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Performance Evaluation of PWM Converter Control Strategy for PMSG Based Variable Speed Wind Turbine

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Abstract
Integration of wind power to grid introduces power quality issues, which mainly consist of voltage regulation and reactive power compensation. Induction machines are mostly used as generators in wind power based generations. Induction generators draw reactive power from the grid to which they are connected. Therefore, the integration of wind power to power system networks is one of the main concerns of the power system engineers. The addition of wind power into the electric grid affect's the power quality This paper describes the modeling and control of a variable speed wind turbine system for medium power based Permanent Magnet Synchronous Generator (PMSG) which feeds an AC power grid. The generator speed is regulated under fluctuating wind speed through this converter. A dc link voltage controller is used to regulate the dc bus voltage under fluctuating wind and grid disturbance. The direct drive PMSG is connected to the load through a switch mode rectifier and a vector controlled pulse width modulated (PWM) IGBT-inverter. The generator side switch mode rectifier is controlled to achieve maximum power from the wind. The load side PWM inverter is using a relatively complex vector control scheme to control the amplitude and frequency of the inverter output voltage. The simulation results are obtained using MATLAB/SIMULINK software.
Keywords: Renewable Energy Sources; Variable Speed Wind Turbine; PMSG; PWM Rectifier; HBCC, STATCOM.

I. INTRODUCTION

Nowadays, the demand for electricity is increasing. Faced with this problem, and so in order to limit the use of the fossil and natural resources such as uranium, hydrocarbons and water, and to reduce pollution, some countries, have turned to new forms of energy called "renewable". These energy sources use directly or indirectly solar energy. Among these, wind is clearly in good place, not to replace conventional sources, but as complementary energy booster.

The constant speed wind turbines and induction generators were often used, in the early stages of wind power development. Some of the disadvantages of the fixed speed generators are the low efficiency, poor power quality, high mechanical stress but also that by having a fixed speed operation the maximum coefficient of performance is obtained only at a particular wind speed. Due to development of power electronics and their falling costs, the variable speed operation became the most attractive option. By running the wind turbine generator in variable speed, variable frequency mode, and the maximum power can be extracted, at low and medium wind speeds. Among all kinds of wind energy conversion systems (WECSs), a variable speed wind turbine (WT) equipped with a multi pole permanent magnet synchronous generator (PMSG) is found to be

very attractive and suitable for application in large wind farms. With gearless construction, such PMSG concept requires low maintenance, reduced losses and costs, high efficiency and good controllability. Currently, the PMSG-based WECS has been commercialized by some WT manufactures, such as Siemens Power Generation and GE Energy.

Direct-drive wind energy conversion systems based on PMSG (Permanent-Magnet Synchronous Generator) have some advantages such as no gearbox, high power density, high precision, and simple control method [1], [2]. In order to achieve objectives such as continuity and security, high levels of wind power are confronted with new challenges as well as other new approaches in the power system operation. Therefore some countries have issued dedicated grid codes for connecting the wind power systems to the grid [3]. Lately, the micro- and smart-grid have been researched for the efficiency of power management [4]. However, in these systems, the grid voltage is much fluctuated in comparison with the conventional grid. Therefore, robust control of the wind power generation system is needed for grid variations.

In general, DC-link voltage is controlled by the grid side converter. The grid-side converter may be out of control for the grid voltage sags in the conventional control method. When the grid fault

happens, the DC-link voltage is increased due to the continuous operation of the wind turbine and generator. In the proposed method, the generator- side converter controls the DC-link voltage, and the grid-side converter controls the power of the PMSG wind turbine system. The DC-link voltage control strategy by the generator- side converter has been proposed.

The STATCOM (or SSC) is a shunt-connected reactive-power compensation device that is capable of generating or absorbing reactive power and in which the output can be varied to control the specific parameters of an electric power system. It is in general a solid-state switching converter capable of generating or absorbing independently controllable real and reactive power at its output terminals when it is fed from an energy source or energy-storage device at its input terminals. Specifically, the STATCOM considered in this project is a voltage source converter that, from a given input of dc voltage, produces a set of 3-phase ac-output voltages, each in phase with and coupled to the corresponding ac system voltage through a relatively small reactance. The dc voltage is provided by an energy-storage capacitor [5] [6].
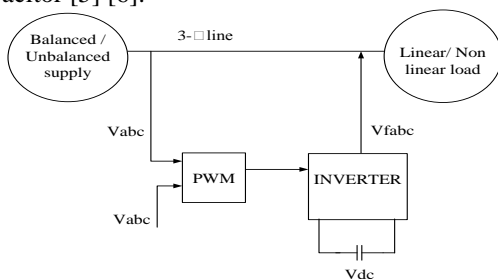

Fig.1 STATCOM Principal Diagram

A STATCOM can improve power-system performance in such areas as the following:

The dynamic voltage control in transmission and distribution systems, The power-oscillation damping in power-transmission systems, The transient stability, The voltage flicker control and The control of not only reactive power but also (if needed) active power in the connected line, requiring a dc energy source. A STATCOM is analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages—at the fundamental frequency—with controllable amplitude and phase angle. This ideal machine has no inertia, is practically instantaneous, does not significantly alter the existing system impedance, and can internally generate reactive (both capacitive and inductive) power.

II. WIND TURBINE MODEL

The rotor converts the energy contained by the wind into rotate mechanical energy. The power captured from the wind turbine is obtained as

$$P_{aer} = C_p(\lambda,\beta).\frac{\rho.S.v^3}{2} \tag{1}$$

Where Paer is the mechanical power of the wind turbine, ρ is the air density [kg/m3], S is the cross sectional area of the turbine [m2], v is the wind velocity [m/s], λ is the tip speed ratio, β is the pitch angle of rotor blades [deg], and Cp is the power coefficient.

Although this equation seems simple, Cp is dependent on the ratio between the turbine's angular velocity Ω turbine and the wind speed v. This ratio, called the tip speed ratio λ, it is given by

$$\lambda = \frac{\Omega_{turbine}R}{v} \tag{2}$$

Where: R is the radius of the turbine [m].

The power coefficient 'C$_p$' is the most important parameter for the wind energy conversion system design. It represents the turbine efficiency, and is defined as the fraction of wind energy extracted by the turbine of the total energy that would have flowed through the area swept by the rotor blades if the turbine had not been there [4]. In general, Cp is a non-linear function of the tip speed ratio λ and therefore changes with wind velocity. It is calculated from the turbine design, the pitch angle β [5]. In practice, the Cp is difficult to obtain and is different for every turbine type.

In many instances, it is provided by the manufacturer documentation which are used in many control schemes as look-up tables to generate optimal target power references [6], [7]. Various models are used to describe Cp in the literature (see e.g. [8], [9]). However, these models are only approximate and in many cases there is no valid justification for their use [10]. In all researches, authors give this coefficient 'Cp' in a mathematic function has a mechanic relationship between λ and β. In this paper the following function will be used.

$$C_p = [(0.3 - 0.0016\beta).\sin\frac{\pi(\lambda+0.1)}{10-0.3.\beta} - 0.0018(\lambda-3).\beta] \tag{3}$$
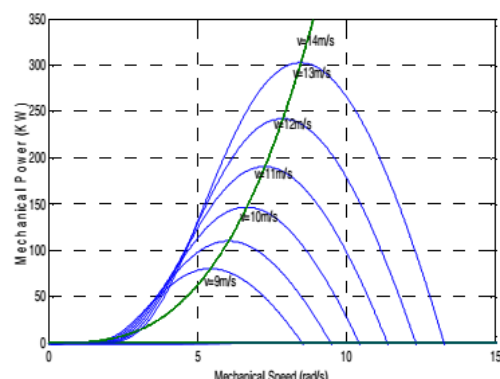

Fig.2. Typical turbine power relationships for various wind speed.

A typical relationship between Cp and λ is shown in Fig.2. It is clear from this figure that there is a value of λ for which Cp is maximized thus maximizing the power for a given wind speed.

III. PERMANENT MAGNET SYNCHRONOUS GENERATOR MODEL

The paper Theoretical models for the generator producing power from a wind turbine have been previously developed in [1]. The PMSG dynamic equations are expressed in the "d-q reference" frame. The voltage equations are given by [2].

$$v_d = -(R_s + pL_d)i_d + \omega_r L_q i_q \qquad (4)$$

$$v_q = -(R_s + pL_q)i_q - \omega_r L_d i_d + \omega_r \phi_f \qquad (5)$$

Where R_s is the phase resistance of the stator winding (ohm), L_d and L_q are the direct and quadratic stator inductance (H), v_d and v_q are the two-axis machine voltages, id and iq are the two-axis machine currents, and ϕ_f is the amplitude of the flux linkages established by the permanent magnet.

The components of the stator flux (direct and quadratic fluxes) can be given as follow

$$\phi_d = L_d i_d + \phi_f$$

$$\phi_q = L_q i_q \qquad (6)$$

The expression for the electromagnetic torque in the rotor is written as

$$T_{em} = \left(\frac{3}{2}\right) p\left[(L_d - L_q)i_d i_q - \phi_f i_q\right] \qquad (7)$$

Where p is the pair's poles number of the PMSG. The relationship between the angular frequency (ω_r) of the stator voltage and the mechanical angular velocity of the rotor (ω_m) which can be expressed as

$$\omega_m = \frac{\omega_r}{p} \qquad (8)$$

IV. MODEL OF THREE PHASE RECTIFIER

To achieve The PWM technique refers to a special switching scheme of the six power transistors of a 3-phase power converter. It generates minimum harmonic distortion to the currents wave form [4-10].
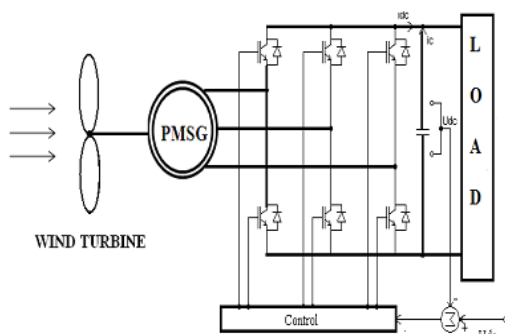

Fig.3. Basic topologies of PWM rectifier

Line to line input voltages of PWM rectifier can be described as

$$v_{ab} = (S_a - S_b)U_{dc}$$

$$v_{bc} = (S_b - S_c)U_{dc}$$

$$v_{ca} = (S_c - S_a)U_{dc} \qquad (9)$$

Where S_a, S_b, S_c Switching state of the converter and phase voltages are equal:

$$v_a = f_a U_{dc}$$

$$v_b = f_b U_{dc}$$

$$v_c = f_c U_{dc} \qquad (10)$$

Where

$$f_a = \frac{2S_a - (S_b + S_c)}{3}$$

$$f_b = \frac{2S_b - (S_a + S_c)}{3}$$

$$f_c = \frac{2S_c - (S_a + S_b)}{3} \qquad (11)$$

The voltage equations for balanced three-phase system without the neutral connection can be written as

$$\bar{e} = \bar{v_l} + \bar{v} \qquad (12)$$

$$\bar{e} = R\bar{i} + L\frac{d\bar{i}}{dt} + \bar{v} \qquad (13)$$

$$\begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (14)$$

And additionally for currents

$$i_c = i_{dc} - i_{ch} \qquad (15)$$

$$C\frac{dU_{dc}}{dt} = S_a i_a + S_b i_b + S_c i_c - i_{ch} \qquad (16)$$

The voltage equations in the stationary α, β are written as

$$Ri_\alpha + L\frac{di_a}{dt} = e_\alpha - U_{dc}S_\alpha \qquad (17)$$

$$Ri_\beta + L\frac{di_\beta}{dt} = e_\beta - U_{dc}S_\beta \qquad (18)$$

And

$$C\frac{dU_{dc}}{dt} = \sum_{k=\alpha}^{\beta} S_n i_n - i_{ch} = \frac{3}{2}(S_\alpha i_\alpha + S_\beta i_\beta) - i_{ch} \qquad (19)$$

Where

$$S_\alpha = \frac{1}{\sqrt{6}}(2S_a - S_b - S_c) \tag{20}$$

$$S_\beta = \frac{1}{\sqrt{2}}(S_b - S_c) \tag{21}$$

The equations in the synchronous d-q coordinates are obtained using the following transformations

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/2 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{22}$$

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} \cos\gamma & \sin\gamma \\ -\sin\gamma & \cos\gamma \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{23}$$

$$e_d = Ri_d + L\frac{di_d}{dt} - \omega L i_q + v_d \tag{24}$$

$$e_q = Ri_q + L\frac{di_q}{dt} + \omega L i_d + v_q$$

$$C\frac{dU_{dc}}{dt} = \frac{3}{2}\sum_{k=d}^{q} S_n i_n - i_{ch} = (S_d i_d + S_q i_q) - i_{dc} \tag{25}$$

Where

$$S_d = S_\alpha \cos\omega t + S_\beta \sin\omega t \tag{26}$$

$$S_q = S_\beta \cos\omega t - S_\alpha \sin\omega t \tag{27}$$

V. HYSTERESIS BAND CURRENT CONTROL STRATEGY

The three-phase line currents are compared with stationary three-phase reference currents to generate a current error Δi_0 , which is applied to a current controller constituting a hysteresis loop to generate variable frequency PWM pulses. The characteristics of HBCC can be represented as

$$a = \begin{cases} 0 \\ 1 \end{cases} \quad \text{If} \quad \begin{cases} \Delta i_0 \le \Delta h/2 \\ \Delta i_0 > \Delta h/2 \end{cases} \tag{28}$$

Where Δh is the hysteresis band width and 'a' is a variable. Fig.5 shows the block diagram of a wind generation system controlled by HBCC technique. It is important to note that the pulses used to drive the controlled rectifier have a variable frequency because the current variations are limited from the upper to the lower level and vice versa. HBCC has a fast response to brapid variations in reference currents with a small delay. The direct voltage Udc is measured and

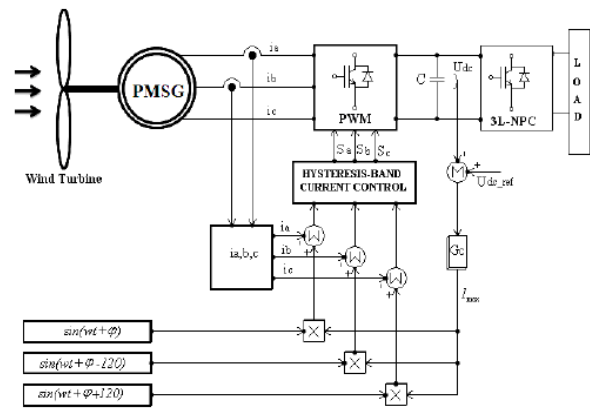compared with the Udc_ref. the resulted signal is used to create the current reference.

Fig. 4. Power conversion system with a hysteresis band Pulse Width Modulation (PWM).

VI. FLUX ORIENTED CONTROL STRATEGY

The concept of Flux oriented control (FOC) can also be applied to improve (VOC) scheme, because disturbances superimposed onto the line voltage influence directly the coordinate transformation in control system (36). Sometimes this is solved only by phase-locked loops (PLL.s) only, but the quality of the controlled system depends on how effectively the (PLL.s) have been designed [10]. Therefore, it is easier to replace angle of the line voltage vector γe by angle of flux vector γ_Ψ, because γ_Ψ is less sensitive than γe to disturbances in the line voltage, For this reason, it is not necessary to implement (PLL.s) to achieve robustness in the flux oriented scheme, since $\overline{\Psi}$ rotates much more smoothly, the angular displacement of flux vector $\overline{\Psi}$ in α-β coordinate is defined as [9].

$$\sin\gamma_\Psi = \Psi_\beta / \sqrt{(\Psi_\alpha)^2 + (\Psi_\beta)^2}$$

$$\cos\gamma_\Psi = \Psi_\alpha / \sqrt{(\Psi_\alpha)^2 + (\Psi_\beta)^2} \tag{29}$$
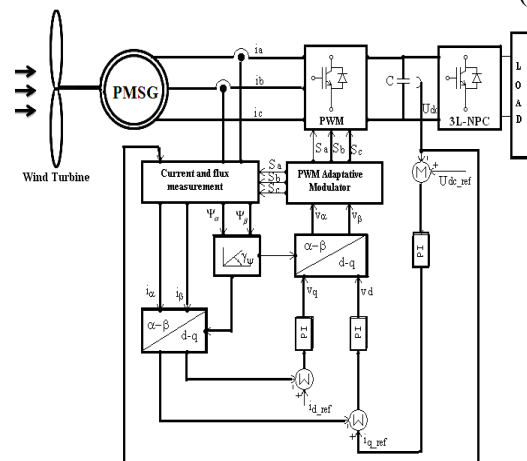

Fig.8. Block diagram of FOC

The vector flux lags the voltage vector by 90^0 (Fig.6). Therefore, for the unity power factor condition, the d-component of the current vector i should be zero.
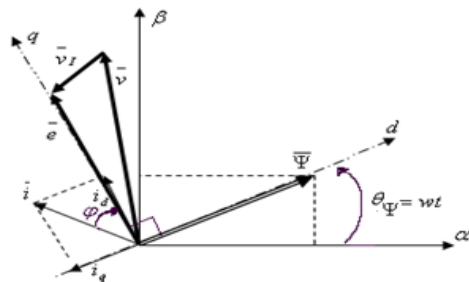

Fig.9. Flux Oriented Control phasor diagram

In the flux oriented coordinates voltage equations are transformed into

$$0 = L\frac{di_d}{dt} - \omega.Li_q + v_d$$

$$e_q = L\frac{di_q}{dt} + \omega.Li_d + v_q \qquad (30)$$

For id = 0 equations (37) can be described as

$$0 = v_d - \omega.Li_q$$

$$e_q = L\frac{di_q}{dt} + v_q \qquad (31)$$

As current controller, the PI-type can be used. However, the PI current controller has no satisfactory tracing performance, especially, for the coupled system described by equation (30). Therefore for high performance application with accuracy current tracking at dynamic state the decoupled controller diagram for the PWM rectifier should be applied what is shown in (Fig.7) [10]
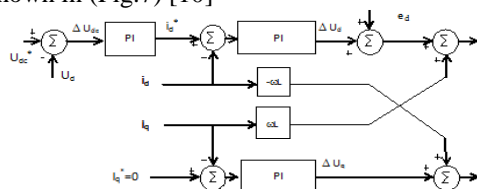
Fig.7. Decoupled current control of PWM rectifier

$$V_d = e_d + \omega.L.i_q + u_d$$

$$V_q = -\omega.L.i_d + U_q \qquad (32)$$

Where u_d and u_q the output signals of the current controllers.

VII. MATLAB/SIMULATION RESULTS

Here simulation is carried out in different cases, in that
1). Implementation of Proposed High Performance PWM Converter based on FOC STATCOM. 2). Implementation of Proposed High Performance PWM

Converter based on Hysteresis Band Control STATCOM.

Case 1: Implementation of Proposed High Performance PWM Converter based on FOC STATCOM
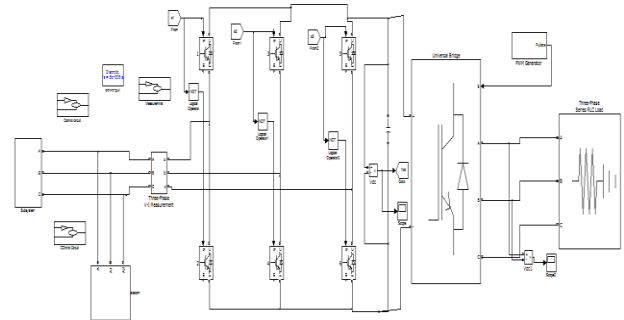

Fig.10 Matlab/Simulink Model of Proposed High Performance PWM Converter based on FOC STATCOM

Fig.10 shows the Matlab/Simulink Model of Proposed High Performance PWM Converter based on FOC STATCOM using Matlab/Simulink Platform.
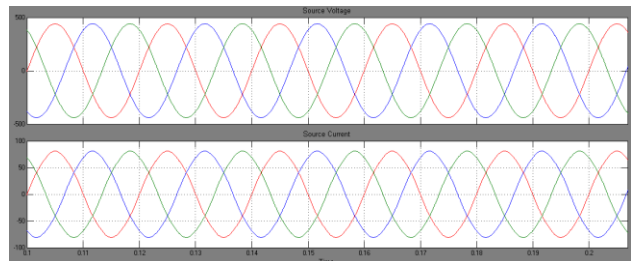

Fig.11 Source Voltage & Source Current

Fig.11 shows the Source Voltage & Source Current of Proposed High Performance PWM Converter based on FOC STATCOM.
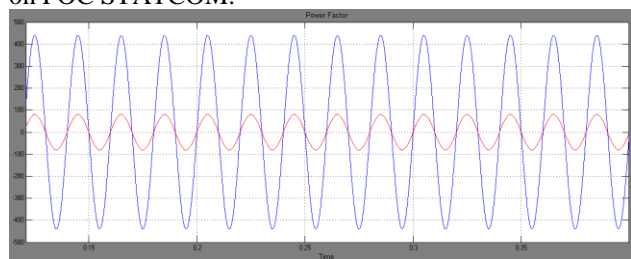

Fig.12 Source Power Factor

Fig.12 shows the Source Power Factor of Proposed High Performance PWM Converter based on FOC STATCOM.
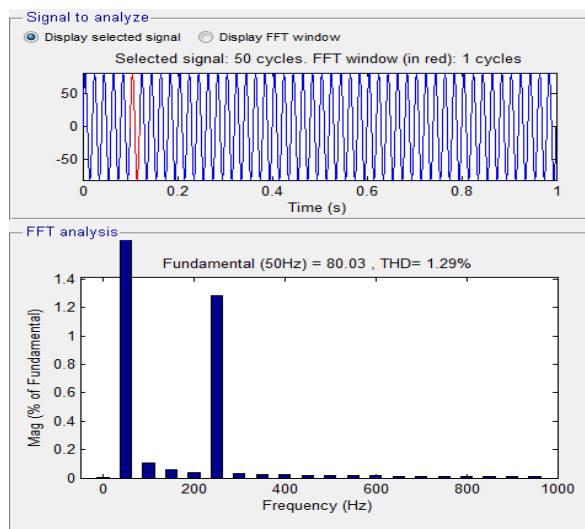
Fig.13 FFT Analysis of Source Current of Proposed High Performance PWM Converter based on FOC STATCOM

Fig.13 FFT Analysis of Source Current of Proposed High Performance PWM Converter based on FOC STATCOM.
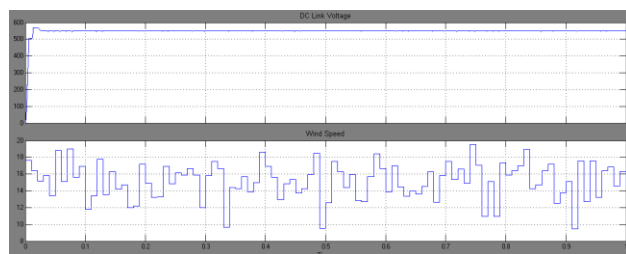

Fig.14 DC Link Voltage & Wind Speed

Fig.14 shows the DC Link Voltage & Wind Speed of Proposed High Performance PWM Converter based on FOC STATCOM.

Case 2: Implementation of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM
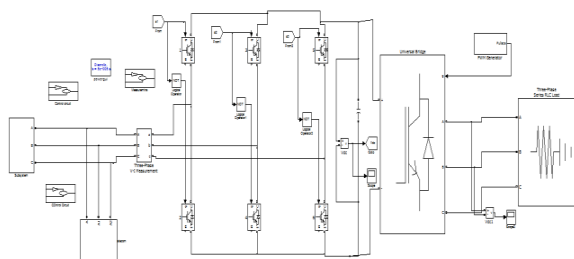

Fig.15 Matlab/Simulink Model of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM

Fig.15 shows the Matlab/Simulink Model of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM using Matlab/Simulink Platform.
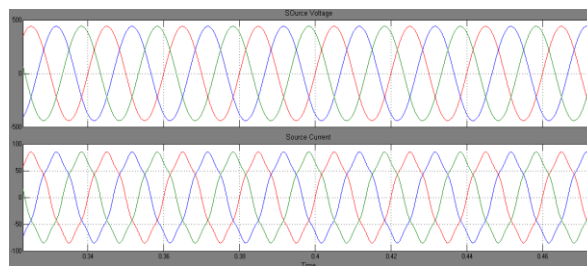

Fig.16 Source Voltage & Source Current

Fig.16 shows the Source Voltage & Source Current of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM.
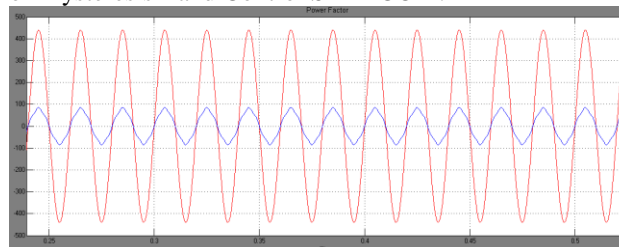

Fig.17 Source Power Factor

Fig.17 shows the Source Power Factor of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM.
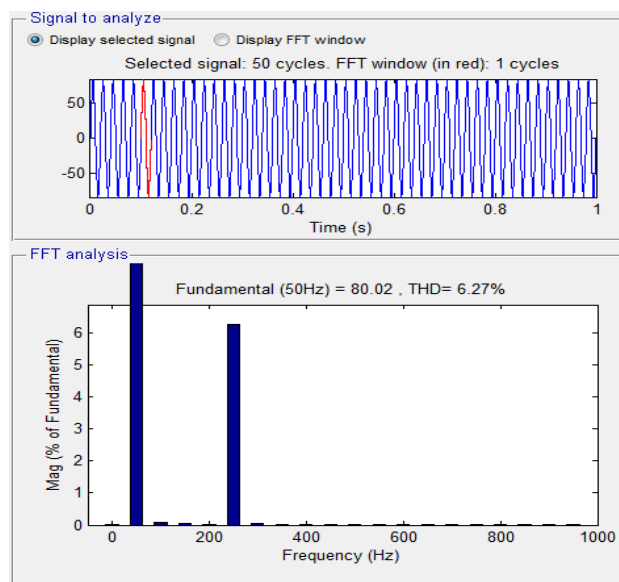

Fig.18 FFT Analysis of Source Current of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM

Fig.18 FFT Analysis of Source Current of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM.
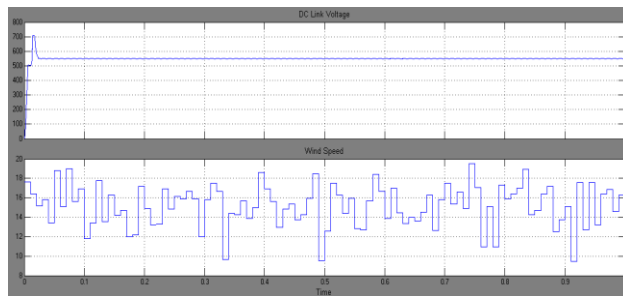
Fig.19 DC Link Voltage & Wind Speed

Fig.19 shows the DC Link Voltage & Wind Speed of Proposed High Performance PWM Converter based on Hysteresis Band Control STATCOM.

VIII. CONCLUSION

The impact of ever-changing wind speed on power quality coupled with the need for an excitation current make the voltage regulation difficult, especially when the IG is connected to a weak ac system. A STATCOM composed of a three phase IGBT-based VSI, a filter and a dc capacitor, is employed. The basic STATCOM active and reactive current control can be derived from the STATCOM model. Using Matlab and Simulink, we establish a wind turbine simulation model for having best wind-speed ratio coefficient at variable wind speed adjustment. The simulation can achieve various static performance of the system by inputting or adjusting parameters or data during simulation. The simulation result showing a wave form indicates that the tracking of best speed ratio of wind turbine can be realized. In these results, we can affirm that the PWM-HBCC which gives fast dynamic response, good precision and high robustness. But, shown in simulation FOC and HBCC control strategie with STATCOM give a small THD in comparison by the FOC and HBCC without STATCOM, and also the FOC is better than the HBCC. So these results affirm that the field estimation ameliorates the HBCC.

REFERENCES

[1] R. Mittal, K.S. Sandu and D.K. Jain, "Isolated operation of variable speed driven PMSG for wind energy conversion system", IACSIT International Journal of Engineering and Technology vol. 1, no.3, pp. 269-273, August 2009.
[2] M. Malinowski, "Sensorless control strategies for three – phase PWM rectifiers". Phd Thesis, Faculty of Electrical Engineering Institute of Control and Industrial Electronics, 2001.
[3] S. R. Hadian-Amrei and H. Iranmanseh, "Novel direct power control for compensating voltage unbalance and load fluctuations in PWM rectifiers", ACSE Journal, vol. 6, no. 4, Dec., 2006; pp. 39-45.
[4] J. F. Walker and N. Jenkins, "Wind eEnergy technology". John Wiley & Sons, Inc., United States, 1997.
[5] T. Thiringer and J. Linders, "Control by variable rotor speed of a fixed-pitched wind turbine operating in a wide speed range". IEEE Transactions on Energy Conversion, vol. 8, no. 3, 1993.
[6] E. Muljadi, K. Pierce and P. Migliore. "Control strategy for variable-speed, stall-regulated wind turbines". Proceedings of the American Control Conference, 1998. vol. 3, pp. 1710 – 1714, 24- 26 June 1998.
[7] R. Datta, V. T. Ranganathan, "Variable-speed wind power generation using doubly fed wound rotor induction machine – a comparison with alternative schemes". IEEE Transactions on Energy Conversion, vol. 17, no. 3, 2002.
[8] J. G. Slootweg, H. Polinder and W. L. Kling, "Representing wind Turbine electrical generating systems in fundamental frequency simulations". IEEE Transactions on Energy Conversion, vol. 18, no. 4, 2003.
[9] L. Dodson, K. Busawon and M. Jovanovic, "Estimation of the power coefficient in a wind conversion system". Proceedings of the 44th IEEE Conference on Decision and Control and the European Control Conference, Seville, Spain, pp. 3450-3455, December 12-15, 2005.
[10] M. Malinowski, "Sensorless control strategies for three – phase PWM rectifiers". Phd Thesis, Faculty of Electrical Engineering Institute of Control and Industrial Electronics, 2001.

BIOGRAPHY

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