Point of Common Coupling Voltage Control of a DFIG Wind Turbine Connected to Weak Grid

BIJAYA POKHAREL and OLORUNFEMI OJO
Department of Electrical and Computer Engineering/Center for Energy System Research
Tennessee Technological University
Cookeville, TN38505
bpokharel42@students.tetech.edu
jojo@tntech.edu

ABSTRACT

DFIG wind turbine system is the most popular wind power generator in current market. Even though the active and reactive power output of DFIG can be controlled independently, the active power output of those wind turbines varies with wind speed. The converters in DFIG have limited capacity as a result it cannot supply usually required reactive power hence the terminal voltage of the wind turbine system connected to weak distribution grid fluctuates. So voltage regulation device is required for safe operation of power grid. This paper proposes the use of Static Synchronous Compensator (STATCOM) as a voltage regulating device at the point of common coupling to minimize terminal voltage fluctuation of the wind turbine system operating at maximum power point tracking mode (MPPT) during varying wind speed. The control scheme for DFIG wind turbine system and STATCOM is systematically developed and the effectiveness of the proposed system is verified by simulating in MATLAB/Simulink software.

Keywords: DFIG wind turbine system, STATCOM, Voltage Regulation, Voltage Fluctuation, MPPT

1. INTRODUCTION

Wind power is the most reliable and developed renewable energy source over past decades. The increased awareness of people towards renewable energy, support from governmental institution and rapid advancement in power electronics industry, which is the core of wind power system, are the most contributing factors for the development of wind power systems. Hence the share of wind power with respect to total installed power capacity is increasing. With the increased penetration level of wind power in power system, additional services, such as voltage control provided by the wind turbines, become more important [1]. Most utility companies want wind turbine generator systems to behave analogous to conventional synchronous generators in terms of supplying active and reactive powers [2]. Unfortunately, most wind farms are usually located at remote places, driven by wind and weather patterns with little up-front analysis performed regarding the existing power grid in that location and such locations tend to be weaker points in the distribution system. So they require extra reactive power compensation devices for connecting wind farms to the grid [3].

Variable speed wind turbines generators utilizing doubly fed induction generators (DFIGs) are most popular in the wind power industry especially for multimegawatt wind turbine generators [2]. DFIG is a wound-rotor induction generator which is connected to the grid at the stator terminals, as well as at the rotor mains via a partially rated variable frequency ac/dc/ac converter (VFC), which only needs to handle a fraction (25 –30 %) of the total power to accomplish full control of the generator. The functional principle of this variable speed generator is the combination of DFIG and four-quadrant ac/dc/ac VFC equipped with IGBTs. The ac/dc/ac converter system consists of a rotor-side converter (RSC) and a grid-side converter (GSC) connected back-to-back by a dc-link capacitor. The beauty of DFIG is its efficient power conversion capability at variable wind speed with low price because of partial size rated converter.

Although wind turbines with DFIG are able to control active and reactive power independently, the reactive power capability of those generators is subject to several limitations resulting from the voltage, current, and speed, which change with the operating point [2]. The aerodynamic aspects of the wind turbines create terminal voltage fluctuation in wind turbine [4]. Since the DFIG has power electronic converters with limited capacity, it cannot supply usually demanded reactive power on a continuous basis. If the wind farm is far from the point of common coupling (PCC), then there will be more loss if reactive power is generated from DFIG.

In [4] and [5], STATCOM is proposed to minimize voltage fluctuation in DFIG system. In [6], reactive power compensation using STATCOM is proposed for improving fault ride-through capability and transient voltage stability in DFIG system. Although external hardware increases the cost of overall system, STATCOM can be used to provide reactive power in already installed DFIG system that has voltage regulation problem.

Hence in this paper, use of STATCOM connected at the PCC with the weak distribution grid to regulate the voltage so that connected load to the system always gets required power with regulated voltage during varying wind speed is investigated. DFIG wind turbine system operating in maximum power point tracking mode (MPPT) and blade pitch control (power regulation) mode is modeled. Vector control approach is used for the electrical power output control from DFIG. A STATCOM is designed to regulate voltage at the PCC with the weak distribution grid so that connected load to the system always gets required power with regulated voltage during varying wind speed in the wind generation system.

The remainder of the paper is organized as follows. Section II describes about variable speed wind turbine modeling and control. Section III discusses about DFIG control scheme. Section IV introduces the STATCOM modeling and controller design whereas section V briefly shows the studied system. Section VI shows the results obtained using MATLAB/Simulink and finally section VII concludes the paper.

2. WIND TURBINE MODELING AND CONTROL

The turbine is the prime mover of Wind Energy Conversion System (WECS) that enables the conversion of kinetic energy of wind E_w into mechanical power P_m and eventually into electricity.

$$P_m = \frac{\partial E_w}{\partial t}\ C_p = \frac{1}{2}\rho\ A\,V_w^{\ 3}\ C_p \qquad (1)$$

where V_w is the wind speed at the center of the rotor (m/sec), ρ is the air density (kg/m^3), A is the frontal area of the wind turbine (m^2); R being the rotor radius. C_p is the performance coefficient which in turn depends upon turbine characteristics (blade pitch angle β and tip speed ratio (TSR)) that is responsible for the losses in the energy conversion process. The numerical approximation of C_p used in this study is [7]:

$$C_p(\lambda,\beta) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-21/\lambda_i} + 0.0068\lambda \quad (2)$$

where the TSR λ and $\lambda_i = f(\lambda,\beta)$ are given by-

$$\lambda = \frac{\omega_t R}{V_w} \text{ and } \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (3)$$

where ω_t is the turbine speed and R is the blade radius of the wind turbine. The plot of C_p Vs λ at various values of β is shown in Fig. 1.

2.1 MAXIMUM POWER POINT TRACKING MODE

From the plot shown in Fig. 1, we can state that-

For β= 0 degree, $\lambda_{opt} = 8.1$ and $C_{p\_\max} = 0.48$

Now the rotor mechanical torque extracted from the wind that in turn drives wind generator is: $T_t = \frac{P_m}{\omega_t}$

Now from equations (1) and (3),

$$T_t = \frac{1}{2\omega_t}\rho A V_w{}^3 C_p = \frac{R}{2\lambda}\rho A V_w{}^2 C_p \quad (4)$$

From equation (4) if we are able to run the wind generator that corresponds to wind speed V_w in such a way that wind turbine will be operating in maximum power point (as shown in Fig. 2) then we can extract maximum available power from the available wind speed via wind turbine.

2.2 Blade Pitch Control Mode

Pitch angle control is the most common means for adjusting the aerodynamic torque of the wind turbine when wind speed is above rated speed. In high speed operation, generator power begins to exceed its rated power so the pitch control will be activated which pitches the wind turbine blades by angle β so as to extract less mechanical power (as shown in Fig.1. when β increases, C_p decreases means P_m decreases) from wind. In this study the combined turbine speed and turbine mechanical power is chosen as the controlling variables for pitch control as shown in Fig. 4. The proportional and integral gains of the pitch controller are specified by the manufacturer.

Two distinct operating modes of DFIG wind turbines at different wind speed is clearly shown in Fig. 3.

3. DFIG MODELLING AND CONTROL

The dynamics of DFIG is represented by a fourth-order state space model using the synchronously rotating reference frame (qd-frame) as follows [8]:

(where $p = \frac{d}{dt}$ throughout the paper)

$$V_{qs} = r_s I_{qs} + \omega\lambda_{ds} + p\lambda_{qs} \quad (5)$$

$$V_{ds} = r_s I_{ds} - \omega\lambda_{qs} + p\lambda_{ds} \quad (6)$$

$$V_{qr} = r_r I_{qr} + (\omega - \omega_r)\lambda_{dr} + p\lambda_{qr} \quad (7)$$

$$V_{dr} = r_r I_{dr} - (\omega - \omega_r)\lambda_{qr} + p\lambda_{dr} \quad (8)$$

where V_{qs}, V_{ds}, V_{qr}, V_{dr} are the q and d-axis stator and rotor voltages; I_{qs}, I_{ds}, I_{qr}, I_{dr} are the q and d-axis stator and rotor currents; λ_{qs}, λ_{ds}, λ_{qr}, λ_{dr} are the q and d-axis stator and rotor fluxes; ω is the angular velocity of the synchronously rotating reference frame; ω_r is the rotor angular velocity and r_s and r_r are the stator and rotor resistances. The flux linkage equations are given as:

$$\lambda_{qs} = L_s I_{qs} + L_m I_{qr} \quad (9)$$

$$\lambda_{ds} = L_s I_{ds} + L_m I_{dr} \quad (10)$$

$$\lambda_{qr} = L_m I_{qs} + L_r I_{qr} \quad (11)$$

$$\lambda_{dr} = L_m I_{ds} + L_r I_{dr} \quad (12)$$

where L_s, L_r and L_m are the stator, rotor and mutual inductances respectively with $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$: L_{ls} being the self inductance of stator and L_{lr} being the self inductance of rotor.

All the equations above are induction motor equations, if induction motor acts as generator then current direction will be opposite. Assuming negligible power losses in stator and rotor resistances, the active and reactive powers are given as:

$$P_s = -\frac{3}{2}\left[V_{qs} I_{qs} + V_{ds} I_{ds}\right] \quad (13)$$

$$Q_s = -\frac{3}{2}\left[V_{qs} I_{ds} - V_{ds} I_{qs}\right] \quad (14)$$

$$P_r = -\frac{3}{2}\left[V_{qr} I_{qr} + V_{dr} I_{dr}\right] \quad (15)$$

$$Q_r = -\frac{3}{2}\left[V_{qr} I_{dr} - V_{dr} I_{qr}\right] \quad (16)$$

The total active and reactive power generated by DFIG is:

$$P_{Total} = P_s + P_r \text{ and } Q_{Total} = Q_s + Q_r$$

If P_{Total} and Q_{Total} both are positive; DFIG is supplying power to the power grid, else it is drawing power from the grid. The rotor speed dynamics of the DFIG is given as:

$$p\omega_r = \frac{P}{2J}(T_m - T_e - C_f \omega_r) \quad (17)$$

where P is number of poles of the machine, C_f is friction coefficient, J is inertia of the rotor, T_m is the mechanical torque generated by wind turbine and T_e is the electromagnetic torque generated by the machine which is given as:

$$T_e = \frac{3}{2}\left[\lambda_{qs} I_{ds} - \lambda_{ds} I_{qs}\right] \quad (18)$$

where positive (negative) values of T_e means DFIG works as a generator (motor).

Electrical control of DFIG is achieved by controlling the RSC and GSC. The control objective of RSC is to regulate the stator side active power P_s (or rotor speed ω_r) and the reactive power Q_s independently. Similarly the control objective of GSC is to maintain constant dc-link voltage and to control reactive power injected by GSC to the grid regardless of magnitude and direction of rotor power [9].

3.1 Control of the RSC

Fig. 5 shows the general vector control scheme of the RSC in which independent control of P_s and Q_s is achieved by controlling rotor current. Aligning the d-axis of reference frame along the stator flux linkage vector then λ_{qs} = 0 and λ_{ds} = λ_s. Substituting λ_{qs} = 0 in (18) and (9) and solving we get,

$$T_e = -\frac{3P}{4}\frac{L_m}{L_s}\lambda_{ds} i_{qr} \quad (19)$$

From (17) and (19):

$$i_{qr} = \left(\frac{2J}{P}p\omega_r - T_m\right)\frac{4}{3P}\frac{L_s}{L_m \lambda_{ds}} \quad (20)$$

Equation (20) gives the rotor speed dynamics for designing speed control. Similarly substituting λ_{qs} = 0 and solving (9), (10) and (14) gives:

$$i_{dr} = \frac{\lambda_{ds}}{L_m} - \frac{2}{3}\frac{L_s Q_s^*}{L_m V_{qs}} \quad (21)$$

where Q_s^* is the desired reactive power that stator supplies to the grid. Equation (21) gives the stator reactive power control equation. Now substituting values of λ_{dr} and λ_{qr} given by (11) and (12) into (7) and (8) and during steady state and further simplification yields,

$$V_{qr} = r_r i_{qr} + \sigma L_r p i_{qr} + \omega_{so}\left(\frac{L_m}{L_s}\lambda_{ds} + \sigma L_r i_{dr}\right) \quad (22)$$

$$V_{dr} = r_r i_{dr} + \sigma L_r p i_{dr} - \omega_{so}\sigma L_r i_{qr} \quad (23)$$

where $\omega_{so} = (\omega - \omega_r)$ and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$.

Equation (22) and (23) gives the inner current control loop for the RSC control.

3.2 Control of the GSC

Fig. 6 shows the general vector control scheme of the GSC where control of dc-link voltage V_{dc} and reactive power exchange between GSC and power grid is achieved by controlling current in synchronously reference frame [8].

Aligning the stator voltage vector along q-axis of reference frame then $V_{ds} = 0$ and $V_{qs} = V_s$. Now dc voltage dynamics in dc-link is given by,

$$C\ pV_{dc} = I_o + \frac{3}{4}\left(M_{df} i_{df} + M_{qf} i_{qf}\right) \quad (24)$$

where C is the dc-link capacitance, I_o is the dc current from RSC towards GSC and M_{df} and M_{qf} are q and d-axis modulation indexes of GSC respectively. Since $V_{ds} = 0$, assuming $V_{ds} \approx V_{df}$ and $V_{qs} \approx V_{qf}$ so, $M_{df} \approx 0$. Hence equation (24) will be:

$$i_{qf} = \frac{4}{3}\frac{1}{M_{qf}}\left(C\ pV_{dc} - I_o\right) \quad (25)$$

Similarly, the GSC supplied reactive power is controlled using d-axis current given by following relation.

$$i_{df} = \frac{2}{3}\frac{Q_f^*}{V_{qf}} \quad (26)$$

where Q_f^* is the desired reactive power to be supplied to the grid via GSC. Again using KVL across the RL filter gives:

$$V_{qf} = r_f i_{qf} + L_f p i_{qf} + \omega_s L_f i_{df} + V_{qs} \quad (27)$$

$$V_{df} = r_f i_{df} + L_f p i_{df} - \omega_s L_f i_{qf} \quad (28)$$

Equation (27) and (28) gives the inner current control loop for the GSC control.

3.1 STATCOM MODELLING AND CONTROLLER DESIGN

STATCOM is modelled as a PWM converter comprising of IGBT with a dc-link capacitor and a coupling transformer connected in shunt to the distribution network through a coupling transformer as shown in Fig. 7. The objective of STATCOM is to regulate the voltage magnitude swiftly at the PCC bus within a desired range by exchanging the reactive power with the distribution system. At the same time the converter in STATCOM should maintain constant dc-link voltage. A filter capacitor C_m is also connected in shunt to the same bus for mitigating harmonics.

Dynamic equations of the STATCOM converter in qd reference frame:

$$V_{q1} = r_s I_{q1} + L_s pI_{q1} + \omega L_s I_{d1} + V_{q2} = M_{q1}\frac{V_{dc}}{2} \quad (29)$$

$$V_{d1} = r_s I_{d1} + L_s pI_{d1} - \omega L_s I_{q1} + V_{d2} = M_{d1}\frac{V_{dc}}{2} \quad (30)$$

where V_{q1}, V_{d1}, V_{q2}, V_{d2} are the q and d-axis converter output voltages and PCC bus voltages respectively, I_{q1}, I_{d1} are the q and d-axis converter output currents, r_s and L_s are line resistance and inductance respectively, M_{q1} and M_{d1} are q and d-axis modulation indexes of the converter respectively, V_{dc} is the dc-link voltage and ω is the angular velocity of the synchronously rotating reference frame.

Again in the converter, dc voltage dynamics in dc-link is given by:

$$C_{dc} pV_{dc} = -\frac{3}{4}(M_{q1}I_{q1} + M_{d1}I_{d1}) \qquad (31)$$

The voltage magnitude (V_m) at PCC is given as.

$$V_m^2 = V_{q2}^2 + V_{d2}^2 \qquad (32)$$

Differentiating (32) w.r.t. time,

$$pV_m^2 = 2V_{q2}pV_{q2} + 2V_{d2}pV_{d2} \qquad (33)$$

Equation (33) gives the square of voltage magnitude dynamics at PCC. Then the voltage magnitude will be: $V_m = \left|\sqrt{V_m^2}\right|$.

DC-voltage control:

Equation (31) can be rewritten as:

$$-\frac{4}{3}C_{dc} pV_{dc} = (M_{q1}I_{q1} + M_{d1}I_{d1}) = \sigma_{dc} = k_{dc}(V_{dc}^* - V_{dc}) \qquad (34)$$

where k_{dc} is the PI controller for dc-voltage control given as:

$k_{dc} = \left(k_{Pdc} + \frac{k_{Idc}}{s}\right)$. Then equation (34) will be:

$$\frac{4}{3}C_{dc} pV_{dc} = \left(k_{Pdc} + \frac{k_{Idc}}{s}\right)V_{dc}^* - \left(k_{Pdc} + \frac{k_{Idc}}{s}\right)V_{dc}$$

$$\Rightarrow \frac{V_{dc}}{V_{dc}^*} = \frac{\frac{3}{4C_{dc}}\left(sk_{Pdc} + k_{Idc}\right)}{s^2 + s\frac{3k_{Pdc}}{4C_{dc}} + \frac{3k_{Idc}}{4C_{dc}}} \qquad (35)$$

Comparing denominator of (34) with Butterworth second order polynomial i.e. $s^2 + \sqrt{2}\omega_{0dc}s + \omega_{0dc}^2$,

$$k_{Pdc} = \frac{4}{3}\sqrt{2}\omega_{0dc}C_{dc} \; and \; k_{Idc} = \frac{4}{3}C_{dc}\omega_{0dc}{}^2$$

where ω_{0dc} is the bandwidth of the DC-voltage controller, which depends upon the design value.

Voltage magnitude control:

From Fig. 7, the dynamic voltage equations at PCC can be written as:

$$C_m \; pV_{q2} = I_{q1} - I_{q2} - C_m\omega V_{d2} \qquad (36)$$

$$C_m \; pV_{d2} = I_{d1} - I_{d2} + C_m\omega V_{q2} \qquad (37)$$

Substituting (36) and (37) into (33) gives:

$$\frac{C_m}{2} pV_m^2 = V_{q2}\left(I_{q1} - I_{q2}\right) + V_{d2}\left(I_{d1} - I_{d2}\right) = \sigma_m = k_m(V_m^{2*} - V_m^2) \qquad (38)$$

where $k_m = \left(k_{Pm} + \frac{k_{\text{Im}}}{s}\right)$ is the PI controller for voltage magnitude control. Then equation (38) can be written as:

$$C_m pV_m^2 = \left(k_{Pm} + \frac{k_{\text{Im}}}{s}\right)V_m^{2^*} - \left(k_{Pm} + \frac{k_{\text{Im}}}{s}\right)V_m^2 \qquad (39)$$

$$\frac{V_m^2}{V_m^{2^*}} = \frac{\frac{2}{C_m}\left(sk_{Pm} + k_{\text{Im}}\right)}{s^2 + s\frac{2k_{Pm}}{C_m} + \frac{2k_{\text{Im}}}{C_m}} \quad (40)$$

Comparing denominator of (40) with Butterworth second order polynomial, we get:

$$k_{Pm} = \sqrt{2}\omega_{0m}\frac{C_m}{2} \;\; and \;\; k_{\text{Im}} = \frac{C_m}{2}\omega_{0m}{}^2$$

where ω_{0m} is the bandwidth of the voltage controller, which depends upon the design value.

Inner current control:

If we assume:

$$r_s I_{q1} + L_s p I_{q1} = K_{1q}(I^*{}_{q1} - I_{q1}) = \sigma_{1q} \quad (41)$$

$$r_s I_{d1} + L_s p I_{d1} = K_{1d}(I^*{}_{d1} - I_{d1}) = \sigma_{1d} \quad (42)$$

Then equation (29) and (30) can be written as:

$$M_{q1} = (\sigma_{1q} + \omega L_s I_{d1} + V_{q2})\frac{2}{V_{dc}} \quad (43)$$

$$M_{d1} = (\sigma_{1d} - \omega L_s I_{q1} + V_{d2})\frac{2}{V_{dc}} \quad (44)$$

Equation (43) and (44) gives modulation indexes which are the output of the converter. And K_{1q} and K_{1d} are PI current controllers for q and d axis currents respectively, where:

$$K_{1q} = K_{1d} = \left(k_{P1} + \frac{k_{I1}}{s}\right) \quad (45)$$

Combining equations (41) and (45) gives:

$$\left(r_s + sL_s\right)I_{q1} = \left(k_{P1} + \frac{k_{I1}}{s}\right)I_{q1}{}^* - \left(k_{P1} + \frac{k_{I1}}{s}\right)I_{q1}$$

$$\Rightarrow \frac{I_{q1}}{I_{q1}{}^*} = \frac{\frac{1}{L_s}\left(sk_{P1} + k_{I1}\right)}{s^2 + s\frac{1}{L_s}(r_s + k_{P1}) + \frac{1}{L_s}k_{I1}} \quad (46)$$

Comparing denominator of (46) with Butterworth second order polynomial,

$$k_{P1} = \sqrt{2}\omega_{0c}L_s - r_s \;\; and \;\; k_{I1} = L_s\omega_{0c}{}^2$$

where ω_{0c} is the bandwidth of the current controller, which depends upon the design value. Bandwidth of the controller depends upon the switching frequency at which converter is operating. If $\omega_{sw} = 2 * \prod * f_{sw}$ is the switching frequency then, for this design, current controllers and voltage controllers bandwidth is taken as:

$$\omega_{oc} = \frac{1}{10}\omega_{sw} \text{ and } \omega_{om} = \omega_{odc} = \frac{1}{10}\omega_{oc}.$$

3.2 TEST SYSTEM

Fig. 8 demonstrates the single line diagram of the test system. A 1.5 MW DFIG wind turbine system is connected to the distribution network at PCC bus where a STATCOM is connected to regulate the voltage. Three different types of loads, a linear RL load, a constant load (P, Q) and a nonlinear load (P_{non}, Q_{non}) are also connected in shunt to the same PCC bus. The DFIG wind turbine system is always generating its optimum reactive power (0.4 Mvar, closely equal to 30% of total power rating of DFIG. The distribution network is modeled as weak ($X/R = 5$). The wind speed in the wind turbine varies and so does the power output from wind turbine system. The connected electrical load remains constant during the entire study period. When the wind speed is low (above cut-in speed but below rated speed), at that time DFIG turbine will be operating in MPPT mode and at higher wind speed (above rated speed but below cut-out speed), DFIG turbine will operate in power regulation mode so it will generated the rated power. When the overall system does not have enough power (at low wind speed), the STATCOM supplies the extra reactive power required regulating the voltage at PCC within normal range $(\pm 10\%)$.

The dynamic equations of the system are shown below. For the RL loads, voltage equation is:

$$V_{PCC} = r_L I_L + L_L pI_L + \omega L_L I_L \quad (47)$$

where r_L and L_L is the resistance and inductance of RL load.

The capacitor voltage equation is:

$$C_m \ pV_{PCC} = I_s + I_w - I_g - I_L - I_{LL} - I_{nL} \quad (48)$$

where C_m is the filter capacitor, I_s and I_w are the current supplied by STATCOM and DFIG wind turbine system respectively and I_g, I_L, I_{LL} and I_{nL} are current drawn by distribution grid, RL load, linear load and non-linear load respectively.

Non-linear load representation:

$$P_{non} = P_o \left(\frac{V_m}{V_{rated}} \right)^3 \left(\frac{f_m}{f_{rated}} \right)^3 \quad (49)$$

$$Q_{non} = Q_o \left(\frac{V_m}{V_{rated}} \right)^3 \left(\frac{f_m}{f_{rated}} \right)^3 \quad (50)$$

where P_o and Q_o are base active and reactive powers of non-linear loads respectively. V_m and f_m are local voltage magnitude and frequency respectively. V_{rated} and f_{rated} are nominal voltage magnitude and frequency of the distribution system respectively.

Constant load current equations:

$$I_{qLL} = \frac{2}{3} \frac{PV_{qPCC} - QV_{dPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (51)$$

$$I_{dLL} = \frac{2}{3} \frac{PV_{dPCC} + QV_{qPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (52)$$

Non-linear load current equations:

$$I_{qnL} = \frac{2}{3} \frac{P_{non} V_{qPCC} - Q_{non} V_{dPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (53)$$

$$I_{dnL} = \frac{2}{3} \frac{P_{non} V_{dPCC} + Q_{non} V_{qPCC}}{V_{qPCC}^2 + V_{dPCC}^2} \quad (54)$$

4. SIMULATION RESULTS

Simulation studies are carried out for a 1.5 MW DFIG wind turbine system to verify the effectiveness of proposed voltage regulation scheme using STATCOM at PCC under varying wind speed. The DFIG wind turbine is connected to distribution grid with 690 V (l-l). The distribution grid is model as weak grid. Overall system is simulated in MATLAB/Simulink. Table I shows the DFIG wind turbine parameters [7] and [10], Table II shows the STATCOM and the system parameters used for simulation study.

Fig. 9 shows the wind speed profile of DFIG wind turbine system. The wind speed varies in a range of ± 4 m/s around its mean value of 12 m/s. The variation of wind speed causes fluctuations in electrical power output (active power) from wind generator as shown in Fig. 14. But the connected load in the system will remain constant; as a result there will be voltage fluctuation (as shown in Fig. 11) in the distribution system if there is no additional reactive power compensation device; because the distribution network is modelled as weak as a result cannot provide demanded extra reactive power.

When a STATCOM is connected at the PCC as shown in Fig. 8, then as soon as wind speed is low, it supplies extra reactive power required (shown in Fig. 13) to the distribution grid to maintain voltage magnitude at PCC within nominal range shown in Fig. 10. The positive (negative) active/reactive power supplied to the grid as shown in Fig. 15 means grid is receiving (supplying) power. As depicted clearly in Fig. 15, the weak distribution grid cannot supply additional reactive power when system needs it at lower wind speed.

5. CONCLUSION

In the DFIG wind turbine system operating in maximum power point operation mode connected to weak distribution grid, terminal voltage fluctuates with fluctuation in wind speed if there is no additional reactive power compensation device. This fluctuation is more significant in lower wind speed. This paper proposes a STATCOM to be connected at PCC in distribution grid for voltage regulation purpose. Simulation results have shown that fast voltage regulation of the overall grid can be achieved by connecting STATCOM at PCC during varying wind speed.

REFERENCES

[1] Mustafa Kayıkc¸ı and Jovica V. Milanovi´c, "Reactive Power Control Strategies for DFIG-Based Plants," IEEE Trans. on Energy Conversion, Vol. 22, No. 2, pp. 389-396, June 2007.

[2] Stephan Engelhardt, IstvanErlich, Christian Feltes, J¨orgKretschmann, and FekaduShewarega, "Reactive Power Capability of Wind Turbines Based on Doubly Fed Induction Generator," IEEE Trans. on Energy Conversion, Vol. 26, No. 1, pp. 364-372, March 2011.

[3] Tim Poor, American Superconductor, "Using FACTS Technology To Address Grid Interconnection Issues for Wind Farms," Electric Energy Publications Inc., 2010.

[4] Fadaeinedjad, R., Moschopoulos, G.; Moallem, M., "Using STATCOM to Mitigate Voltage Fluctuations due to Aerodynamic Aspects of Wind Turbines," PESC, 15-19 June 2008. IEEE, Rhodes.

[5] Jorge Martinez Gracia, "Voltage Control in Wind Power Plants with Doubly Fed Generators,"Ph.D. Thesis, Alaborg University, Denmark, Sept. 2010.

[6] Wei Qiao, Ganesh Kumar Venayagamoorthy, and Ronald G. Harley, "Real-Time Implementation of a STATCOM on a Wind Farm Equipped With Doubly Fed Induction Generators," IEEE Trans. on Industry Application, Vol. 45, No. 1, pp. 98-107, Jan./Feb. 2009.

[7] Endusa Billy Muhando, TomonobuSenjyu, Aki Uehara, Toshihisa Funabashi and Chul-Hwan Kim, "LQG Design for Megawatt-Class WECS With DFIG Based on Functional Models' Fidelity Prerequisites," IEEE Trans. on Energy Conversion, Vol. 24, No. 4, pp. 893-904, Dec. 2009.

[8] Krause, O. Wasynczuk and S. D. Sudhoff, "Analysis of Electric Machinery and Drive Systems," *IEEE Press, Wiley-Interscience, John Wiley & Sons, Inc*., New Jersey, 2002.

[9] R. Pena, J.C. Clare and G.M. Asher, "Doubly fed induction generator using back-to-back PWM converters and its application on variable speed wind-energy generation," *IEE Proc. Electr. Power Appl*. Vol. 143, No. 3, pp. 231-241, May 1996.

[10] Sheng Yang and VenkataramanaAjjarapu, "A Speed-Adaptive Reduced-Order Observer for Sensorless Vector Control of Doubly Fed Induction Generator-Based Variable-Speed Wind Turbines," IEEE Trans. on Energy Conversion, Vol. 25, No. 3, pp. 891-900, Sept. 2010.