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Power Quality Improvement of Grid Connected Wind Energy System Using DSTATCOM-BESS

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Abstract- Electricity generation from wind energy has increased rapidly in recent years and the trend is likely to continue. Due to intermittent environmental factors and integration of wind power generation system with the grid, creates power quality issues including voltage swells, voltage dips, harmonics, power factor and poor voltage regulation. When wind power is injected into the grid, it affects the performance of the power system. Distribution Static Compensator (DSTATCOM) is used to esclate the power quality. This paper itroduces the power quality improvement technique for grid connected wind power plant using DSTATCOM with battery energy storage system (BESS). The proposed scheme mainly depends on the reactive power supply requirements of the load and the induction generator. The proposed scheme is simulated in MATLAB/Simulink software.

Keywords Power quality, Distribution Static Compensator (DSTATCOM), battery energy storage system (BESS), Power factor, Stability, point of common coupling (PCC).

Nomenclature

P	Power output (kW)	Q	Reactive powe (KVAR)
R	Radius of the turbine blade	V_{tref}	Reference terminal voltage (V)
V_t	Terminal voltage (V)	V	Line voltage (V)
X	Reactance	V_{PCC}	Voltage at point of common coupling (V)
V_c	Converter output voltage (V)	Va, Vb, Vc	Phase voltages
Vd, Vq, Vo	d-axis and q-axis voltages	V_{error}	Error voltage

1. Introduction

With the rise in population and industrialization, power demand has increased in recent years. Therefore, power generation can be upcoming a massive challenge. The source of electricity generation can be renewable as well as non-renewable. Owing to consecutive usage of nonrenewable energy sources for generation of electrical energy increasing global warming, air pollution, diminishing fossil fuels and their cost is increasing. So, it is necessary to pay attention to renewable energy sources (RES) as a future energy solution. Wind energy generation system is cost effective and reliable among all other renewable energy sources for generation of electricity [1]. Electricity could also be generated using wind turbine, which are synchronized with the grid. Therefore, integrating renewables to the grid is of paramount importance. This minimizes the environmental impact of generation [2],[3]. The trend of using wind generation system is increasing in the recent years. The generation of electricity from wind turbine is very small and individual unit can generate up to 5 MW [4]. Wind power generation is the most commonly used renewable energy source in power system[5]. European reported more than 44% of wind energy generation [6]. Nowadays, wind turbines (WTs) are becoming the main source of power generations in some areas such as Jiuquan in Fansu province of China [7]. Problems during connection of wind turbine to the grid are voltage sag/swell, voltage flicker, harmonic current, frequency and power factor [4], [8].

There are so many techniques to get rid of the power quality problems of wind turbine power plants. One of the best solutions is to use electronic based fllexible alternating current transmission system (FACTS) devices and found very helpful for improving power quality [9], [15]. If the fault occurs on the grid that is connected to the wind turbine power plant, FACTS Devices are the best solution to maintain the stability of large power system network. This is because if the wind turbine generator's circuit breaker gets open during grid disturbances, it will reclose when normal operation is resumed because of switching control of FACT device.

The consumption of reactive power reduces the power factor. Wind turbine induction generators requires reactive power for magnetization [10]. For compensation of reactive power, FACTS devices are used [11]-[13]. FACTS devices are used for continuous supply to the load. It supports the voltage stability during disturbance of grid and during intermitent weather conditions that will affect the wind turbine output. FACTS device provides reactive power for stabilization of voltage in the network and improves the power factor of the system[14].

Lei and Shen [15] used STATCOM with LiFePO4 lithium battery and supercapacitor hybrid battery for improving the power quality of wind energy-based distribution systems. It used the squirrel cage induction generator (SCIG) for wind energy generation. It provides real and reactive power, thus reduces the fluctuation of wind turbine. In this work, the SCIG cannot extract maximum energy at low wind speed. Amen and Djamel [16] proposed the usage of unified power flow controller (UPFC) which is the most versatile and complex device of the FACTS family for controlling power flow in transmission and distribution systems. Mohanty and M. Vishwananda [17] used the UPFC controller for the compensation of reactive power using FUZZY based control technique. It enhanced the voltage stability in a hybrid wind diesel system for distribution network using SCIG for wind energy generation. In [16] and [17], UPFC is used that is costly among all other FACTS devices. She and Huang [18] used **the static synchronous compensator** (STATCOM) for voltage conversion, active and reactive power transfer in a distribution system. In this work, STATCOM cannot compensate for active power in a better way without a battery energy storage system. Bhattacharjee and Roy [19] used the supply of power to the inductive load using FUZZY logic-based control technique for DSTATCOM. It improves the power quality for constant speed wind energy system in distribution network. Suresh and Srinivas [20] used DSTATCOM for voltage regulation, stability and power quality issues. Arya and Singh [21], the proposed control technique is to extract the distorted load currents. These extracted currents are used as a reference source currents to generate gate signals of DSTATCOM. This control technique is used for mitigation of reactive power, distortion of harmonics and balancing of load. Mahela and A. G. Shaik [22] used DSTATCOM for fast control of reactive power, voltage flicker, harmonics current, frequency and voltage regulation in distribution network. In [21] and [22] , battery energy storage system can be utilized with DSTATCOM for controlling both active and reactive power in a better way if a fault occurs in the power system. Mahmoud M. Amin [23] proposed a technique for a grid-connected wind energy system using a self-excited induction generator (SEIG). Voltage source inverters (VSIs) and voltage-oriented controls (VOCs) are utilized to minimize the harmonic current and voltage. It improves the power quality of wind energy conversion systems (WECS). In this work, the SEIG is used which is dependent on the system to which it is connected. If the fault occures in a system, it will not work properly. Koti [24] introduced indirect current control techniques to obtain gated signals for insulated gate bipolar transistor (IGBT) devices used as DSTATCOM current controlled voltage source inverters (CC-VSI). In this work, the used technique is not very fast for switching of IGBT.

In this research, the problems during the connectivity of wind turbine to the grid and afterwards i.e. voltage sag/swell, harmonics and power factor are elaborated. Many researchers have proposed UPFC and some of others have proposed static VAR compensator (SVC) to improve power quality. UPFC is mostely used to compensate reactive power in high voltage transmission lines. It is very costly to use UPFC for low voltage distribution system. Therefore, the use of UPFC is not suitable for improving the quality of power in distribution network. SVC is the 1st generation device of FACTS family. It was used in the past for improving the quality of power. The switching technology of the SVC controller is not very fast. Therefore, its usage is not very common now. The DSTATCOM used in [19] and [22] only compensates for reactive power and the techniques used are not very fast for IGBT switching. In this paper, DSTATCOM with battery energy storage system using PI controller based phase locked loop (PLL) technique is used for IGBT switching. This technique is faster than previously used techniques for IGBT switching. It improves the power quality in distribution system. It also controls both active and reactive power. The proposed scheme for improving power quality has the following objectives.

- Power quality improvement (voltage sag and swell, power factor and harmonics) using DSTATCOM.
- Reactive power support from DSTATCOM to load and wind induction generator.

2. Wind Turbine Issues and Consequences of Poor Power Quality

2.1. Power Quality Issues

Wind turbines which are integrated with the grid, harmonic voltages and currents are acceptable at a limited level. Distortion in voltage takes place due to change in current which is already distorted owing to nonlinear loads connected to the grid system [25]. It also takes place due to change in wind speed [26]-[28]. Fast variation in the supply voltage causes the voltage to flicker. It changes the brilliance of light [29], [30].

2.2. Consequences of Poor Power Quality

Voltage variations, harmonics, flickering cause failures of equipment such as IT equipment, programmable logic controllers, process control equipment, microprocessor based control systems, measuring and controlling equipment, screens and flickering of lights [31]-[33]. It affects the telecommunications system. It can cause nuisances to the tripping of protective devices, contractors and the stopping of sensitive equipment.

3. Grid Coordination Rules

The first grid was constructed in the United States in 2003. The United States has developed its own stable operating specifications for wind power grids as per IEC standards. The quality constraints of grid and characteristics are presented as a reference for customer and grid utility [34].

1) *Voltage Dips (d):* When the wind turbine is start up, sudden decrease in voltage occurs. The limiting dip value is less than 3%.
2) *Voltage Rise (V):* Rise in voltage at PCC could be owing to the tripping of load, the phase angle ϕ and line impedances R and X [35]. The limiting rise in voltage is less than 2%.
3) *Flicker:* Flickering is the measure of maximum switching operation; minutes are 10 minutes and 2 hours. The limit of the flicker coefficient is ≤ 0.4 for 2 hour [36].
4) *Harmonics:* Harmonic distortion occurs due to the change in speed of the wind turbine [37]. For 11kV, the THD limit is <4%, while the 132kV limit is <2.5%.
5) *Grid Frequency:* The grid frequency specified by Pakistan is 47.5–51.5Hz for connecting with wind turbines. Wind turbine should be capable to withstand a frequency change of 0.5 Hz [38].

4. Modeling of the System

In this paper, DSTATCOM with BESS is proposed and PI controller-based phase locked loop (PLL) technique is used for IGBT switching, which is cost effective, fast switching and efficient for distribution system among all other techniques. The goal of this technique is to synchronize the phase angle of voltage and current at variable wind speed.

In this model, the wind power generation system is coupled with the grid at PCC according to the distribution organization center in Pakistan. These two sources are connected at PCC through bus bars as shown in Fig. 1. These two sources are also connected with DSTATCOM-BESS and nonlinear load at PCC. Parameters of the proposed system are given in Table 1.

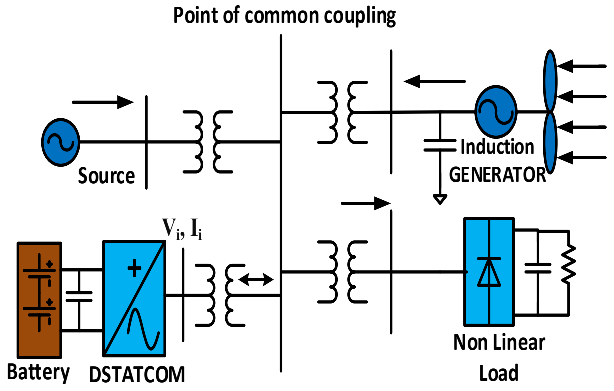


Fig. 1. DG connected wind turbine using FACTS device

Table 1. System parameters

S. No.	Parameters	Ratings
1	Grid voltage	3-phase,11 kV, 50Hz
2	DFIG	9 MVA (6x1.5 MVA), 50Hz, P=3, speed= 1440 rpm, Rs= 0.0071Ω, Rr= 0.005 Ω, Ls= 0.171 H, Lr= 0.156 H
3	Line Series Inductance	0.05 mH
4	Inverter Rating	DC interface voltage = 1200 V, DC interface capacitance = 10000µF
5	Load Parameter	Non-Linear Load 500kW

The system consists of two generator systems. Distribution generator (DG) is the voltage source of 132kV grid system, which is stepped down to 11kV with a 132kV/11kV transformer. The other is a DFIG-based wind turbine that produces 575V which is stepped up to 11kV using 575V/11kV transformer for distribution network. Wind system transport power to a grid through 11kV line.

When the grid is connected to a wind farm and a non-linear load, the power quality will drop as the wind farm does not have enough reactive power. Therefore, an external device is used to provide reactive power [39],[40]. The proposed scheme is simulated in MATLAB/SIMULINK as shown in Fig. 2.

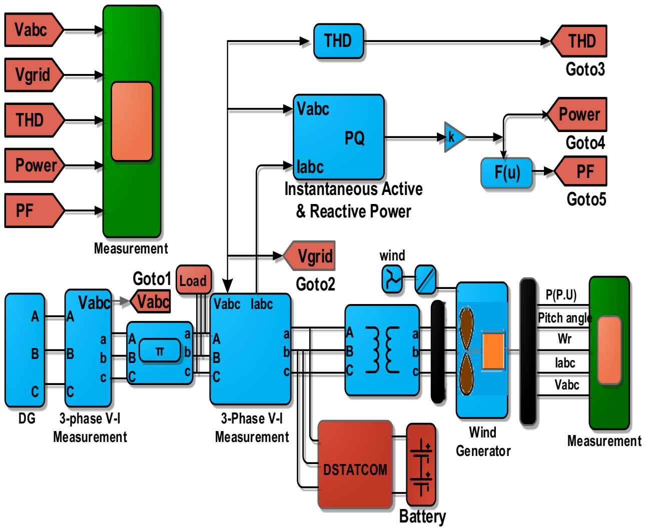


Fig. 2. DG connected wind turbine with FACTS device

4.1. BESS-DSTATCOM

A battery energy storage system (BESS) is used as the energy storing element. It is coupled in parallel with DSTATCOM's direct current (DC) interface capacitor. The goal of BESS is to regulate the voltage. The BESS generally maintains the DC capacitor voltage [41]. If the fault occurs in a system, it provides or absorbs reactive power to achieve stability of the system. It controls the actual and reactive power of the system at extremely quick rate.

4.2. DSTATCOM Control Scheme

In this model, DSTATCOM is connected at PCC between the wind turbine and the grid. DSTATCOM monitors voltage and current. It supply and absorb reactive power at PCC [42], [43]. The schematic diagram of DSTATCOM is shown in Fig. 3. The compensator compares the voltage and supplies lagging or leading current to stabilize the power system. With the use of DSTATCOM, the power factor can be improved by compensation for reactive power. The DSTATCOM control system based on voltage source converter (VSC) is shown in Fig. 4.

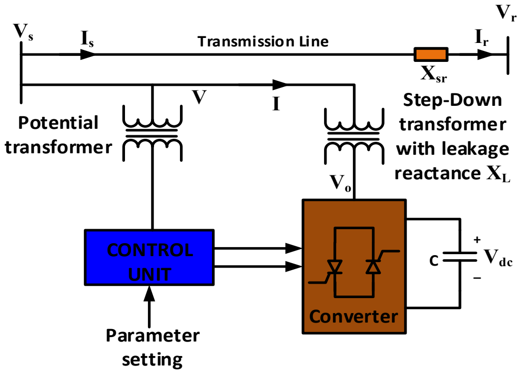


Fig. 3. Schematic diagram of DSTATCOM

DSTATCOM contains the VSC based control system. If the voltage V of the transmission line and the output voltage V_o of converter are in phase and the magnitude is also same such that $V \angle 0^0 = V_o \angle 0^0$, the compensator will not supply or absorb the current and there is no reactive power to exchange with the line. If $V < V_o$, the compensator takes a leading current which acts as a capacitor and supplies VAR. Conversely, if $V > V_o$, it takes a lagging current which acts as an inductor and absorbs VAR.

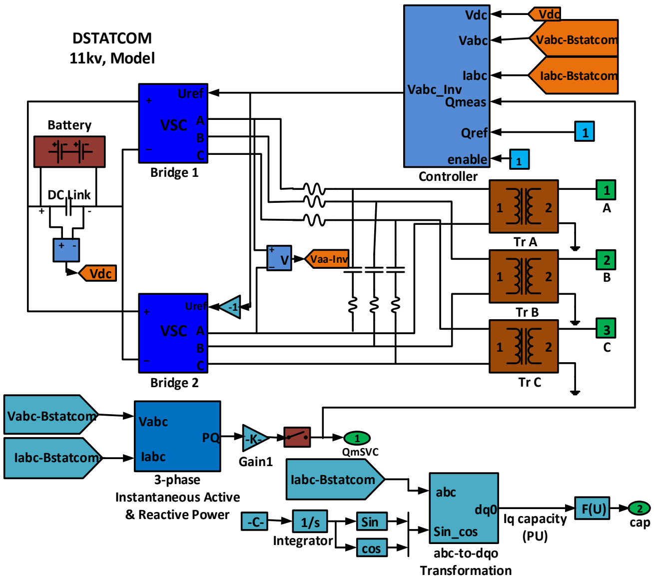


Fig. 4. VSC control system

DSTATCOM consists of two bridged VSCs, a couple transformer is connected in parallel with the distribution network, and a DC link capacitor is connected with BESS as shown in Fig. 4. When the load on the system increases, VSC converts the DC voltage of BESS to an AC voltage and provides it to the system. When the load on the system decreases, VSC receives AC voltage and convert it into DC voltage for storing of extra system voltage. The output voltage of the compensator is in phase to an AC system voltage with the help of PI controller based PLL and connected to the distribution system using couple transformers. Proper adjustment of phase angle and magnitude of DSTATCOM's output voltage with the AC system allows efective control of power exchange between the AC system and the DSTATCOM.

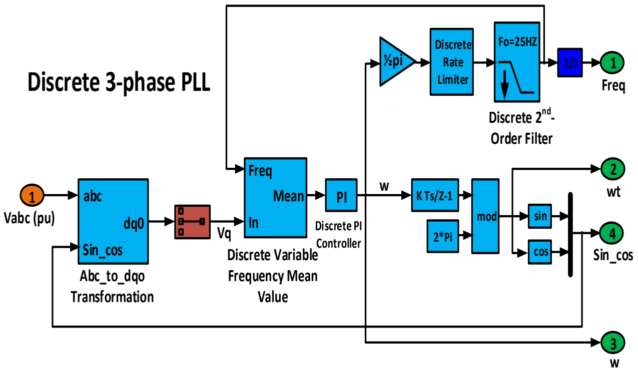


Fig. 5. PI Controller base PLL

$$\begin{bmatrix} Vd \\ Vq \\ V0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(wt) & \sin(wt-\frac{2\pi}{3}) & \sin(wt+\frac{2\pi}{3}) \\ \cos(wt) & \cos(wt-\frac{2\pi}{3}) & \cos(wt+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} \quad (1)$$

Inverse transformation is given by

$$\begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(wt) & \cos(wt) & 1 \\ \sin(wt-\frac{2\pi}{3}) & \cos(wt-\frac{2\pi}{3}) & 1 \\ \sin(wt+\frac{2\pi}{3}) & \cos(wt+\frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} Vd \\ Vq \\ V0 \end{bmatrix} \quad (2)$$

The phase voltages are used to calculate the terminal voltages at PCC as written in Eq. (6)

$$V_t = \sqrt{\frac{2}{3}(\mathrm{V}^2\mathrm{a} + \mathrm{V}^2\mathrm{b} + \mathrm{V}^2\mathrm{c})} \quad (3)$$

The error voltage given to the PI controller is given as

$$\mathrm{V}_{error} = \mathrm{V}_{tref} - \mathrm{V}_t \quad (4)$$

Where θ is the transformation angle. Cosθ amd sinθ are taken from the phase voltage. The PI controller based PLL technique is shown in Fig. 5. The PLL is synchronized with the primary voltage of transformer. The transformation block converts the phase voltages into d-axis and q-axis voltages.

The PI controller compares the d-axis and q-axis components of the voltage and current and generates an error signal. This error signal produces a pulse width modulation (PWM) signal that is used as a gate signal for the IGBT of VSC shown in Fig. 4. The DSTATCOM control system is shown in Fig. 6.

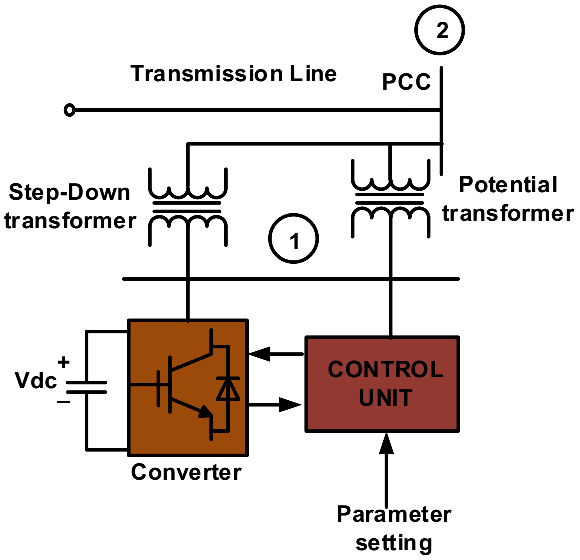


Fig. 6. DSTATCOM control system

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{array}\right] \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix}$$

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (5)$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (6)$$

$$P_2 = |V_2||V_1||Y_{21}| \cos(\theta_{21} - \delta_2 + \delta_1) + |V_2|^2 |Y_{22}| \cos(\theta_{22}) \quad (7)$$

$$Q_2 = -|V_2||V_1||Y_{21}| \sin(\theta_{21} - \delta_2 + \delta_1) - |V_2|^2 |Y_{22}| \sin(\theta_{22}) \quad (8)$$

Differentiate P_2 and Q_2

$$P_2 = |V_2||V_1||Y_{21}| \sin(\theta_{21} - \delta_2 + \delta_1) + |V_2|^2 |Y_{22}| \sin(\theta_{22}) \quad (9)$$

$$Q_2 = |V_2|^2 |Y_{22}| \cos(\theta_{22}) - |V_2||V_1||Y_{21}| \cos(\theta_{21} - \delta_2 + \delta_1) \quad (10)$$

$\delta_1 = \delta_2 = 0$, $Y_{22} = Y_{21} = X$

$$P = \frac{V_2 V_1 \sin\theta_{21}}{X} = \frac{V_{PCC} V_C \sin\theta}{X} \quad (11)$$

$$Q = \frac{V_2 (V_2 - V_1 \cos\theta_{21})}{X} = \frac{V_{PCC} (V_{PCC} - V_C \cos\theta)}{X} \quad (12)$$

Where δ and X are the angle and the reactance respectively between the PCC and the converter output terminal.

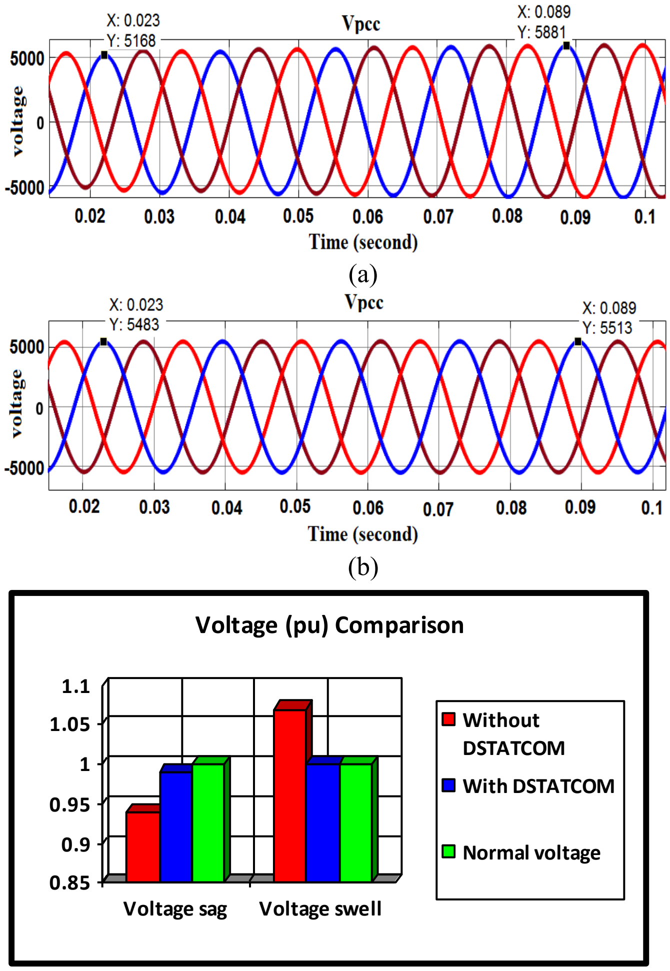
Where P and Q are the active and reactive power of the DSTATCOM controller at PCC. Eq. (14) and Eq. (15) represents the demand of actual and reactive power for the load and induction generator. Eq (15) shows that DSTATCOM provides reactive power when the power factor of the system decreases while DSTATCOM consumes reactive power when the power factor increases.

5. Results and Discussion

The wind power system is connected to the grid and to non-linear loads. The system performance is measured. DSTATCOM provides real and reactive power requirements for induction generators and non-linear loads. The variation in voltage occurs due to the variation in wind speed is shown in Fig. 7.

5.1. Voltage Fluctuation

When the grid is connected to a wind turbine, power quality issues such as voltage sag, swell, harmonics occur. DSTATCOM is used to reduce these issues. DSTATCOM produces a critically damped oscillation and returns to equilibrium as quickly as possible without oscillation. The Voltage at PCC with and without DSTATCOM is shown in Fig. 7.



(a)

(b)

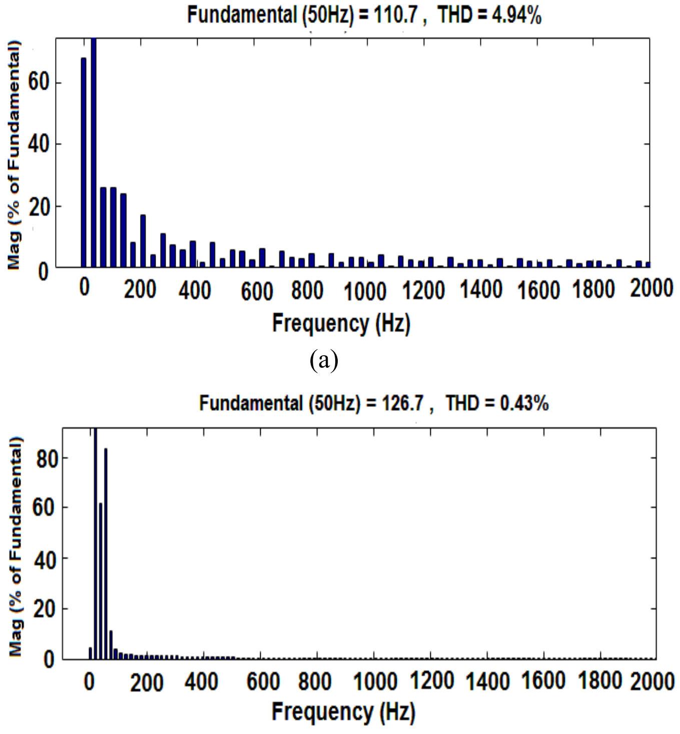
(c)

Fig. 7. Common coupling point voltage (a) with-out FACTS device (b) with DSTATCOM (c) voltage comparison

Variations in voltage decreases the power quality. DSTATCOM reduces the fluctuation in voltage and regulate the voltage at PCC to an acceptable range by injecting reactive power at PCC. The voltage sag and swell of DSTATCOM are 0.996 p.u and 1.002 p.u respectively which shows the voltage stability at PCC as shown in Fig. 7 (c).

5.2. Total Harmonic Distortion (THD)

The total harmonic distortion is a measure of the harmonic distortion present in the signal. In power system, total harmonic distortion measures how much of power waveform is distorted caused by harmonics. The distortion occurs in power system when the grid is connected with wind turbine. The distortion occurs in a power system due to the variation in load or wind speed.



(a)

(b)

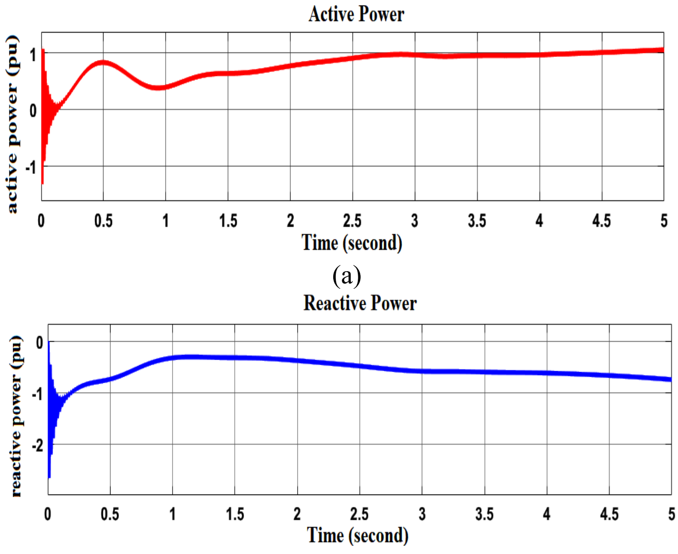
Fig. 8. THD (a) with-out FACTS device. (b) with DSTATCOM.

The THD without FACTS device is 4.94%, and for 11Kv should be less than 4%. According to the IEC-61400-21 standard, THD 4.94% is not acceptable. The THD for DSTATCOM is 0.43%, indicating that it has been greatly improved and meets the standard specifications as shown in Fig. 8.

5.3. Active and Reactive Power

When the system does not use FACTS device, the active and reactive power fluctuate from the normal values. The induction generator and load consume both active and reactive power. As the inductive load increases, DSTATCOM acts as a capacitor and provides reactive power to improve the power factor. On the other hand, when the inductive load decreases, DSTATCOM acts as an inductor and consumes reactive power.

Without DSTATCOM, power factor of the system cannot be controlled. When the load and the wind speed changes, it fluctuates the rotor speed, active and reactive power from the normal values as shown in Fig. 9.

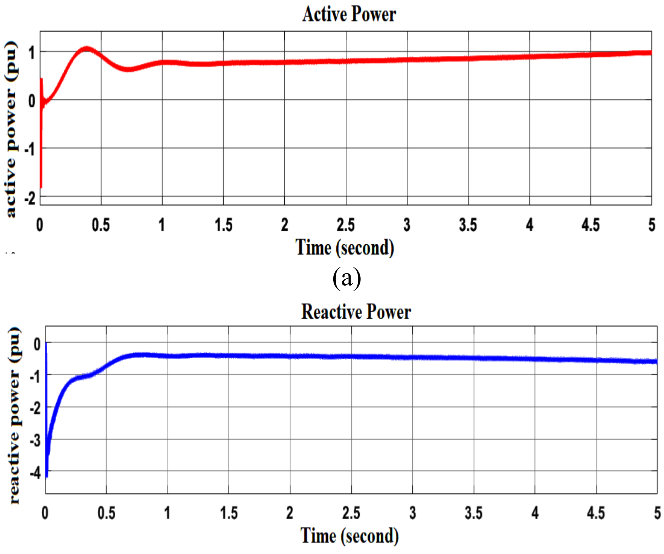


(a)

(b)

Fig. 9. Without FACTS device (a) Active power (b) Reactive power

When the wind speed changes, DSTATCOM controls the speed of the rotor. Figure 10 shows that when the DSTATCOM is used at PCC, the active and reactive power comes to stable condition.



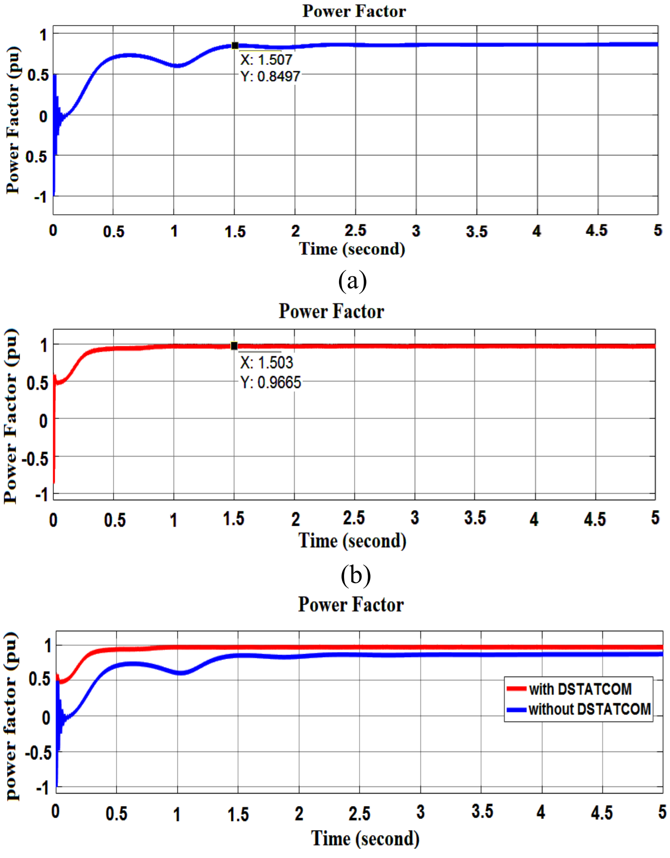
(a)

(b)

Fig. 10. With FACTS device (a) Active power (b) Reactive power

5.4. Power Factor

The power factor is primarily a function of the non-linear load. It varies mostly due to non-linear load. In this model, when the grid is connected to wind generation system, the power factor of the system is decreased because the wind turbine is connected with induction generator. Power factor has been improved using DSTATCOM-BESS. The results are shown in Fig. 11.



(a)

(b)

(c)

Fig. 11. Power factor (a) with-out FACTS device. (b) with DSTATCOM. (c) comparison of power factor with and without DSTATCOM.

The Power factor without the FACTS device is 0.8497 pu, which is unacceptable for reliable operation. DSTATCOM has a power factor of 0.9665 pu which is beneficial for reliable and satisfactory operation of grid-connected wind farms as shown in Figure 11(b). The steady state error (SSE) using DSTATCOM has been reduced as shown in Table 2. All of these factors shows that the power quality has been improved.

Table 2. Comparatıve analysis

Name of FACTS Device	Voltage (P.U) at PCC Actual/base			TH %	Steady State Error (P.U)	Power Factor (P.U)
	Sag	Normal	Swell			
Without DSTATCOM	0.94	1	1.07	4.94	0.1503	0.8497
DSTATCOM	0.99	1	1.00	1.32	0.0335	0.9665

6. Conclusion and Future Recomendation

This paper presents the power quality improvement of the grid-connected wind energy system. The power quality issues and their effects are presented. DSTATCOM has the ability to offset harmonics in load current, reduction in voltage variations and provides reactive power requirements for loads and wind turbines. Wind power plants do not have sufficient reactive power. So an external device is used for the compensation of reactive power. DSTATCOM is an important device for reactive power compensation. DSTATCOM cannot properly control the active power. So a BESS is used for better control of actual power. The PLL based PI controller is used for fast switching of IGBT. It has been concluded that DSTATCOM with BESS can be effectively used to improve the power quality of wind power distribution networks.

The transient response of DFIG-based WTs is distinct and more complex than those of synchronous generator (SG). The transient response occurs in a power system under grid fault. Transient stability can be achieved using stator voltage oriented (SVO)-based control, PLL to capture the frequency and phase of terminal voltage. For increased power driving capability by coupled DSTATCOM can utilitarian. So, the transient stability of coupled DSTATCOM can be considered as a future work.

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