted into non-DC quantities with a frequency shift of 50 Hz. currents in By using park transformation ,Eq,(12) can be expressed as follow:

$$v_{dg} = R_g i_{dg} + L_g \frac{di_{dg}}{dt} - \omega_s L_g i_{qg} + v_{dinv} \tag{13}$$

$$v_{qg} = R_g i_{qg} + L_g \frac{di_{qg}}{dt} + \omega_s L_g i_{dg} + v_{qinv} \tag{14}$$

The active and reactive powers, exchanged between the grid and the GSC, are given by (15) the following equations:

$$\left.\begin{aligned} P_g &= \frac{3}{2}\left(v_{dg} i_{dg} + v_{qg} i_{qg}\right) \\ Q_g &= \frac{3}{2}\left(v_{qg} i_{qg} + v_{dg} i_{dg}\right) \end{aligned}\right\} \tag{15}$$

If the *d*-axis is aligned with the stator voltage, one can write: $v_{dg} = us$ and $v_{qg} = 0$. Hence, the active and reactive powers expressions are easily simplified as follows:

$$\left.\begin{aligned} P_g &= \frac{3}{2} u_s i_{dg} \\ Q_g &= -\frac{3}{2} u_s i_{qg} \end{aligned}\right\} \tag{16}$$

The DC capacitor voltage V_{dc} is controlled by the current i_{dg} in the voltage vector-oriented reference frame. Thus, a reference current i_{dgref} was derived from the DC link voltage error e_c and its Δe_c by tuning the FLC controller, as shown in Fig.3. To control the reactive power (Q_g) to a desired value (Q_{gref}), a command current i_{qgref} is derived from Eq. (). After a dq-abc transformation of these reference currents, hysteresis modulation may then be implemented as shown in Fig. 3.

5. Active Filtering

There are various methods to identify the harmonic currents of a nonlinear load. The most classical methods are "instantaneous power theory *p-q*" or "*d-q* or synchronous detection method" Ref.[6]. Practically, SPBF (selective pass band filter) or LPF (low pass filter) has been used to extract the harmonic currents components . Frequency domain compensation, which is based on Fourier analysis, is not very used because it requires more real time processing power. In the case, the I instantaneous power theory is used For being compensated, by the GSC, the resulting *d-q* reference harmonic currents (i_{ldh}, i_{lqh}) must be subtracted from the currents (i_{dgref}, i_{qgref}) as shown in Fig. 6.

6. Maximum Active Power Generation by the MPPT Strategy

In this section, the system is controlled to track its maximum power operating point. Fig. 3 shows the responses for a wind speed in ramp form. The graphs shown correspond (in order of appearance): (1) wind speed; (2) generator speed and its reference; As can be seen from the plots, the generator rotor speed is controlled according to MPPT strategy. Also, the power coefficient is kept around its optimum *Cpmax* = 0.4993. The stator active power is varied according to the MPPT strategy and a unity power factor is ensured at the stator side. Moreover, the reactive power is maintained to zero. The zoom of a stator voltage and the corresponding current shows that the DFIG produces active power to the grid (Fig. 6).

SIMULATION RESULTS

1. WIND SPEED

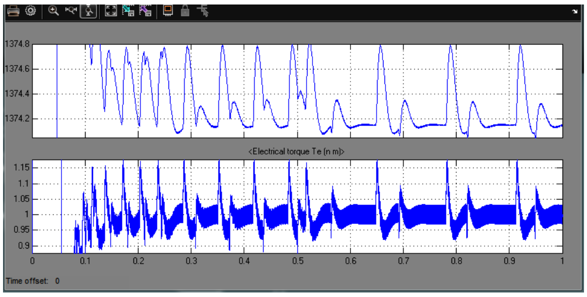

Fig.4.Wind Speed

This Fig.4 shows variation of the amplitude of speed of the wind with time.From this graph we have concluded that the speed of wind will not remain constant and vary with time.

WIND SPEED =1400

2. MPPT power generation

This Fig.5 shows that maximum constant power can be extracted from the wind power plant using MPPT algorithm. MPPT can be implemented by varying the pitch angle and yawing.

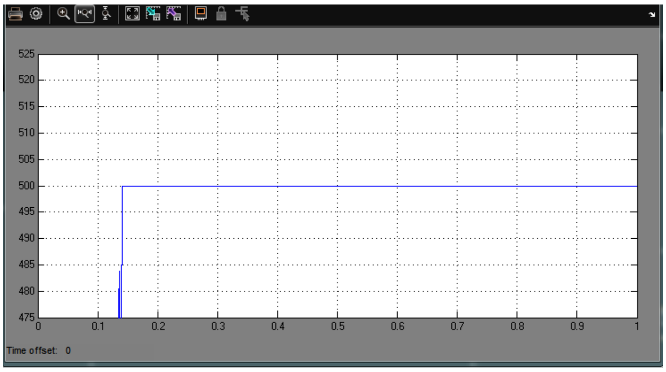

Fig.5. MPPT Power Generation

3.GRID CURRENT (iG)

In this Fig.6 shows that the constant grid current can be maintained in the grid.

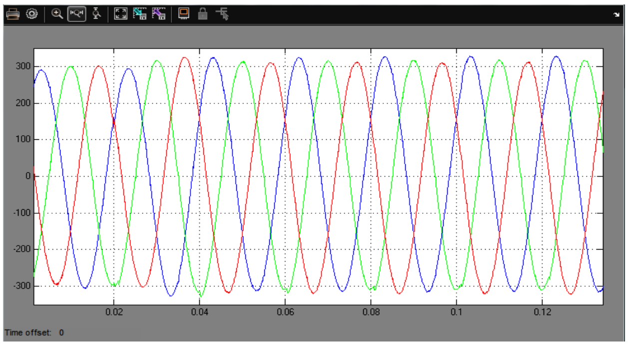

Fig.6 Grid Current (iG)

5.STATOR SIDE

The Fig.7 given below shown that the amplitude and waveform of the induced stator side voltage and currents.

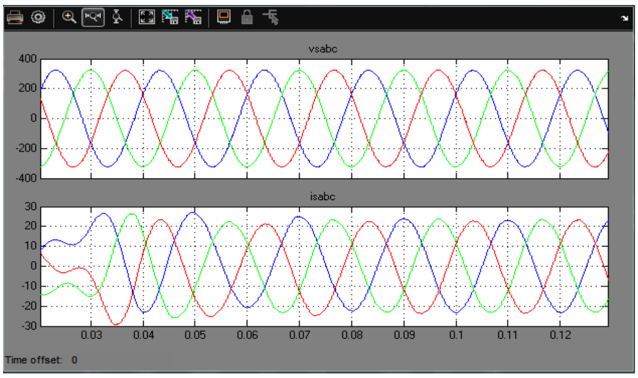

Fig.8 Stator Side

6.ROTOR SIDE

The Fig.9 shown below represents current induced in the rotor are not pure and contain some harmonics.There convertors are used to eliminate the harmonics and maintain the Voltage.we can able to connect rotor side to the grid only by maintaining the rotor side voltage constant.

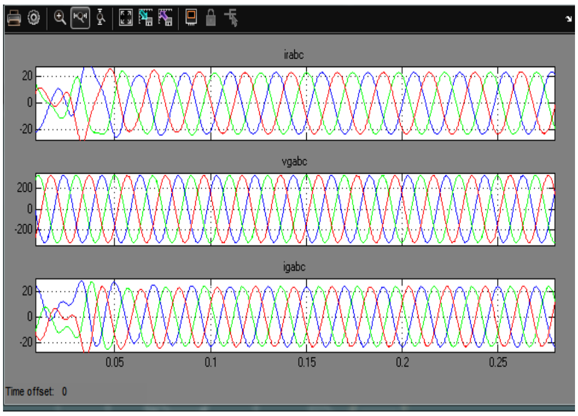

Fig.9 Rotor Side

Conclusion

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.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

References

(1) H. Polinder, S. W. H. de Haan, J. G. Slootweg, and M. R. Dubois, “Basic operation principles and electrical conversion systems of wind turbines,” *EPE J.*, vol. 15, no. 4, pp. 43–50, Dec. 2005.

(2) S. Muller, M. Deicke and R. W. De Doncker, “Doubly fed induction generator systems for wind turbines,” *IEEE Ind. Appl. Magazine*, vol.8, no.3, pp.26-33, May/Jun 2002.

(3) A. Gaillard, P. Poure and S. Saadate, “Active filtering capability of WECS with DFIG for grid power quality improvement”, *Proc. IEEE Int. Symp. Ind. Electron.*, Jun. 30, 2008, pp. 2365 -2370.

(4) Z. Boutoubat, L. Mokrani, and M. Machmoum, “Control of a wind energy conversion system equipped by a DFIG for active power generation and power quality improvement,” *Renewable Energy*, vol. 50, pp. 378-386, Feb 2013.

(5) A. Gaillard, P. Poure, S. Saadate, M. Machmoum, Variable speed DFIG wind energy system for power generation and harmonic mitigation, Renewable Energy 34 (6) (2009) 1545-1553.

(6) E. Tremblay, A Chandra and P. J. Lagace, “Grid-side converter control of DFIG wind turbines to enhance power quality of distribution network,” *2006. IEEE PES General Meeting*, pp. 6.

(7) E. Tremblay, S. Atayde and A Chandra, “Direct power control of a DFIG-based WECS with active filter capabilities,” *2009 IEEE Electrical Power & Energy Conference (EPEC)*, 22-23 Oct. 2009, pp.1-6.

(8) R Datta, “Rotor side control of grid-connected wound rotor induction machine and its application to wind power generation,” Ph.D. dissertation, Dept. Electr. Eng., Indian Inst. Sci., Bangalore, India, 2000.

(9) B. Rabelo and W. Hofmann, "Control of an optimized power flow in wind power plants with doubly-fed induction generators, " in Proc.34th Annu. Power Electronics Specialists Conf, 2003, Vol.4, pp.1563-1568.