

## Research Article

# Improving the Power Quality of Six Parallel Operated Onshore Wind Turbines using UPFC

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**Abstract:** This study is aimed at improving the power quality of an onshore wind turbine connected to the grid, using a Unified Power Factor Controller. A six parallel operated onshore wind turbine is used as a model to demonstrate the effectiveness of the proposed system. The wind generating system consists of doubly fed induction generator connected to the wind turbine. An average model of the doubly fed induction generator is used and the control signals are generated using closed loop control. The unified power factor controller is modeled using grid and rotor side converters and controlled using closed loop pulse width modulated signals. The proposed system reduces the reactive power of the system, which is proved by simulating the system using MATLAB SIMULINK environment.

**Keywords:** DFIG, FACTS, grid integration, power quality

## INTRODUCTION

Renewable energy has become an inevitable source of energy in the modern world. The advent of renewable energy for power generation has provided and economically and environmentally superior alternative to fossil fuels. Hence the scope of power generation from renewable energy such as solar and wind is increasing day by day and so are their issues. With such situation prevailing and with highly unpredictable nature of these energy sources, it is very important to stabilize the generating system to utilize its capacity to the maximum. Focus is on wind as a energy source and mitigating the stability issues of this system. Integrating wind to the grid affects the power systems due to fluctuations in wind energy, because of varying weather conditions. Various issues in integrating wind with power grid include power quality, system security and system stability.

Wind generating system can be onshore or offshore based on the natural resources and landscape available in a geographical location. The system generally uses either Permanent Magnet Synchronous Generator (PMSG) or Doubly Fed Induction Generator (DFIG). The system under consideration includes onshore wind turbines connected to an onshore power grid and uses a DFIG.

Considering an historical point of view, modular permanent magnet synchronous generator for variable-speed wind turbines with direct coupling was proposed and single-phase outputs were separately rectified to obtain a smooth dc-link voltage (Chen and Spooner, 1995). Muljadi *et al.* (2006) have discussed various power quality issues related to wind farms and

suggestions to mitigate these issues (Muljadi *et al.*, 2006; Larsson, 1997). A control strategy for smoothing active power fluctuation of wind farm using flywheel energy storage system was proposed based on wind power prediction algorithm (Wang and Wang, 2013). A new control topology was proposed (Rawn *et al.*, 2007) and a controller was designed that isolates wind power fluctuations from the power grid. A new method for interconnecting two or more wind turbines was proposed using power electronic devices and their characteristics was presented (Nishikata and Tatsuta, 2010). For enhancing low voltage ride through problem, an advanced control strategy was proposed (Yang *et al.*, 2012), for both rotor side and grid side converters of DFIG based wind turbine. The necessity of the wind turbine to remain connected to the grid was explained (Mohammadi *et al.*, 2014) and an efficient control strategy was proposed to improve fault ride through capability of DFIG based wind turbine.

To control the transmission of power in grid, Unified Power Factor Controller (UPFC) was first proposed to control the real and reactive power separately (Gyugyi *et al.*, 1995; Grünbaum *et al.*, 1999). Regarding the application of UPFC to wind farms, UPFC was applied to improve the dynamic stability of offshore and marine integrated wind farm (Sindhura and Sridhar, 2012). The application of UPFC to control the power flow and its application as voltage injector is discussed (Vibhor, 2010). The proposed method also improves transient stability and steady state behavior of the system.

Six parallel operated DFIG based wind turbines of 1.5 MW each are modeled and connected to the power

grid. The DFIG is modeled using an average model with grid side and rotor side control. UPFC with closed loop control for shunt and series converter is connected to the system to reduce the reactive power absorbed from the source. The model is simulated in MATLAB SIMULINK environment and the results are analyzed and compared to the system without UPFC.

**MATERIALS AND METHODS**

**Power quality issues:** Injecting wind energy into the power grid causes a lot of power quality issues. The quality of power transmitted over the network depends on the degree of deviation of the voltage and current waveforms from the standard sinusoidal nature. The major quality issues include voltage variations and harmonics. The severity of these issues is based on the tolerance level of the loads connected. Also the amount of distortion in quality is based on a lot of factors including, geographical location of the wind farm, load connected to the grid, length and strength of the network and utility operator's practice (Patsalides *et al.*, 2008). The effect of poor quality includes malfunctioning of electrical equipments, losses on the grid and even leads to loss of synchronism and hence network failure.

Voltage variations may be a voltage sag, voltage swell, short/long duration interruptions and flickers. All these results from dynamic variations in wind velocity and generated torque. All wind generating systems involve many power electronic devices for converters. This introduces harmonics in the line voltage and current, which has to be maintained within a certain limit as per the IEEE 519-1992 guideline. The proposed system improves the power quality by compensating the reactive power.

**Configuration of the system:** The layout of the proposed UPFC based wind energy system is shown in Fig. 1.

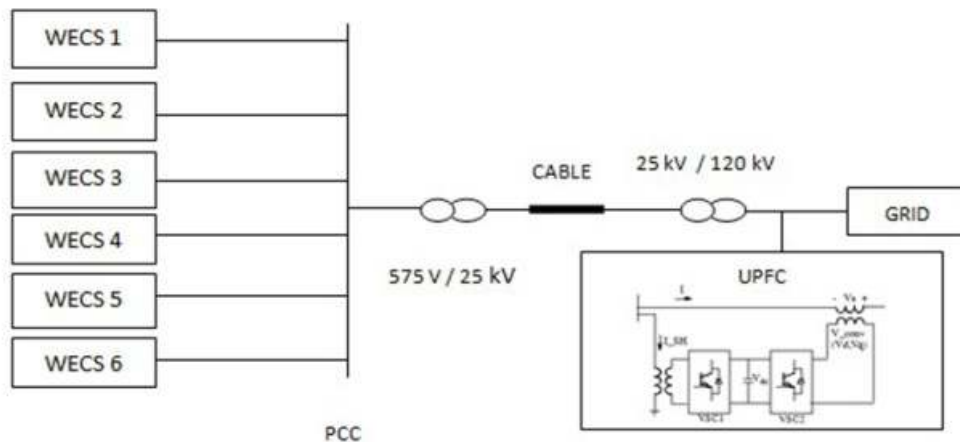


Fig. 1: Proposed layout

The model consists of six wind energy conversion systems, each 1.5 MW, connected in parallel, with interconnecting transformer of 575/25 kV with a cable length of 30 km. This system is in-turn connected to the grid, generating 120 kV at 50 Hz. The proposed UPFC system is connected to the grid side circuit with 25/120 kV transformer. A single wind energy conversion system is shown in Fig. 2.

The mathematical model of the proposed system, which consists of the wind turbine, DFIG and converter and the UPFC module is discussed in this section.

**Wind turbine model:** In this system, a variable speed wind turbine with speed and pitch angle control is used. The wind power available for generation is given in Eq. (1):

$$P_{wind} = \frac{1}{2} \rho AV^3 \tag{1}$$

where,  $\rho$  (kg/m<sup>3</sup>) is the air density and A (m<sup>2</sup>) is the area swept out by the turbine blade and V (m/sec), the wind speed. Of this power, only a fraction is utilized, which is determined by the power coefficient, Cp, as shown in Eq. (2). The value of Cp depends on the type of wind turbine:

$$P_{mech} = C_p P_{wind} \tag{2}$$

The reference rotor speed, actual rotor speed and measured value of power (Pmeas) are used to calculate the electromagnetic torque and pitch angle of the wind turbine. The value of Pmeas can be obtained using Eq. (3):

$$P_{meas} = \frac{1}{P_{nom} [P + \frac{C}{Q} (\frac{\sqrt{2}V}{\sqrt{3}V_{nom}})]} \tag{3}$$

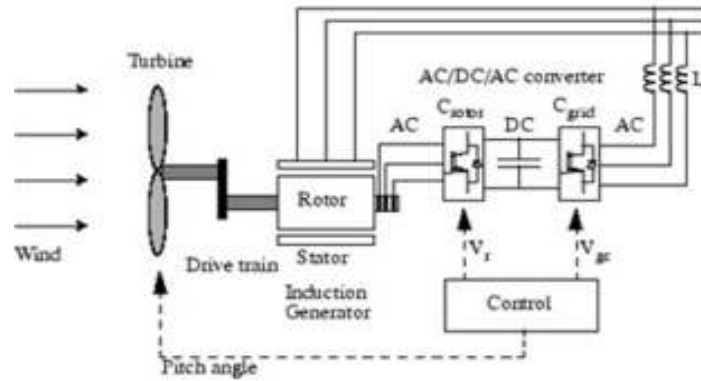


Fig. 2: Wind energy conversion system

where,  $V_{nom}$  and  $P_{nom}$  are the nominal values of voltage and power of the DFIG,  $P$ , the power obtained from the fundamental values of Voltage ( $V$ ) and current,  $C/Q$  is the active power of the filter.

**DFIG and converter model:** Average model of DFIG is used in the system, in which, the voltage source converters are replaced by their equivalent controlled voltage sources that are averaged over one cycle of the switching frequency (Coster *et al.*, 2008). Control for both the grid side and rotor side converters is employed using the d-q parameters, in three steps: Voltage regulation, current regulation, modulation and phase regulation.

**Grid side control:** The voltage regulation block generates the reference voltage for current regulation block using Eq. (4) as:

$$I_{dref} = V_{dcnom} - \frac{V_{dcmeas}}{V_{dcnom}} \quad (4)$$

In the current regulation module:

$$V_{dcontrol} = V_{ds} + (\omega L i_{qref}) + (R i_{dref}) - V_{d'} \quad (5)$$

where,  $V_{ds}$  and  $V_{qs}$  are the dq values of the output voltage of wind turbine,  $i_{dgc}$  and  $i_{qgc}$  and dq values of grid side converter current:

$$V_{d'} = i_{dref} - i_{dgc} \quad (6)$$

$$V_{qcontrol} = V_{qs} - (\omega L i_{dref}) - (R i_{qref}) - V_{q'} \quad (7)$$

where,

$$V_{q'} = i_{qref} - i_{qgc}$$

The modulation index is set as in Eq. (8):

$$m = 2\sqrt{2} \frac{V_{nom}}{3V_{dc}} \quad (8)$$

**Rotor side control:** First stator flux is estimated using  $V_{dq}$ ,  $I_{dq}$  and  $\omega$ . Then  $I_{dqr}$  ref is obtained using the flux and electromagnetic torque values. The control voltages are obtained using Eq. (9) and (10):

$$V_{dcontrol} = V_{d'} + [R i_{dr} ref + \omega r' (L + L_m i_{qr} ref + \omega r' L_m i_{qs} estim)] \quad (9)$$

$$V_{d'} = \frac{2}{\pi} (\tan^{-1}(i_{dr} ref - i_{dr}))$$

where,  $i_{qs} estim$  is the estimated value of fundamental current:

$$V_{qcontrol} = V_{q'} + [R i_{qr} ref + \omega r' (L + L_m) i_{dr} ref + \omega r' L_m i_{ds} estim] \quad (10)$$

$$V_{q'} = \frac{2}{\pi} (\tan^{-1}(i_{qr} ref - i_{qr}))$$

$$\omega r' = \omega - \omega_r$$

$$\omega = \frac{f}{f_{nom}}$$

The modulation index is same as that of the grid side control.

**UPFC model:** FACTS devices are power electronic based controllers employed in power systems to improve controllability and to increase power transfer capability. Controllability is required as there are various dynamic and steady state constraints in transmission system. Steady state constraints include uneven power flow, excessive reactive power flow, voltage capability and thermal capability. Dynamic constraints include sub-synchronous oscillations, dynamic over voltage and under voltage and voltage and frequency collapse. There are various FACTS devices like Static VAR Compensator, Thyristor Controlled Series Compensator, Thyristor Controlled

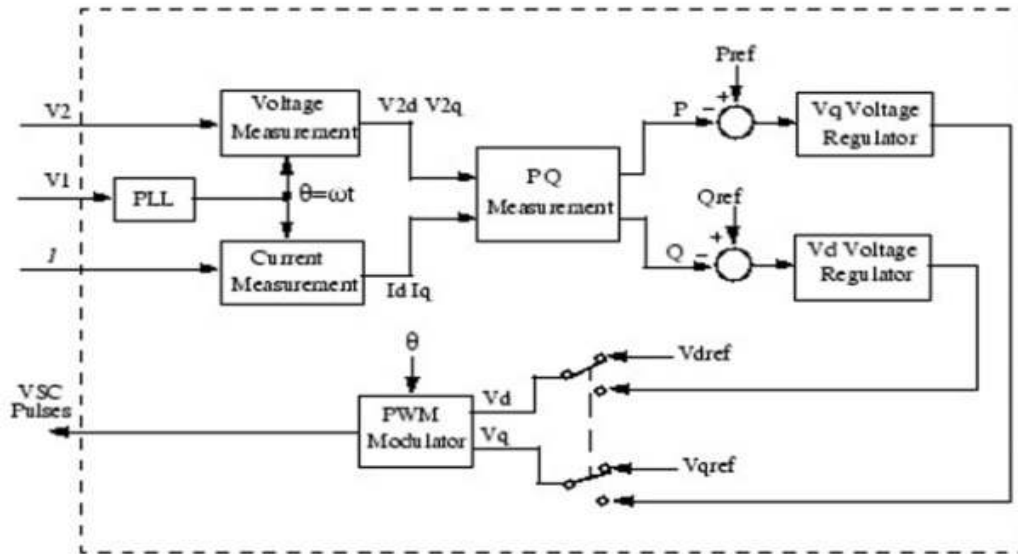


Fig. 3: Control strategy for series converter

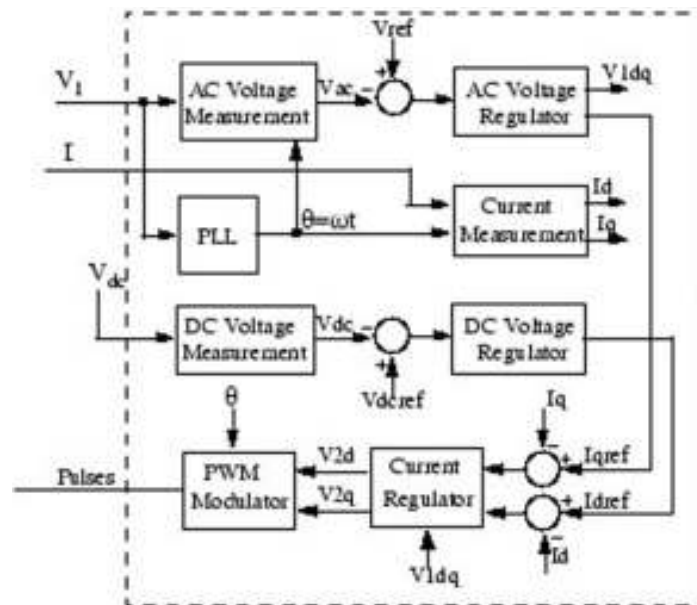


Fig. 4: Control strategy for shunt converter

Phase Angle Regulator, STATCOM, Static Synchronous Series Compensator and UPFC. In all the above said devices, either a shunt converter or a series converter is used. Unified Power Factor Controller includes both shunt and series converters.

UPFC can be used to control voltage, current and angle in a power system. It can also impact the active and reactive power flow. In the UPFC, reactive power is generated or absorbed by the shunt inverter to control bus voltage. Series inverter also generates or absorbs reactive power thereby controlling the real and/or reactive power flow on the transmission line. The shunt converter draws a portion of the real power flow on the transmission line to charge the DC capacitor and returns

it through the series converter (Federal Energy Regulatory Commission Report, 2005)

In the proposed system, pulse width modulation is used to generate gating signals for the shunt and series converter. A closed loop control is used to maintain a constant voltage and current. It also maintains a constant real power and near-zero reactive power thereby maintaining the power factor of the system.  $V_{dq}$  and  $I_{dq}$  signals are used to generate PWM for the series converter.

The series converter control circuit is given in Fig. 3. Line voltage and DC link voltage are used to generate the PWM signals for the shunt converter. The control circuitry of shunt converter is given in Fig. 4.

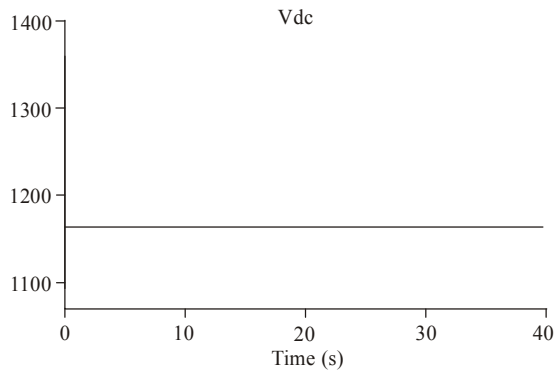


Fig. 5: DC link voltage

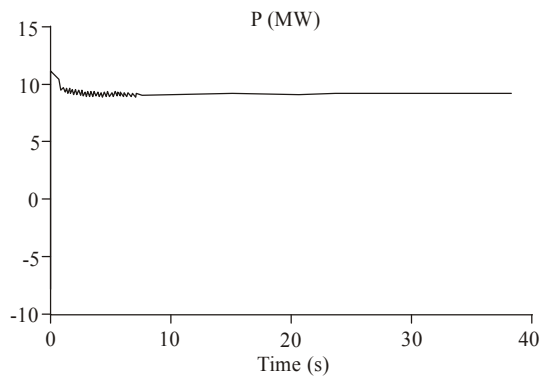


Fig. 6: Active power

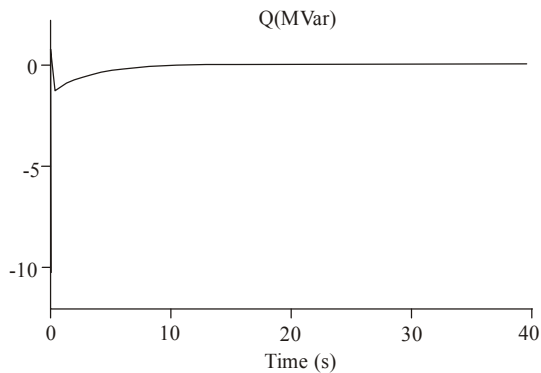


Fig. 7: Reactive power with UPFC

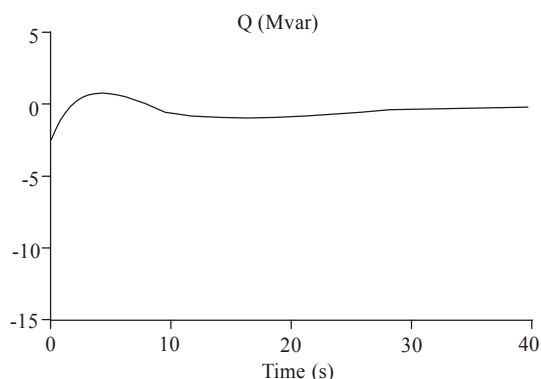


Fig. 8: Reactive power without UPFC

## RESULTS AND DISCUSSION

This section utilizes the DFIG average model developed in section IV and the integrated UPFC model to demonstrate the effectiveness of the proposed system. The system is modeled in MATLAB SIMULINK environment. The system consists of six 1.5 MW (6×1.5 MW) wind systems connected to a 120 kV three phase grid. The UPFC is modeled using two voltage source converters (one series and one shunt) controlled by PWM generated signals, whose control circuit is given in the previous section. The system with and without UPFC is simulated in the same environment in order to justify the effectiveness of the proposed system. Figure 5 shows the DC link voltage of the DFIG converter, which is maintained at 1150 V.

The active power is maintained at 9 MW in both the systems, which is shown in Fig. 6.

The reactive power obtained is reduced to at 0 MVar in UPFC based system, whereas it is around 0.5 MVar in the system without UPFC. This is shown in Fig. 7 and 8, respectively.

## CONCLUSION

The proposed system consists of six parallel operated WECS connected to a grid system. To improve the quality of power in the system, power electronics based UPFC system was proposed. The WECS used DFIG system, the control system of which is discussed extensively. The system is modeled in MATLAB SIMULINK environment and the system performance is discussed in the previous section. It clearly shows the improvement in the power quality of the system by reducing the reactive power in the system.

## REFERENCES

- Chen, Z. and E. Spooner, 1995. A modular, permanent-magnet generator for variable speed wind turbines. Proceeding of 7th International Conference on Electrical Machines and Drives (Conf. Publ. No. 412), pp: 453-457.
- Coster, E.J., A. Ishchenko, J.M.A. Myrzik and W.L. Kling, 2008. Comparison of practical fault ride-through capability for MV-connected DG units. Proceeding of the 16th Power Systems Computation Conference (PSCC). Glasgow, Scotland, July 14-18.
- Federal Energy Regulatory Commission Report, 2005. Principles for efficient and reliable reactive power supply and consumption. Federal Energy Regulatory Commission Staff Report, Docket No. AD05-1-000, February 4, 2005 888 First Street, N.E. Washington, D.C. 20426.
- Grünbaum, R., M. Noroozian and B. Thorvaldsson, 1999. FACTS-Powerful systems for flexible power transmission. ABB Review, 5/1999.

- Gyugyi, L., C.D. Schauder, S.L. Williams, T.R. Rietman, D.R. Torgerson and A. Edris, 1995. The unified power flow controller: A new approach to power transmission control. *IEEE T. Power Deliver.*, 10(2): 1085-1097.
- Larsson, Å., 1997. Power quality of wind turbine generating systems and their interaction with the Grid. Technical Report No. 4R, Department of Electric Power Engineering, Chalmers University of Technology, Goteborg, Sweden.
- Mohammadi, J., S. Afsharnia and S. Vaez-Zadeh, 2014. Efficient fault-ride-through control strategy of DFIG-based wind turbines during the grid faults. *Energ. Convers. Manage.*, 78: 88-95.
- Muljadi, E., C.P. Butterfield, J. Chacon and H. Romanowitz, 2006. Power quality aspects in a wind power plant. *Proceeding of IEEE Power Engineering Society General Meeting*. Montreal, Que, June 18-22.
- Nishikata, S. and F. Tatsuta, 2010. A new interconnecting method for wind turbine/generators in a wind farm and basic performances of the integrated system. *IEEE T. Ind. Electron*, 57(2): 468-475.
- Patsalides, M., A. Stavrou, G. Makrides, V. Efthimiou and G.E. Georghiou, 2008. Harmonic response of distributed grid connected photovoltaic systems. *J. PV Technol.*, pp: 187-263.
- Rawn, B.G., P.W. Lehn and M. Maggiore, 2007. A control methodology to mitigate the grid impact of wind turbines. *IEEE T. Energy Convers.*, 22(2): 431-438.
- Sindhura, J. and M. Sridhar, 2012. Improve the dynamic stability of an integrated grid-connected offshore wind farm and marine-current farm using FACTS. *Int. J. Eng. Res. Technol.*, 1(7): 1-11.
- Vibhor, G., 2010. Study and effects of UPFC and its control system for power flow control and voltage injection in a power system. *Int. J. Eng. Sci. Technol.*, 2(7): 2558-2566.
- Wang, J.C. and X.R. Wang, 2013. A control strategy for smoothing active power fluctuation of wind farm with flywheel energy storage system based on improved wind power prediction algorithm. *Energ. Power Eng.*, 5(4B): 387-392.
- Yang, L., Z. Xu, J. Østergaard, Z.Y. Dong and K.P. Wong, 2012. Advanced control strategy of DFIG wind turbines for power system fault ride through. *IEEE T. Power Syst.*, 27(2): 713-722.