ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 3, Issue 5, May 2015

Direct active and reactive power control of DFIG for wind energy generation

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Abstract: Wind energy is gaining interest now-a-days as one of the most important renewable sources of energy due to its eco-friendly nature. But the major disadvantage lies in variable speed wind generation and this paper gives a study on control of Wind driven doubly fed Induction Generators. The speeds above and below Synchronous speeds are obtained using a bidirectional power flow converter. By using this reactive power is controlled and hence the overall Power factor of system can be kept at unity under varying load conditions. . This paper presents a novel method for power quality improvement of Wind Energy Conversion System (WECS) by compensation of grid harmonic currents produced by non-linear loads. The proposed method which has been applied to a Doubly Fed Induction Generator (DFIG) through rotor side converter(RSC), provides simultaneous speed control and power quality improvement. The Direct Power Control (DPC) method with constant switching frequency has been used for RSC control and power quality improvement has been performed by compensation of harmonic's active and reactive power of nonlinear load. This paper presents simulation results of a Grid-connected DFIG.

Keywords: DFIG; Power quality improvement; Wind Energy Conversion System (WECS); Harmonic current mitigation. Direct Power Control (DPC).

I. INTRODUCTION

Industrial drive applications are generally classified into constant speed and variable speed operations. For constant speed applications generally ac machines are used where as for variable speed applications dc machines are used. But due to the disadvantages of dc machines lies mainly with commutators and brushes which limit the machine speed and peak current. As a result for variable speed applications ac machines are gaining more importance than the dc machines recently. In order to meet power needs, taking into account economical and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy.

With increased penetration of wind power into electrical grids, wind turbines are largely deployed due to their variable speed feature and hence influencing system dynamics. But unbalances in wind energy are highly impacting the energy conversion and this problem can be overcome by using a Doubly Fed Induction Generator (DFIG)[1].

Doubly fed wound rotor induction machine with vector control is very attractive to the high performance variable speed drive and generating applications. In variable speed drive application, the so called slip power recovery scheme is a common practice here the power due to the rotor slip below or above synchronous speed is recovered to or supplied from the power source resulting in a highly efficient variable speed system. Slip power control can be obtained by using popular Static Scherbius drive for bi directional power flow. The major advantage of the DFIG is that the power electronic equipment used of the DFIG is that the power electronic equipment used i.e. a back to back converter that handles a fraction of (20-30%) total system power. The back to back converter consists of two converters i.e. Grid Side Converter (GSC) and Rotor Side Converter (RSC) connected back to back through a dc link capacitor for energy storage purpose[2].

Control strategies of DFIG have been discussed in literatures [3-5]. Control of DFIG through the Field Oriented Control (FOC) which is performed by rotor currents control has been developed in [6]. FOC method depends on parameters variation and its power dynamics can be influenced by these variations. Although, DFIG control using Input-Output Feedback Linearization (IOFL) method can operate below and above synchronous speed [7], but complication of control method and dependence on parameters are its disadvantages. Direct Power Control (DPC) provides fast dynamic response, simple structure and proper operation in presence of parameter variations [8]. However, basic DPC suffers large ripple in currents, active and reactive power. Also, variable switching frequency is another disadvantage of this method. Recently, many researches have been done about power quality improvement capability of Wind Energy Conversion System (WECS).

In [9], non-linear load compensation has been studied for DFIG in an stand alone grid. In [10], harmonic mitigation has been done using control of DFIG grid side converter. Boutoubat et al have proposed a control strategy for using filtering capability of RSC to achieve harmonic mitigation. A method based on Field Oriented Control (FOC) applied to DFIG has been used for compensation of main harmonic components of loads.

DOI 10.17148/IJIREEICE.2015.3536

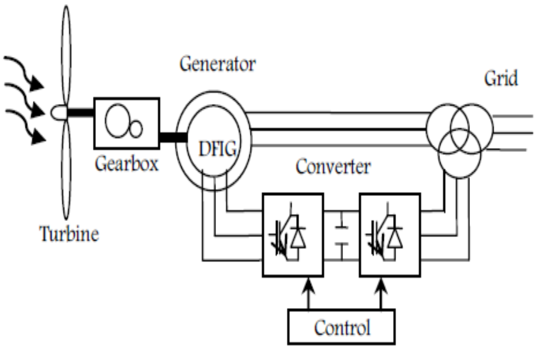


Fig.1
Basis diagram of WECS system with grid connected DFIG

In this paper DPC is combined with Space vector modulation (SVM) to achieve better operation of DFIG's control system with constant switching frequency. Also, a novel method has proposed for simultaneous active and reactive power control of a variable speed DFIG and power quality improvement by full harmonics compensation of nonlinear loads thorough RSC. Moreover, GSC control provides smooth DC voltage and unity power factor operation.

II. PRINCIPLE OF OPERATION

Figure.2 shows the basic scheme adopted in the majority of systems. The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DFIG to operate at a variety of speeds in response to changing wind speed. 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.

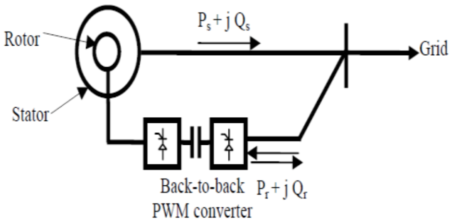


Fig. 2 Schematic Diagram of a Doubly Fed Induction Generator.

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-side or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the motoring mode, rotor-side converter operates as an inverter and stator side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

III. WIND TURBINE MODEL

Several models for power production capability of wind turbines have been developed. The mechanical power captured Pmech by a wind turbine, depends on its power coefficient Cp given for a wind velocity and can be represented by

$$P_{mech} = \frac{1}{2} Cp\, \rho\, \pi\, R^2 V^3 \qquad (1)$$

Where ρ and R correspond to the air density and the radius of the turbine propeller, respectively. The power coefficient can be described as the portion of mechanical power extracted from the total power available from the wind, and it is unique for each turbine. This power coefficient Cp is generally defined as a function of the tip-speed-ratio which, in turn, is given by λ.

$$\lambda = \omega R/V \qquad (2)$$

where ω represents the rotational speed of the wind turbine. Figure3. shows a typical relationship between the power coefficient Cp and the tip-speed-ratio. It should be noted that there is a value of λ to ensure a maximum of Cp . Thus, it can be stated that, for a specified wind velocity, there is a turbine rotational speed value that allows capturing the maximum mechanical power attainable from the wind, and this is, precisely, the turbine speed to be followed.

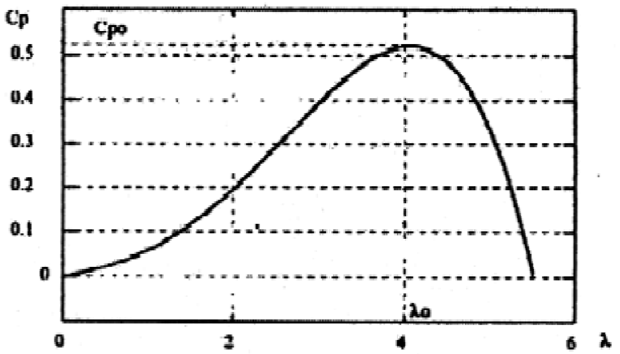


Fig. 3 Typical Power Coefficient Versus Tip-Speed-Ratio Curve

The method followed in this paper in order to reach the optimum tip-speed-ratio at each wind velocity consists in, based on the generator rotor speed, estimating and, therefore, trying to achieve the optimum active power to be generated by means of the rotor current stator-flux-oriented vector control.

IV. MATHEMATICAL MODEL OF DFIG

The dynamic performance of ac machine is somewhat complex because the three phase rotor windings move

DOI 10.17148/IJIREEICE.2015.3536

with respect to three phase stator windings. Hence a three phase machine can be represented with an equivalent two phase machine replacing the variables associated with the stator windings of a machine with variables associated with fictious windings rotating with the rotor at synchronous speed. The analysis can be simplified greatly by transforming the three phase stator and rotor windings(with angular displacement) to a fictious two phase stator and rotor(with no displacement).These fictious two phase windings are called d-q windings. The stator and rotor a-,b- and c-phase voltage equations can be transformed to the d-q axis. Then the model of doubly fed induction generator in general reference frame can be written as below:

$$V_{ds}=R_sI_{ds}+d\phi_{ds}/dt-\omega_g\phi_{qs}$$
$$V_{qs}=R_sI_{qs}+d\phi_{qs}/dt-\omega_d\phi_{ds} \qquad (3)$$

$$V_{dr}=R_rI_{dr}+d\phi_{dr}/dt-(\omega_g-\omega_r)\phi_{qr}$$
$$V_{qr}=R_rI_{qr}+d\phi_{qr}/dt-(\omega_g-\omega_r)\phi_{dr} \qquad (4)$$

$$\phi_{ds} = L_sI_{ds}+MI_{dr}$$
$$\phi_{qs} = L_sI_{qs}+MI_{qr} \qquad (5)$$

$$\phi_{dr} = L_rI_{dr}+MI_{ds}$$
$$\phi_{qr} = L_rI_{qr}+MI_{qs} \qquad (6)$$

where ω_g and ω_r are respectively general reference frame speed and rotor speed. Also, electromagnetic torque equals:

$$T_e=\frac{3}{2}\frac{P}{2}(\phi_{ds}\,\phi_{dr}-\phi_{qs}\,\phi_{qr}) \qquad (7)$$

$$J\frac{d\omega}{dt}-B\omega=T_e-T_l \qquad (8)$$

Where P is number of pole pairs, J is inertia and T_l is load Torque.

V. ACTIVE AND REACTIVE POWER CONTROL OF DFIG

The per phase equivalent for a DFIG is shown in the fig. 4.Variables with the ‘notation denote rotor quantities as seen from stator side.

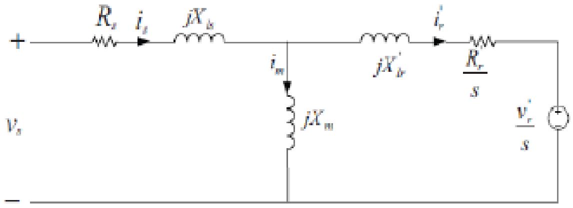


Fig. 4 Per Phase Equivalent Circuit of a DFIG.

By neglecting the effects of Rs, jXls and jXlr the per phase stator power Ss and rotor power Sr can expressed as:

$$S_S = P_S + jQ_S = V_S I_S^* \qquad (9)$$

$$S_r = P_r + jQ_r = V_r I_r^* \qquad (10)$$

VI. CONTROL SCHEME OF DFIG

Configuration of the overall wind generation system is shown in Fig. 1. The stator of DFIG is directly connected to the grid and the rotor is connected through back-to-back PWM converters.

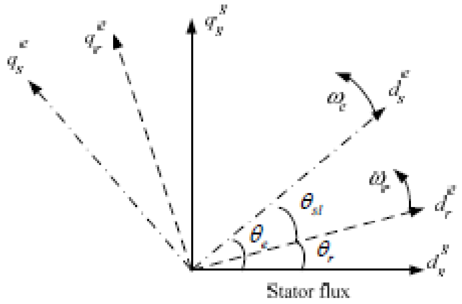


Fig. 5 Vector diagram for stator flux-oriented control.

The DFIG is controlled in a rotating d-q reference frame, with the d-axis aligned with the stator flux vector as shown in Fig. 5. The stator active and reactive powers of DFIG are controlled by regulating the current and voltage of the rotor. Therefore the current and voltage of the rotor needs to be decomposed into the components related to stator active and reactive power.

A. *VOC and DPC Techniques*

Both VOC and DPC have been directly derived from their counterparts, formerly devised for the control of electrical drives, called respectively FOC (Field Oriented Control) and DTC (Direct Torque Control). As in the drive control counterpart, the VOC is based on the idea to find a rotating reference frame in which the current control corresponds to the active and reactive power control. On this basis firstly the VOC has been developed, where the direct axis lies in the direction of the grid voltage space vector, secondly the virtual flux (VF) VOC has been developed, where the direct axis lies in the direction of a virtual flux, obtained on the basis of the time integration of the grid voltage components. Obviously, since the virtual flux lies in quadrature with respect to the grid voltage, the direct and quadrature components of the injected currents are interchanged with respect to the VOC.

At the same time, as in the drive control counterpart, DPC is based on the idea to find instantaneously a switching pattern of the inverter permitting to increase or decrease directly, without current control, and in a decoupled way the active and reactive power exchange between the DC stage and the grid. Even in this case the virtual flux (VF) DPC has been developed as a further improvement, where active and reactive powers are estimated on the basis of the virtual flux components instead of the voltage ones.

B. *Direct power control based on SVM method*

In order to achieve a decouple control of active and reactive power, stator flux oriented vector control scheme is adopted. Based on the previous research the following assumptions are considered:

- Stator voltage drop across resistance has been neglected as the effect of stator resistance is quite low compared to the grid voltage [5].

DOI 10.17148/IJIREEICE.2015.3536

- The DFIG is connected to a stiff grid, i.e. the frequency and amplitude of the stator or grid voltage is assumed constant [7].
- Magnetizing current of the stator is assumed to be determined by the grid [7].
- The q-axis is 90^0 ahead of the d-axis and rotating at synchronous speed in the direction of rotation [8].
- The stator flux vector is aligned with the d-axis of the stator [8].

C. *RSC control*

The above assumptions lead to the following:

$$V_{ds}=0;\ V_{qs}=V_s \quad \text{And} \quad \phi_{ds}=\phi_s\ ;\phi_{qs}=0 \qquad (11)$$

OR

$$V_{ds}=0;\ V_{qs}=\omega_S\ \phi_{ds} \quad \text{and}$$

$$\phi_{ds=}L_sI_{ds}+MI_{dr}=MIms\ ; \qquad \phi_{qs=}L_sI_{qs}+MI_{qr}=0 \qquad (11)$$

$$\phi_{dr}=(M^2/L_s)\ I_{ms}+\sigma L_rI_{dr}\ ; \qquad \phi_{qr=}\ \sigma L_rI_{qs}$$

where $\sigma = 1\text{-}M^2 / L_SL_r$, ω_s is the stator electrical angular velocity and I_{ms} is magnetizing current. Neglecting the stator resistance, i.e. $R_S=0$ in equation no. (3) and (4) , thus it becomes,

$$\left.\begin{aligned} &V_{ds}=0=d\phi_{ds}/dt-\omega_s\phi_{qs}\\ &V_{qs}=\omega_s\phi_{ds}=V_s=d\phi_{qs}/dt+\omega_s\phi_{ds}\\ &V_{dr}=R_rI_{dr}+d\phi_{dr}/dt-(\omega_s-\omega_r)\phi_{qr}\\ &V_{qr}=R_rI_{qr}+d\phi_{qr}/dt-(\omega_s-\omega_r)\phi_{dr} \end{aligned}\right\} \qquad (12)$$

And equation (5) and (6) becomes;

$$\left.\begin{aligned} &\phi_{ds}=\phi_s=L_{ss}I_{ds}+L_m\ I_{dr}\\ &\phi_{qs}=\ 0=L_{ss}I_{qs}+L_m\ I_{qr}\\ &\phi_{dr}=L_{rr}I_{dr}+L_m\ I_{ds}\\ &\phi_{qr}=L_{rr}I_{qr}+L_m\ I_{qs} \end{aligned}\right\} \qquad (13)$$

Also, active and reactive powers of DFIG are equal:

$$P_s=\frac{3}{2}(V_{ds}\ I_{ds}+V_{qs}\ I_{qs}\ )=-\frac{3}{2}\frac{M}{Ls}V_{qs}\ I_{qr}$$
$$Q_s=\frac{3}{2}(V_{qs}\ I_{ds}+V_{ds}\ I_{qs}\ )=-\frac{3}{2}\ V_{qs}\left(\frac{Vqs}{\omega s\ Ls}-\frac{M}{Ls}I_{dr}\right) \qquad (14)$$

Now by using equation (11) ,above equation becomes;

$$P_s=-K_\sigma\,\omega_s\,\phi_{ds}\,\phi_{qr}$$
$$Q_s=K_\sigma\,\omega_s\,\phi_{ds}\left(\frac{Lr}{M}\phi_{ds}-\phi_{qr}\right) \qquad (15)$$

where $K_\sigma=.1.5\ L_m/\ (\sigma L_s\ \ L_r)$. Substituting equation 15 in equation (4), the rotor voltages are equal:

$$V_{dr}=\left(K_{p1}+\frac{Ki1}{S}\right)(Q_s-Q_s^{ref})+\omega_{ss}\frac{Ps}{K\sigma\ \omega s\ \phi ds}$$
$$V_{qr}=\left(K_{p2}+\frac{Ki2}{S}\right)(P_s-P_s^{ref})+\omega_{ss}\left(\frac{Lr}{M}-\frac{Qs}{K\sigma\ \omega s\ \phi ds}\right) \qquad (16)$$

where ω_{ss} is slip angular frequency. Based on equation (12), direct power control scheme of DFIG as shown in figure 6 has proposed. The stator active and reactive power control performed by PI controllers and compensation terms are second parts of equation (16).

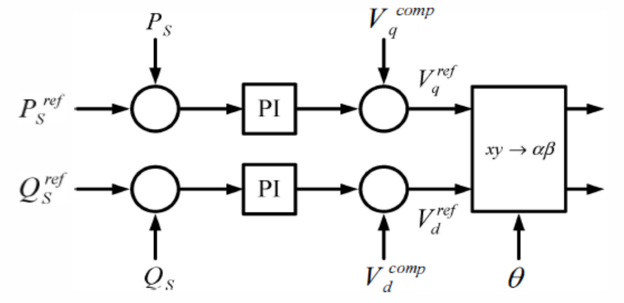


Fig. 6 Direct power control scheme of DFIG

D. *GSC control*

Voltages of grid in stationary reference frame equals:

$$V_{dg}=0;\ V_{qg}=V_x \qquad (17)$$

where 'g' denotes grid and Vx is grid voltage. Active and reactive power of GSC can be calculated as:

$$P_g=V_{qg}\ \ I_{dg}$$
$$Q_g=V_{qg}\ \ I_{qg} \qquad (18)$$

For unity power factor operation, q axis current must set to zero and DC link voltage is controlled by d-axis current. In control scheme of GSC which has shown in figure 6, a PI controller has been used for DC voltage control and produces d-axis reference current. Also, q -axis reference current set to zero for operation of GSC with unity power factor. A PLL has used for estimation of grid voltage angle to transform reference voltages to stationary reference frame for space vector modulation.

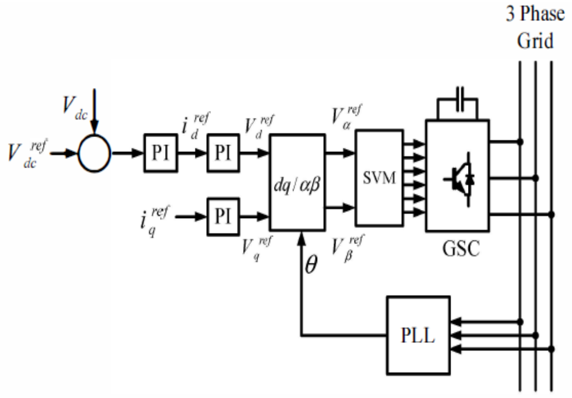


Fig. 7 Control scheme of grid side converter

E. *Nonlinear-load compensation capability*

Increasing use of power electronic convertors and AC dives in few past decades, received more attention from power quality aspects. Different methods have proposed in literatures for harmonic current mitigation of non-linear loads. Figure 4 shows the diagram of instantaneous power p-q theory which has used in this paper for active and reactive power calculation of harmonic components. This method which is most common method for calculation of harmonics active and reactive power, is based on instantaneous PQ power calculation and filtering of fundamental component of power.

A novel method has proposed for simultaneous active and reactive power control of a variable speed DFIG and power quality improvement by full harmonics compensation of nonlinear loads thorough RSC. The DPC method which explained in part VI, is used for active and reactive power control. Thus power quality improvement is performed by compensation of harmonic's active and reactive power of non-linear load.

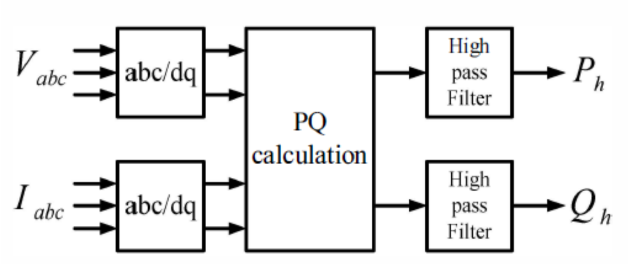


Fig.8 Instantaneous power p-q theory of harmonic calculation

F. Overall control scheme of DFIG

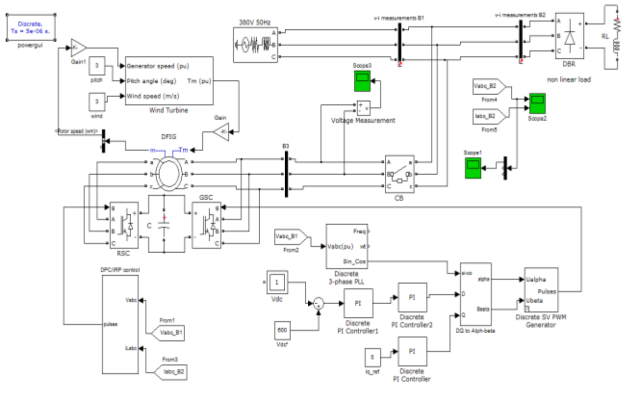


Fig.9 . MATLAB model for active and reactive power control of DFIG

VII. SIMULATION AND RESULTS

In this section simulation results for a WECS with nonlinear load have presented in MATLAB/SIMULINK. The system is based on DFIG which its characteristics are shown in table I. Figure 10 shows voltage of non-linear load which consist of 3-phase diode rectifier with RL load and connected to grid as shown in figure 9.

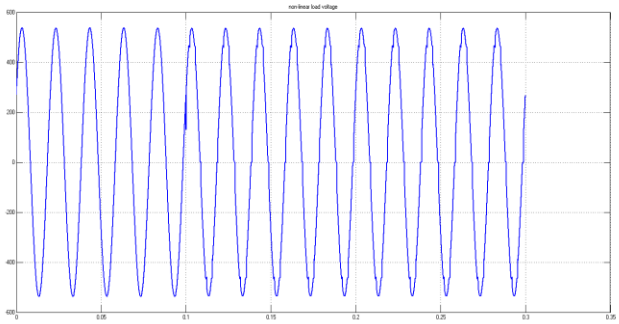


Fig.10. Non-linear load voltage

Also we have a circuit breaker as shown in fig. 9 which closes the connection of DFIG with grid at 0.1 sec. Thus Grid current and voltage before and after compensation of nonlinear load is shown in figure 11. Before compensation is up to 0.1 sec and after compensation is 0.1 sec onwards.

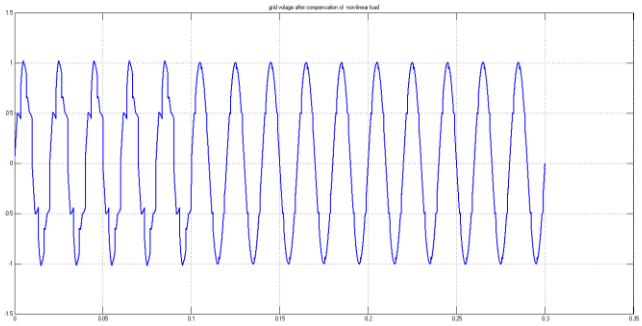


Fig.11(a) Grid voltage

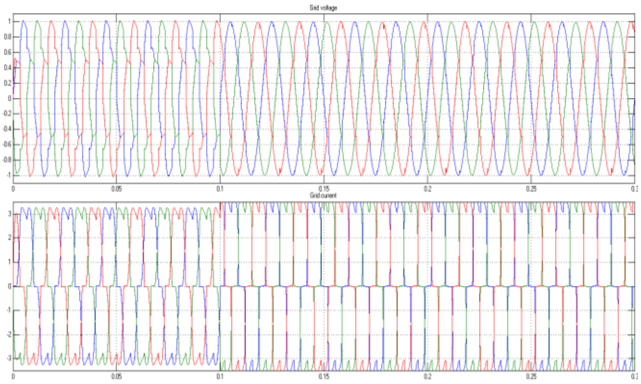


Fig.11(b). Grid current and voltage before and after compensation of non-linear load

As per the non-linear load compensation capability discussed in section VI ,the active and reactive power of DFIG for simultaneous speed control and non-linear load compensation are presented in figure 12.

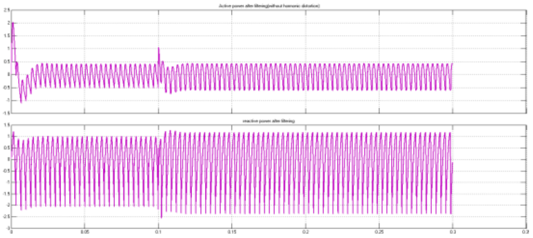
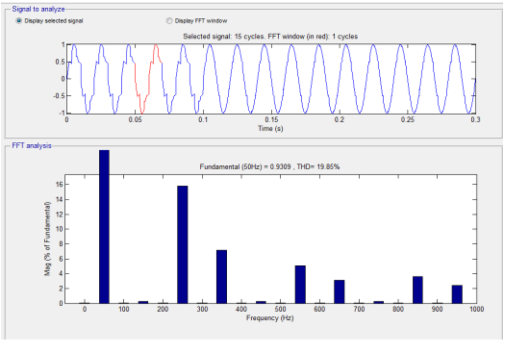


Fig.12. Active and reactive power of DFIG

Now the FFT analysis of figure 10 and 11(a) as shown below in figure 13(a) and 13(b). Also, from figure 13(a) the THD of grid voltage before compensation equals 19.85% while figures after compensation shown effectiveness of proposed method. Figures 13(b) show respectively grid voltage and its THD after compensation.



Signal to analyze
● Display selected signal
○ Display FFT window
Selected signal: 15 cycles. FFT window (in red): 1 cycles
FFT analysis
Fundamental (50Hz) = 0.9309 , THD= 19.85%

Fig.13(a)

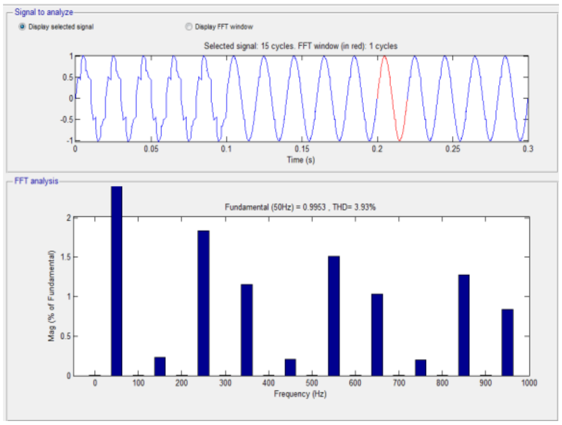


Fig.13(b)

Fig.13. FFT analysis of non-linear load voltage and Grid current of DFIG Wind energy conversion system

VIII. CONCLUSION

In this paper a novel method has proposed for direct active and reactive power control of variable speed DFIG and power quality improvement of grid in presence of non-linear load. Using variable speed DFIG have advantages which maximizing captured energy is the most important of them. In the proposed scheme, RSC controlled in such a way that provides independent control of active and reactive power and compensation of non-linear load harmonics. Active and reactive power of load harmonics calculated and added to references power values. Selective compensation of harmonics can be achieved by using selective filter. Also, GSC control provides its unity power factor operation and smooth DC link voltage. Simulation results prove effectiveness of proposed method.

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