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

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Abstract: In recent years the wind generation of electricity has been increased vastly in power sector and the trend of wind energy generation is expected to remain in consideration. Because of different environmental conditions and grid integration with the wind energy generation system, power quality issues arise these issues can be in the form of harmonics, voltage dips, voltage swells, poor voltage regulation, power factor problems. connection of wind power and grid with each other affects efficiency and quality of the power system. For power quality and efficiency Distribution Static Compensator (DSTATCOM) is used in the system for this purpose. This paper discussed power quality improvement technique with the help of DSTATCOM with battery energy storage system (BESS) for grid connected wind power plant. Reactive power supply is the main focus of induction generator and load to achieve satisfactory results, MATLAB/Simulink is used for the simulation of proposed scheme.

Keywords: *Power efficiency, PLL technique, voltage source converter, D-STATCOM,, Voltage sag swell, wind generation*

1. Introduction

Power efficiency has been the topic of consideration for last twenty years in the fields of utilities and also the end use clients As a result of wide usage of devices like power electronics devices, microprocessor-built devices, controllers used in complex miniature, industrial processes, computer network and non-linear loads the power efficiency and quality has got extensive attention to this field. Due to the industrialization increment in recent years it also has increased the power demand. Therefore, power generation has become a massive challenge. Electricity generation sources are renewable and non-renewable sources. Non-renewable electrical energy source continuous usage has many disadvantages like global warming, its high cost, air pollution is increased and also the fact that fossil fuels are diminishing, so it is essential to take renewable energy source in consideration which is the solution of future energy.

Renewable energy sources comprise of wind energy, solar energy, tidal energy, hydro, geothermal and biomass energy. Amid all further sources of renewable sources of energy wind energy system for electricity generation is the most reliable and cost-effective. The electricity generated by wind turbine could also be synchronized with the grid. Integration of grid and renewable generation of electricity is of highest importance which have given a trend in the recent years of using wind generation system. Wind turbine generation of electricity can be large plant for generation and also it can be very small generate up-to 5 MW. wind generations systems are basically built on the bases of continual speed topologies which are based on pitch control of the turbine. Because of its simplicity the induction generator in the proposed scheme is used. The reason for using it is because a separate field circuit is not required in it, constant and variable loads are accepted in it, and natural protection against short circuit is present in it.

Due to its various advantages wind turbines generation of electricity are becoming the main source. In some of the European countries 44% of wind energy generation is used as source of generation electricity. The efficiency and quality of supplied power of the grid integration of distributed generation (DG) is affected in the case of solar photovoltaic, fuel cell and wind and. Any deviation in voltage, current and frequency from their standard values will result in failure or miss operation of customer equipment. Power efficiency and quality is dependent upon several disturbances like voltage flicker, harmonics, voltage sag, momentary interruption, swell, oscillatory transients, impulsive transient and power factor. voltage source inverters usage is in transmission lines and also in distribution lines that advances in static switches like IGBT, IGCT, GTO, etc. all these switches have high power handling capability.

This consequence in a variety of Voltage-Source Inverter based equipment like (UPFC) Unified Power Flow Controller, (SSSC) static series synchronous compensator and (DSTATCOM) distribution static compensator all of these are developed for the possibility of the Flexible Ac Transmission System (FACTs). Reactive Compensation is one of the main issues in the power systems. Reactive power increases with the Transmission system lines, it reduces transmission capability it also results in the variation of receiving-end voltage. Usage of FACTs devices enable the transmission system to maximize the power transmission capability and it also provide high power efficiency and quality in the distribution system at the point of common coupling (PCC) and reactive power compensation. FACTs devices in general are classified into 3 types, first one is

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series controllers and the second one is shunt controllers the third type is combination of series-shunt controllers these controllers are designed to solve problems like flicker, swell, voltage sag, reactive power, in the power transmission system.

The usage of FACTs devices is used due to their reliable and fast control over parameters of the transmission system these parameters include line impedance of the system, the voltage of the system, phase angle which is angle between sending voltages and receiving voltages. DC capacitor voltage is generally maintained with the help of BESS. When the system fault occurs, to maintain stability the BESS job is to absorbs the additional reactive power or it should provide reactive power to the system in case of need. DSTATCOM is used because of its multifunctionality, the central objective for the implication of control algorithm is to make it flexible easy to use and practice its functionality to the maximum possible level. Voltage source and current source are the two converter configurations, capacitor is used in the voltage converter and in current source the inductor is used. The reasons for the preference of Voltage converters are because of less heat dissipation, miniature size and also capacitor cost is less than the cost of an inductor.

2. Wind Energy Generating System

wind generations systems are basically built on the bases of continual speed topologies which are based on pitch control of the turbine. Because of its simplicity the induction generator in the proposed scheme is used. The reason for using it is because a separate field circuit is not required in it, constant and variable loads are accepted in it, and natural protection against short circuit is present in it.

2.1 Issues of Power Quality

Wind turbines that are incorporated through grid station, current and harmonic level of voltages are only consider acceptable with in a confide level. The reason of distortion in voltage occurs because of the alteration in current value which happens due to the nonlinear loads linked to the grid system [5]. Change in wind speed can also results in distortion in voltages [6][8]. Voltage flicker are caused by Fast variation in the supply voltage. This results in brilliance of light [7], [9].

2.2 Impact of poor power efficiency

Harmonics, variations in the voltage, flickering in the system results in equipment damage and failures like process control apparatus, PLC devices, IT devices, control systems based on microprocessor, and flickering of lights. telecommunications system is affected by it. Poor power efficiency and quality will affect contractors, it is the reason for the tripping of the protective equipment, and it can also stop the operation of sensitive equipment.

2.3 Rules for the Grid Coordination

In 2003 the first grid in United states was built. for wind power grids the United States has established firm specifications for operation as per IEC standards.

1) Voltage Rise (V): The Escalation in voltage values at PCC might result in the load tripping, line impedances R and X and the phase angle ϕ. The restrictive increase in voltage value is less than 2%.

2) Voltage Dips (d): Sudden decrease in voltage occurs when the wind turbine is in startup phase. The limiting value for voltage dip is less than 3%.

3) Harmonics: Harmonic in the system happens when wind turbine speed is changed. For 132kV THD set limit is set to be <2.5%. whereas for 11kV the THD set limit is set to be <4%,

4) Flicker: Measure of maximum switching operation is known as flickering; The flickering limit set for the value of $\leq$ 0.4 intended for 2 hours.

3 D-STATCOM

Distribution Static Compensator is an important device maintaining constant distribution voltage, in correcting power factor, and also for mitigating harmonics in a distribution network. DSTATCOM is basically a power electronics device which is used for reimbursement of the system reactive power. The connection of DSTATCOM with the load is in parallel and its operation is of continuous, the goal is achieving a power factor near the unity margin and also avoiding operational issues.

Common topologies used for the DSTATCOM are multi level topology and multi pulse topology. Multi-level-based topology compromises of more than six switches, voltage level defines the number of switches in each one of the branches, the disadvantage is that this type of operation needs control structures which are complex in nature and its cost is also high [7][12]. Whereas, multi pulse-based topology compromises on six switches, in which branch has two switches. multi-pulse topology is used because of its lower cost and simplicity of control. As DSTATCOM is used because of its multifunctionality, the central objective for the implication of control algorithm is to make it flexible easy to use and practice its functionality to the maximum possible level. Voltage source and current source are the two converter configurations, capacitor is used in the voltage converter and in current source the inductor is used. The reasons for the preference of Voltage converters are because of less heat dissipation, miniature size and also capacitor cost is less than the cost of an inductor.

4 The battery energy storage system (BESS)

The battery energy storage system (BESS) functions as an element for the energy storage the main goal is of voltage regulation in the system. BESS connection with the DSTATCOM is in parallel with DC interface capacitor. the DC capacitor voltage is generally maintained with the help of BESS. When the system fault occurs, to maintain stability the BESS job is to absorbs the additional reactive power or it should provide reactive power to the system in case of need. It also controls the distribution and transmission system in a very fast rate. By charging and discharging operation power fluctuation can be level by the BESS**.** BESS delivers the extra capability of DSTATCOM for reactive power compensation, harmonic current elimination, load balancing and it also functions as un-interruptible power supply (UPS).

5. Methodology

5.1 DG Connected Wind Turbine Using FACTS Device

the designed model system have the wind power generation and the grid these two are coupled at PCC. These two sources at PCC are linked with the help of bus bars Fig. 1 shows their connection with each other. Furthermore, these two are allied with DSTATCOM-BESS the nature of load is nonlinear load at PCC. DSTATCOM is used because of its multifunctionality, the central objective for the implication of control algorithm is to make it flexible easy to use and practice its functionality to the maximum possible level. Voltage source and current source are the two converter configurations, capacitor is used in the voltage converter and in current source the inductor is used. The reasons for the preference of Voltage converters are because of less heat dissipation, miniature size and also capacitor cost is less than the cost of an inductor,

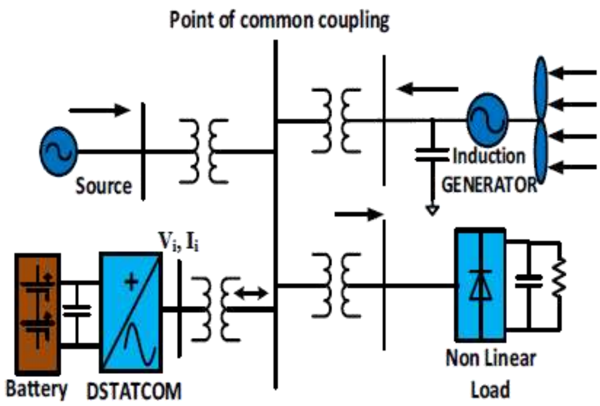

Fig. 1. DG connected wind turbine using FACTS device

The system compromises of two types of generator. Distribution generator (DG) is the first generator which is 132kV voltage source grid generator system, 132kV/11kV transformer is used to stepped down the voltage to 11kV by step down transformer. The second generator is of wind turbine a DFIG generator 575V is produced with it the voltage is further stepped up to the voltage value of 11kV with help of 575V/11kV transformer. The grid linked with a wind farm having a nonlinear load in the system, so power quality in this case will be poor as the wind system is unable to produce required reactive power. Therefore, DSTATCOM-BESS is come into account to produce this required reactive power. MATLAB/SIMULINK is used for the simulation of the proposed scheme as shown in Fig. 2.

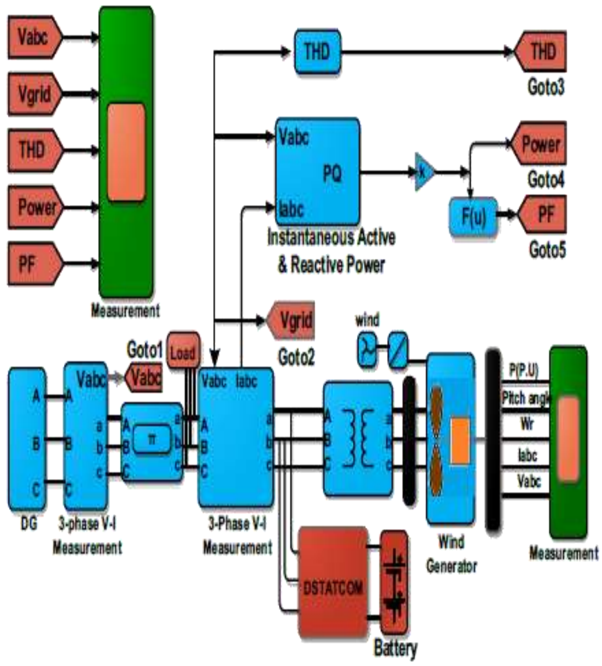

Fig. 2. DG connected wind turbine with FACTS device

Proposed system parameters are given in bellow Table

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

5.2 Voltage Source Converter (VSC) based control system

The compensator used will compare the voltage supplies which is lagging current the other is leading current these are used to stabilize power in the system. Fig.4. represents the voltage source converter (VSC) constructed control system. transmission line voltage V and the Vo which is the output voltage are in phase with each other and the magnitude of V and Vo is also of the same amount in this scenario normal operation will process as no reactive power will be exchanged with the line by the compensator. In the second scenario when V<Vo in this case the leading current is taken by compensator therefore it performs as a capacitor and will supply the required VAR. On the other hand, in case where V>Vo a lagging current happens in this scenario the compensator acts as an inductor to captivates VAR.

DSTATCOM structure consists of two bridges, one is that a DC link capacitor in the system is linked with BESS and VSC, in the second bridge a couple transformer is linked in parallel by means of the distribution system network, as shown in Fig. 4. VSC alters the DC voltages which are taken from BESS to AC when the load on the system increases, and provides it to the system. VSC obtains AC and alter it into D, when the load on the system decreases for storing of extra system voltages.

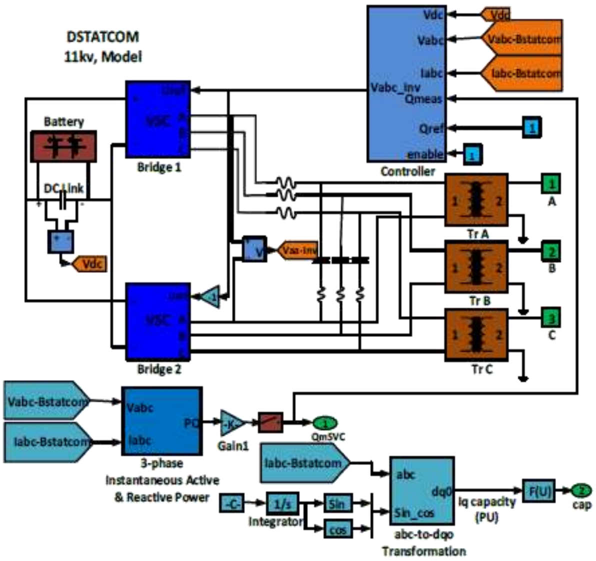

Fig. 4. VSC control system

5.3 Phase Locked Loop (PLL) Technique

In PLL technique the PI controller is used to make the compensator output voltage in phase with that of the AC voltage and the connection of it with the distribution system is with the help of couple transformers. Effective control DSTATCOM and AC system power exchange between them can be achieved with the help of DSTATCOM adjustment of proper phase angle as well as the magnitude of AC system. PLL used basically is a discrete 3 phase.

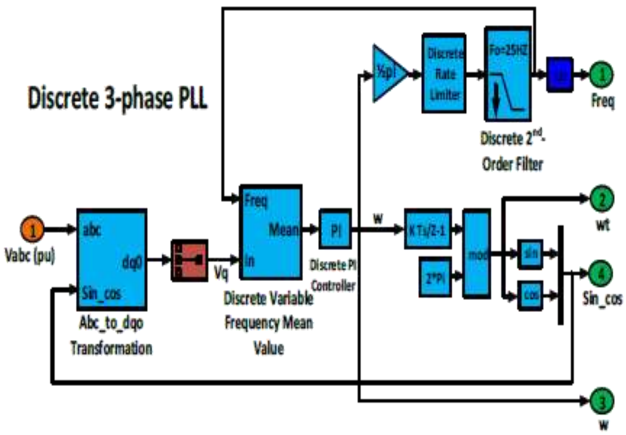

Fig. 5. PI Controller base PLL

5.4 Mathematical analysis

- Equations are

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

- Inverse transformation is given by

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

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

- The error voltage given to the PI controller is given as

$$V_{error} = V_{ref} - V_t \quad (4)$$

System transformation angle is represented by θ. Phase voltage give us the $\sin\theta$ and $\cos\theta$. PLL technique which is based on PI controller is represented in Fig. 5. PLL voltages are coordinated with voltages of the primary transformer. The phase voltages into q-axis and d-axis are converted with the help of transformation block.

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

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

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

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

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

q-axis and d-axis voltage and current components of system are compared with voltages and current values of PI controller after that comparison an error signal is generated. The error signal generated from comparison will create pulse width modulation signal this PWM signal is given to IGBT of VSC as a gate signal, this is represented in Fig. 4.

Differentiate P2 and Q2

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

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

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

$$P = \frac{V_2V_1\sin\theta_{21}}{X} - \frac{V_{PCC}V_C\sin\theta}{X} \quad (11)$$

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

d is the angle whereas X represents the reactance between PCC to that with the converter output terminal. P is the active power and Q represents the reactive power of the controller of DSTATCOM at PCC. Actual power for load is shown in Equation (11) whereas Equation (12) gives the reactive power demand in the system for induction generator. Equation (12) represents that when power factor decreases the reactive power is provided by DSTATCOM when the power factor of the system increase so DSTATCOM will consumes this extra reactive power in that case. Fig. 6 represents the DSTATCOM control system.

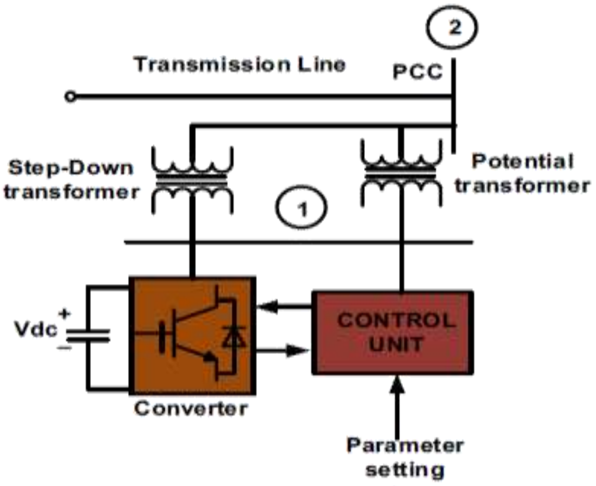

Fig. 6. DSTATCOM control system

4. Results and Discussion

The connection of the wind power system is with the grid and also connected to the non-linear loads. Performance of designed system is calculated. The function of the DSTATCOM is the providence of real power and reactive power when it is required for non-linear loads and also for induction generators. voltage variations is because of the change in wind speed at the system. Voltage fluctuations, total harmonic distortion, active power and reactive power, and power factor are analyzed with the usage of DSTATCOM and without DSTATCOM.

1. Voltage Fluctuation

Power efficiency and quality issues occurs like voltage sag, swell, harmonics when the grid is linked to a wind turbine. These issues are reduced with the help of DSTATCOM. When DSTATCOM is used voltages returns to state of equilibrium as swiftly as possible this produces a critically damped oscillation. Fig 7 (a) and 7(b) illustrates the PCC voltages without and with DSTATCOM respectively.

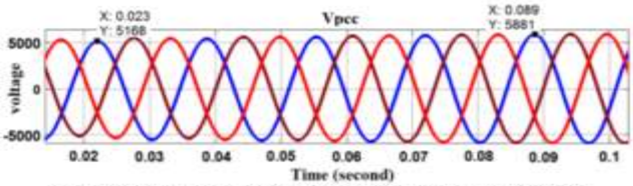

Figure 7 (a) Common coupling point voltage with-out FACTS device

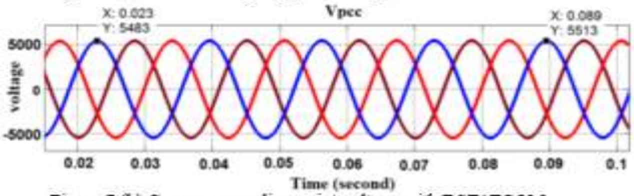

Figure 7 (b) Common coupling point voltage with DSTATCOM

power quality decreases when variations in voltage occurs. DSTATCOM has reduced the voltage fluctuation and it regulate PCC voltage to a range that is acceptable this is done by reactive power injecting at PCC. Value of voltage sag is 0.996 p.u and swell is 1.002 p.u when DSTATCOM is used, these values of sag and swell represents the voltage stability at PCC Figure 7 (c) shows the comparison of normal voltage value with and without DSTATCOM values.

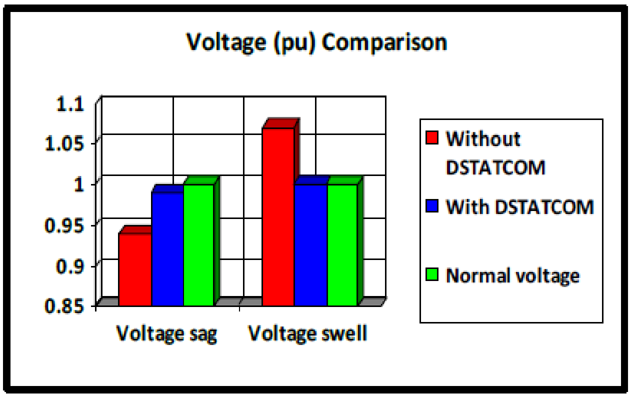

Figure 7 (c) voltage comparison

2. System Total Harmonic Distortion (THD)

In power system, how much of the power waveform is basically distorted which is caused by harmonics. The distortion occurs in a power system due to the variation in load or wind speed. The THD when FACTS device is not used is of the value 4.94%, and as for standard acceptable range for 11Kv must be less than 4% value. In regards to IEC-61400- 21 standard 4.94% THD is not satisfactory. When DSTATCOM is used in the system the total harmonic distortion value becomes 0.43%, this value of the THD represents that the THD is greatly improved when DSTATCOM is used and it meets the standard specifications

Figure 8 (a) shows the THD without DSTATCOM and Figure 8 (b) shows the THD with the usage of DSTATCOM.

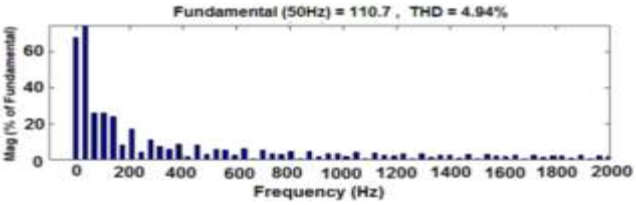

Figure 8 (a) THD with-out FACTS device

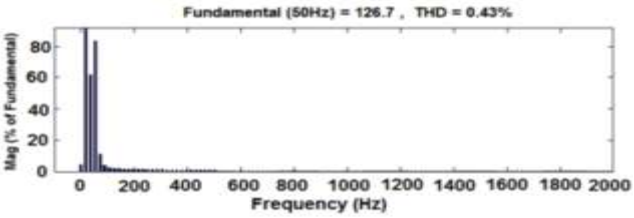

Figure 8 (b) THD with DSTATCOM

3. Active and Reactive Power without or with FACTS device

Active and Reactive Power without FACTS device. When the wind speed and load value changes, this makes the rotor speed to fluctuates. When FACTS devices like DSTATCOM is not used active power and also reactive power of system will fluctuate from normal values. Figure .9 shows active power and reactive power when DSTATCOM is not used fluctuates from the normal values.

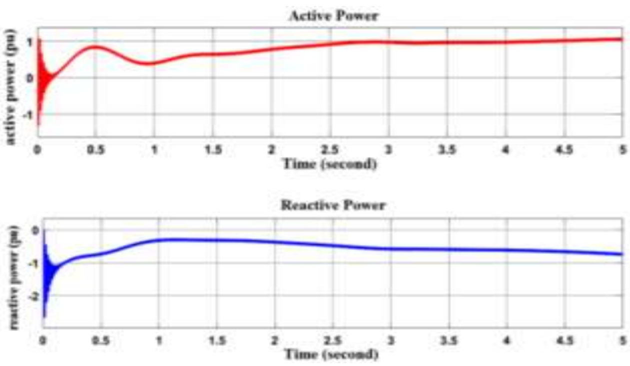

Figure 9. (a) Active power (b) Reactive power without FACTS device

Active and Reactive Power with FACTS device

When DSTATCOM is used if inductive load of the system increases, so the FACT device (DSTATCOM) will start acting as capacitor and will provide the required reactive power to the system. In other scenario if the inductive load of the system decreases, in this case the DSTATCOM used in the system will start acting as an inductor and consumes reactive power. DSTATCOM controls the speed of the rotor, When the wind speed changes. Figure 10 shows that active power and reactive power comes to stable condition when the DSTATCOM is used as represented in Figure 10.

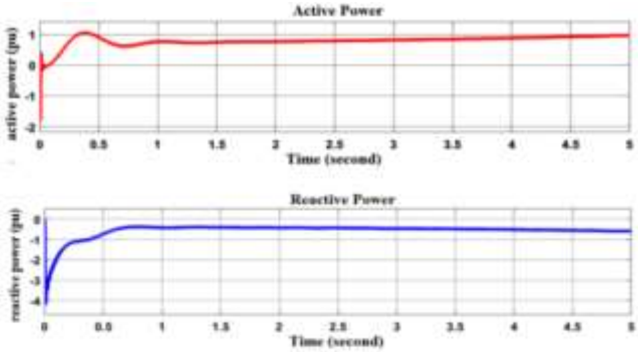

Fig. 10. With FACTS device (a) Active power (b) Reactive power

4. Power Factor

Power factor is basically a function of nonlinear load and it depends on this nonlinear load. In scenario when DSTATCOM is not used in that case power factor is decreased in the grid connected wind generation system, Figure 11(a) when FACT device DSTATCOM is not used. When DSTATCOM-BESS is used power factor has been improved, as shown in Figure 11 (b).

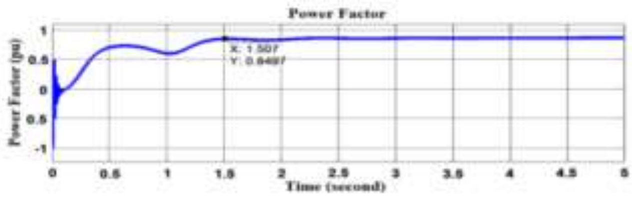

Figure 11 (a) Power factor with-out FACTS device

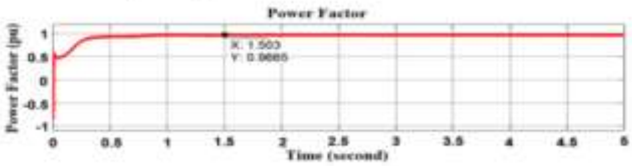

Figure 11 (b) Power factor with DSTATCOM

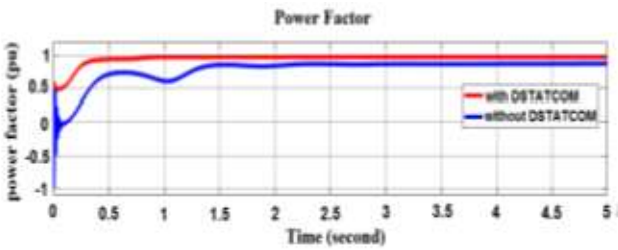

Figure 11 (C) power factor comparison with and without DSTATCOM

Value of power factor when DSTATCOM is not used in the system is 0.8497 pu, this value is undesirable for the well-suited operation. PF value when DSTATCOM is used is 0.9665 pu this value is acceptable for satisfactory and reliable operation in the discussed system. Power factor comparison with and without DSTATCOM is represented in 11(c).

With the usage of DSTATCOM steady state error (SSE) in the system has been reduced. Voltage sag, swell, Total harmonic distortion (TH) power factor and steady state error (SSE) without DSTATCOM and with DSTATCOM are compared as in Table 2. Power quality has been improved as all these factors represents that it is improved.

Table 2. Comparative 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

5. Conclusion

In this study the power efficiency and quality improvement grid-connected wind energy system has been discussed. The power efficiency and quality issues of the system are discussed and their effects on the system parameters are presented. DSTATCOM is used because of its multifunctionality, the central objective for the implication of control algorithm is to make it flexible easy to use and practice its functionality to the maximum possible level. Voltage source and current source are the two converter configurations, capacitor is used in the voltage converter and in current source the inductor is used. The reasons for the preference of Voltage converters are because of less heat dissipation, miniature size and also capacitor cost is less than the cost of an inductor, by only using DSTATCOM for active power control it cannot be done properly the BESS is connected with it and used as for actual power control. For switching of the IGBT fast switching PLL based PI controller is used. From the result achieved it is concluded that DSTATCOM with BESS is useful and effective for wind power distribution network improved power quality. The steady state error (SSE) of the system when DSTATCOM is used is less as compared to a system where DSTATCOM is not used. Voltage sag, swell, Total harmonic distortion (TH) power factor and steady state error (SSE) without DSTATCOM and with DSTATCOM are compared in the Table 2. It is clear form table 2 that the power quality of the system has been improved. DFIG-based wind turbines transient response is distinct it is more complex as compared to the synchronous generator (SG). System transient stability in the system can be achieved with the use of stator voltage oriented based control, DSTATCOM is used for increased power driving capability. In future the transient stability with the help of DSTATCOM coupled system will be in consideration.

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