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Power smoothing method of PMSG based grid integrated wind energy conversion system using BESS/DSTATCOM

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ABSTRACT

The output of the PMSG based wind energy conversion system (WECS) is fluctuating in nature due to intermittency of wind speed. The distribution static synchronous compensator (DSTATCOM) incorporated with the battery energy storage system (BESS) is used to smooth the power produced from wind generator system. The control strategy of BESS/DSTATCOM and its integration to mitigate the power fluctuations of grid connected WECS is presented. Three-leg three-phase voltage source converter (VSC) based DSTATCOM is used and the battery current is controlled to smooth the net power injected to the utility grid from wind power generation system. The control strategy implemented has the capability of supplying the required amount of power to the utility with help of batteries. The PQ control strategy is employed to control the three-phase inverter for managing power exchange with the utility grid. The real time wind speed data is considered for the simulation study of the system. The effectiveness of the control strategy of the system is validated through the simulation results in MATLAB/Simulink environment.

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1. INTRODUCTION

The renewable energy generation systems are attracting great attention due to environmental problems and increasing energy demand. The wind power has potential to compete with fossil fuel, as it is cheaper compared to other renewable power generation systems and requires low maintenance. The permanent magnet synchronous generators (PMSG) based wind systems are most efficient. The output of the PMSG based wind energy system (WES) is fluctuating due to intermittency of wind speed. The dynamic modeling of WES is discussed in [1] and MPPT for optimum power generation are discussed in [2, 3] for grid connected operation of PMSG based WES. A control technique used for DSTATCOM of the grid connected wind energy system for power quality improvement is reported in [4]. Various power smoothing techniques used for the wind power plants which are directly connected to the transmission system are reviewed in [5] with the use of FACTS devices. The energy storage based smoothing techniques are found to be very effective in output power smoothing of the WECS.

The small-scale wind turbines driven using PMSG is getting more attention recently in the market. In wind energy systems, the PMSGs are often directly coupled to the turbine eliminating the need of gearbox that helps in avoiding gear losses which on different wind speeds disturbs generated voltage as well as frequency level. With the help of power electronics devices and control techniques the power and voltage fluctuations can be regulated. These devices are known as the FACTS controllers that mainly include

DSTATCOM, static synchronous series compensator (SSSC) and unified power flow controller (UPFC). While the conventional DSTATCOM and SSSC can control one variable, the UPFC can control three variables [4-6]. This work mainly focuses on the power quality and hence two variable control will be sufficient and which can be achieved by using DSTATCOM or SSSC with ESS. The DSTATCOM is preferred and it is a shunt device that can be used in generation, transmission or distribution side depending on the parameter to be controlled.

The operation of conventional DSTATCOM used for load leveling and voltage control of PMSG based DG set for standalone supply system is discussed in [7]. The principle of DSTATCOM and different control structures such as direct current control, indirect current control, dual loop current control and PI regulation are discussed in [8]. A detailed review of DSTATCOMs used for the electric power system are reported in [9]. The application of DSTATCOM/BESS for wind power smoothening and hydrogen generation is detailed in [10]. The load leveling and control of voltage with BESS/DSTATCOM is discussed [9] for PMSG based generator driven by diesel engine where speed of rotation is approximately constant unlike WES whose voltage and frequency has to be conditioned. The output of wind farm is controlled by absorbing or providing real power and the the reactive power is controlled with DSTATCOM/BESS is reported in [10]. The DSTATCOM with BESS is a capable of providing both reactive power support and also smooth power fluctuations by injecting active power using the BESS [11, 12]. The load compensation and control of voltage of PMSG based diesel generator set for standalone applications with improved fuel efficiency using BESS/DSTATCOM is described in [13].

In this paper, integration of DSTATCOM with a BESS is considered for PMSG based grid tied WECS and its capability for smoothing out intermittent power output has been evaluated. The fuzzy logic based MPPT controller is used to extract maximum power from PMSG based WES. This work primarily aims at smoothing the power injected to the utility grid using BESS based DSTATCOM with the harmonics regulated within the standard limits. The PQ control strategy is used to control the three-phase inverter for managing active and reactive power exchange with the utility grid. The control scheme implemented for DSTATCOM has not only power quality enhancement ability but it also has the capability to supply required amount of power to the utility with help of batteries. The actual wind speed data is considered for the simulation study of the system. The DSTATCOM control scheme for the grid connected WECS for power quality improvement is implemented and simulated using MATLAB/SIMULINK software. The final result of control strategy implemented is a smooth and controlled power output which can be injected to the grid.

2. WIND ENERGY SYSTEM CONFIGURATION

The schematic block diagram of the 20 kW, 415V, wind power generation system connected to utility grid is shown in Figure 1. The PMSG based grid connected WECS consists of uncontrolled rectifier, boost converter and three-phase inverter. In order to extract maximum power from WECS, the fuzzy logic based MPPT controller is used. The PQ control strategy is used to control the grid side inverter. The wind generating system is integrated to the utility grid using 415V/3.3kV step up transformer. In this system, BESS/DSTATCOM is used to mitigate the power fluctuations generated from WES. The BESS is used for supplying or absorbing active power to smooth the output power of WECS. In this paper, the model of DSTATCOM with BESS is implemented in MATLAB/Simulink platform to reduce the power fluctuations of grid integrated WECS.

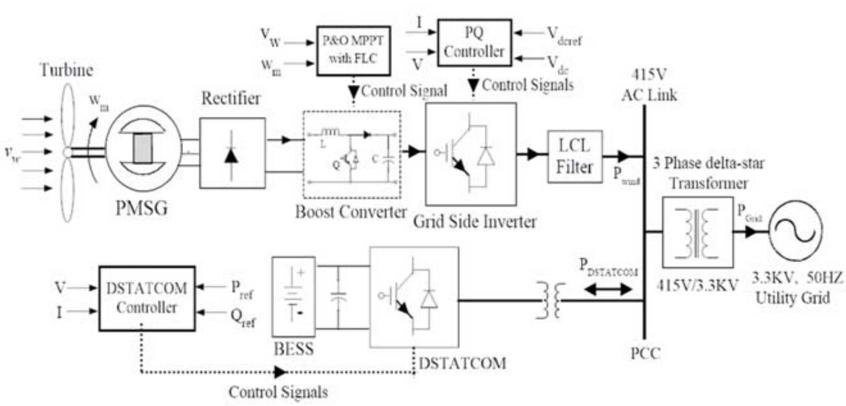

Figure 1. Schematic diagram of the WES with BESS based DSTATCOM

3. MODELING AND CONTROL OF WES

3.1. Modeling of WES with MPPT controller

The mechanical power available from a wind turbine used for PMSG based WES is represented by (1).

$$\boldsymbol{P_m = \frac{1}{2}\rho A {V_w}^3 C_p(\lambda, \beta)} \quad (1)$$

where ρ = air density, A = rotor swept area, V_w=wind speed in m/sec, C_p is coefficient of performance. The tip speed ratio in terms of rotor speed and wind speed of the generator is represented by (2)

$$\lambda = \frac{\omega_m R}{V_w} \quad (2)$$

The wind turbine torque on the shaft can be calculated from the power [1, 2]

$$T_m = \frac{P_m}{\omega_m} = \frac{1}{2}\rho\pi R^5 \frac{{\omega_m}^3}{\lambda^3} C_p(\lambda, \beta) \quad (3)$$

The MPPT algorithm keeps the power coefficient C_p at its maximum, C_p=C_{pmax}, corresponds to λ_{opt} [1].
where

$$\omega_{ref} = \frac{V_w \lambda_{opt}}{R} \quad (4)$$

Hence the maximum power corresponding to C_{pmax} is represented by

$$P_m = 0.5\rho ACpmax \left(\frac{R\omega_{ref}}{\lambda_{opt}}\right)^3 \quad (5)$$

The reference speed of wind turbine ω_{ref} is generated by the MPPT code using Perturb and Observe (P&O) technique. A fuzzy logic controller is used to rotate the rotor of PMSG with the speed corresponding to maximum power point. The schematic diagram of fuzzy logic based MPPT controller used for wind system is shown in Figure 2.

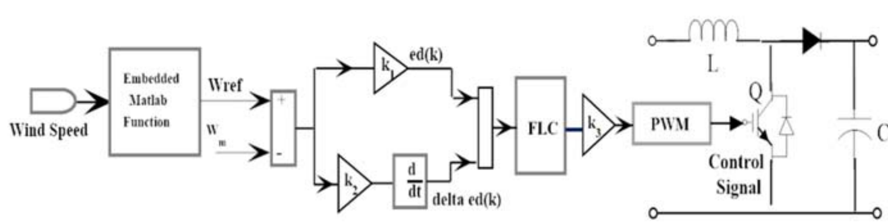

Figure 2. Fuzzy based MPPT controller for WECS

3.2. PQ Control Scheme for Inverter

The relations of active and reactive powers in synchronous reference frame are represented using the following relations as

$$P = \frac{3}{2}(V_{gd} I_d + V_{gq} I_q) \quad (6)$$

$$Q = \frac{3}{2}(V_{gq} I_d - V_{gd} I_q) \quad (7)$$

The active and reactive power control can be realised by controlling the d-axis and q-axis currents respectively with PI controllers. The requirement of unity power factor is achieved regulating the q-axis current at zero value. The phase locked loop (PLL) block that measures the grid voltage phase angle θ_g, which is used to implement Park transformation and to synchronize the inverter with the utility grid. A lower bound on the dc bus voltage can be determined from the following equation at a unity power factor [14, 15],

$$0.6124 \mathrm{m}_a V_{\mathrm{DC}} \geq \sqrt{(V_L)^2 + 3(\omega L_f I_{AC})^2} \tag{8}$$

where I_{AC}=maximum possible RMS value of the AC load current, V_L=line-line RMS voltage on the inverter side, and m_a=modulation index of the inverter. In order to get sinusoidal output output for the inverter, LCL filter [16] is used. If P is rated power, f is load frequency, f_s is inverter switching frequency, f_r is resonance frequency then the filter design equations are as follows [17, 18].

$$C_f \leq 0.01 \frac{P}{2\pi f {V_L}^2} \tag{9}$$

where L_1 and L_2 are inverter side and load side inductances respectively, C_f is filter capacitance. From equation (11) for 20KW of power, 50Hz and 415V line voltage, the resonance frequency is selected as $f_r = 2KHz$.

$$f_r = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \tag{10}$$

For minimizing ($L_1 + L_2$), $L_1 = L_2$ =3.166 mH is chosen. To reduce unnecessary oscillations and instability, a damping resistor 'r' should be added in series with the capacitor and is expressed as

$$r = \frac{1}{6\pi f_r C_f} \tag{11}$$

The design values are L_1 = 3.16 mH, L_2 = 3.167 mH, C_f = 3.8 μF and the damping resistor r=6.98 Ω. The control structure of the grid side converter is depicted in Figure 3.

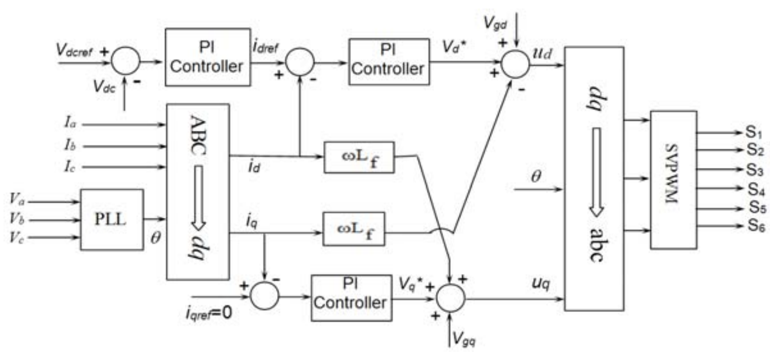

Figure 3. Schematic diagram of PQ control strategy for inverter

4. CONTROL STRATEGY OF BESS BASED DSTATCOM

The output of PMSG based WECS will be highly intermittent in nature due to the variations in velocity of wind. The DSTATCOM incorporated with BESS [19] is used to smooth the power produced from wind generator. The VSC, interfacing inductors (L_f) and ripple filters are the main components for the development of DSTATCOM. The control strategy implemented for BESS based DSTATCOM in order to mitigate the power fluctuations of grid connected WECS. The power injected to the utility system may be constant or variable depending on the grid power requirement. If refernce power is less than output of WES, then it will be absorbed by BESS/DSTATCOM. If the wind power generated is less than the reference value then then the deficit power is supplied by BESS/DSTATCOM. The BESS either absorbs or supplies power depending on the power command signal from the controller as per (12) and (13) so that the smoothed power is injected to the utility grid. To supply a smoothened power to the utility grid, a BESS based DSTATCOM controller is implemented. Figure 4 shows the schematic block diagram of power smoothing controller used for battery based DSTATCOM.

$$P_{net} = P_{wind} + P_{STATCOM} \quad (12)$$

$$Q_{net} = Q_{wind} + Q_{STATCOM} \quad (13)$$

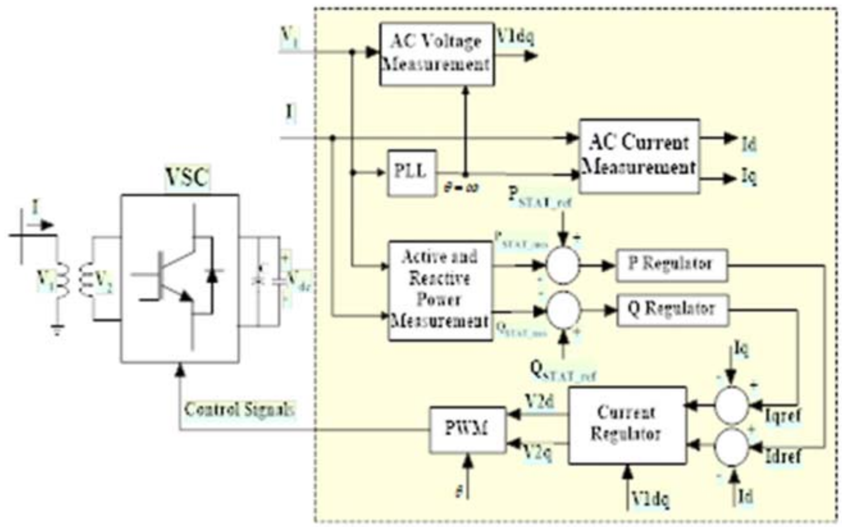

Figure 4. Control strategy of BESS based DSTATCOM

The control scheme has an outer loop for generating current references based on the measured power available from the wind system and power requirement of the utility grid. The inner loop comprises of current regulator to generate the control signals for the inverter depending on the power or current command from the outer loop of the controller. The power reference for BESS is generated by subtracting instantaneous power with average power computed. This helps in minimizing the fluctuations of power generated from WECS. The active power reference is assumed constant or varied in steps depending on grid power requirements. The BESS absorbs or supplies the power based on the power command from the controller and helps in supplying smoothened power to the utility grid. The reactive power reference is taken as zero to maintain the unity power factor. The value of I_{dref} is computed based on the error between the measured and required active power to be injected to the utility grid (P_{mes}-P_{req}). Similarly, the reactive power error (Q_{mes}-Q_{req}) is used to maintain the required reactive power exchange in the system.

5. RESULTS AND DISCUSSION

The main objective of this section is to assess the performance of the grid connected WECS and to demonstrate power smoothing with and without considering BESS/DSTACOM. To test the performance of the system with BESS/DSTATCOM, two different cases are considered. The WES is connected to the utility grid through a 0.415/3.3kV step-up transformer. The real time wind speed data is considered for the simulation study of the wind energy conversion system. The parameters of DSTATCOM and battery storage are reported in Table 1. The power rating of WES is 20 kW, 415V. A BESS with DSTATCOM of capacity 15 kW is used in this work. The voltage at the point of common coupling is 415V.

The pattern of wind speed input to the WES is shown in Figure 5(a). The power generated by PMSG based WES without considering BESS/DSTACOM is shown in Figure 5(b). The power output of WECS is controlled by MPPT controller.

Table 1. DSTATCOM Parameters

Parameters	Values
Inverter	3 Arm IGBT Inverter
Switching Frequency	10 kHz
DC link Voltage	800V
DC link Capacitor	2μF
Battery	800V, 4.2Ah

The current corresponding to the output of WES without BESS/DSTATCOM is shown in Figure 6(a) and it is observed that the current is highly fluctuating in nature. The harmonic spectrum of the current is depicted in Figure 6(b). The total harmonic distortion (THD) of current before PCC is 10.68% and which is more than IEEE standards [20].

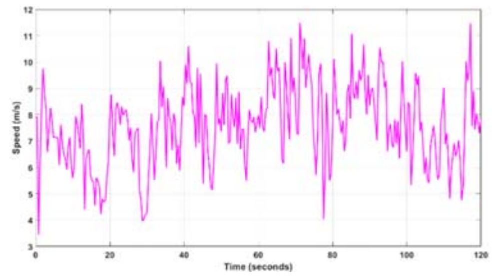

Figure 5(a). Wind velocity data

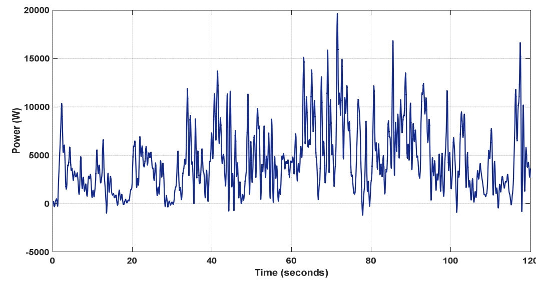

Figure 5(b). Power output of WECS

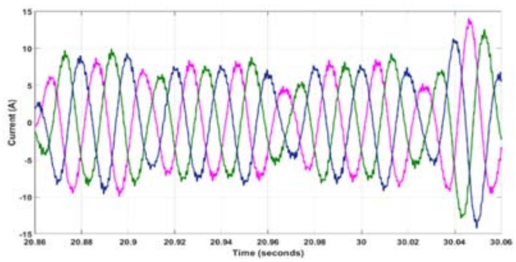

Figure 6(a). Output current of inverter

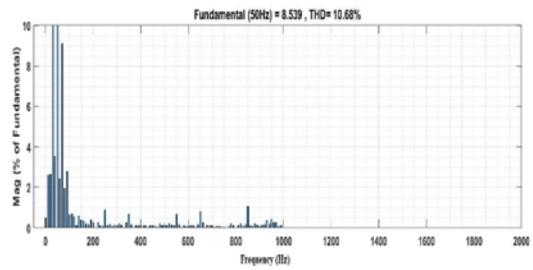

Figure 6(b). Harmonic spectrum of the line current

In order to assess the effectiveness of the control strategy with BESS/DSTATCOM, two different case studies are considered depending on the nature of reference power. The reference power which is to be injected to the utility grid can be either fixed or variable according to grid demand. At any instant, if the reference power is less than output of WES, then it will be absorbed by STATCOM as per equations (12) and (13). If the reference power is more than wind power output, extra power will be supplied to the line so that net power becomes equal to the reference power.

Case 1: Generation of fixed reference power output from WECS

In this case, the power supplied by the WECS to the utility grid is constant and let this reference power P_{ref} is chosen as 10 kW. The variation in the power output of WES, reference power and the net power injected to the utility grid are shown in Figure 7(a). The active and reactive power supplied or absorbed by BESS/DSTATCOM is shown in Figure 7(b). The BESS absorbs or provides power based on the reference power choosen and smoothens the wind power output as per the control scheme implemented. The waveforms of the current supplied to the is shown in Figure 8(a) and it is seen that the current is sinusoidal. The THD of the current is depicted in Figure 8(b) and is observed that the THD is within 5 percent as described by IEEE standards.

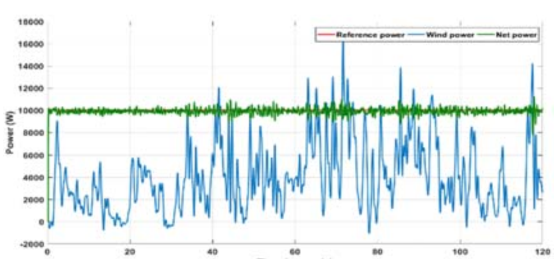

Figure 7(a). Wind power, reference power and net power

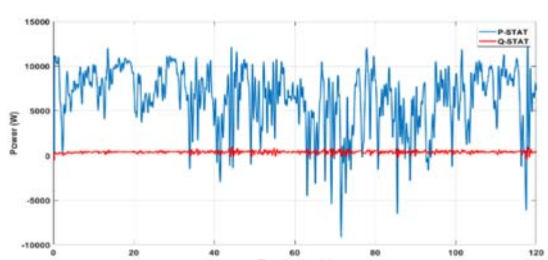

Figure 7(b). Active and reactive power

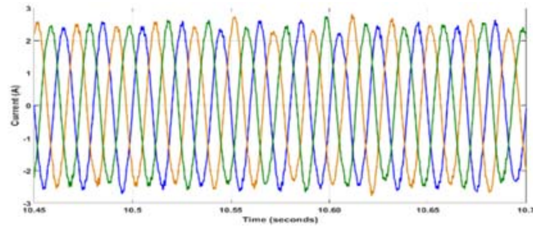

Figure 8(a). The current injected to the grid

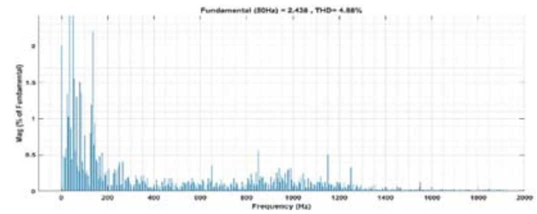

Figure 8(b). Harmonic spectrum of the current

Case 2: Generation of power output of WECS in accordance with the grid requirement

In this case, the WES is supplying power to the utility grid in accordance with the grid requirement. Figure 9(a) shows responses of reference power, power output of WES and net power supplied to the utility grid. It is observed from Figure 9(a) that the fluctuations in the output of WES are minimized and smooth power is supplied to the grid according to the variable grid requirements. The real and reactive power supplied or absorbed by BESS/DSTATCOM is shown in Figure 9(b). It can be seen that the intermittency in wind power output has been succesfully compensated by incorporating BESS based DSTATCOM in the system. The sinusoidal waveform of the current injected to the grid on 3.3 kV side of transformer is depicted in Figure 10(a). The THD of the current supplied to the utility system is reported in Figure 10(b) and it is found that THD is 4.81% which meets the IEEE standards.

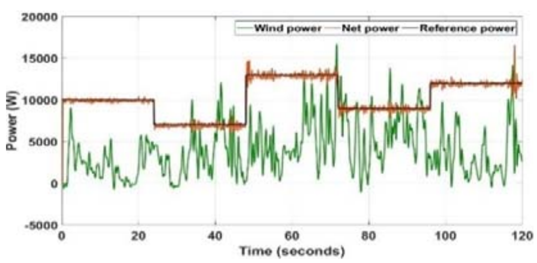

Figure 9(a). Wind power ouput, reference power and net power ouptut with BESS based DSTATCOM

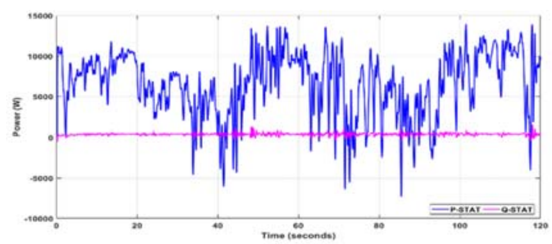

Figure 9(b). Active and reactive power supplied by BESS based DSTATCOM

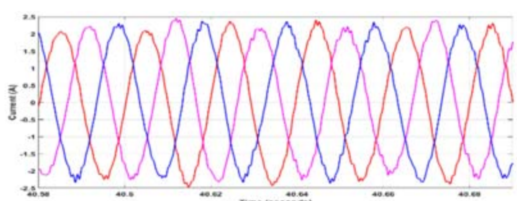

Figure 10(a). The current injected to the grid

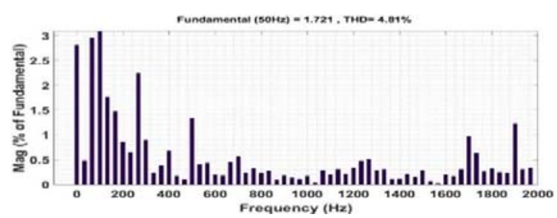

Figure 10(b). Harmonic spectrum of the current

It is evident from the simulated results obtained for both cases considered that the power injected to the utility grid is almost smoothed to a fixed value. The output power variations of wind energy conversion system can be significantly mitigated by incorporating the battery based DSTATCOM system. This confirms the effectiveness of the control strategy implemented to support power-smoothing control using BESS/DSTATCOM and is possible to penetrate higher wind power to the utility system.

6. CONCLUSION

The control scheme of DSTATCOM with a BESS for power quality improvement of the grid integrated WES is presented. The dynamic model of WES with fuzzy logic based MPPT controller coupled with BESS/DSTATCOM is realized in MATLAB/Simulink environment. The developed controller helps in stabilizing the power reducing the lower frequency component of harmonic spectrum thus smoothing the power injected to the utility grid. The regulation of DC bus voltage is maintained using PQ control strategy used for three-phase inverter. The simulated results with proposed scheme implemented for BESS incorporated DSTATCOM has not only power quality enhancement ability but it also has the capability to supply required amount of power to the utility with help of battery bank. Hence, larger integration and penetration of intermittent energy resources to the utility grid is possible.

REFERENCES

[1] Jayalakshmi N. S. and D. N. Gaonkar, "Maximum Power Point Tracking for Grid Integrated Variable Speed Wind based Distributed Generation System with Dynamic Load," *International Journal of Renewable Energy Research*, vol. 4, no. 2, 2014.

[2] Jayalakshmi, N. S. and Gaonkar, D. N., "A New Control Method to Mitigate Power Fluctuations for Grid Integrated PV/Wind Hybrid Power System Using Ultracapacitors," *International Journal of Emerging Electric Power Systems*, vol. 17, no. 4, pp. 451-461, 2016.

[3] Abdul Motin Howlader, Naomitsu Urasaki, Atsushi Yona, Tomonobu Senjyu and Ahmed Yousuf Saber, "A review of output power smoothing methods for wind energy conversion systems," *Renewable and Sustainable Energy Reviews*, vol. 26, pp. 135-146, 2013.

[4] Sharad W. Mohod and Mohan V. Aware, "A STATCOM-Control Scheme for Grid Connected Wind Energy System for Power Quality Improvement," *IEEE Systems Journal*, vol. 4, no. 3, pp. 356-352, 2010.

[5] A. Adamczyk, R. Teodorescu, R.N. Mukerjee and P. Rodriguez, "Overview of FACTS Devices for Wind Power Plants Directly Connected to the Transmission Network," *2010 IEEE, International Symposium on Industrial Electronics (ISIE), IEEE*, pp. 3742-3748, 2010.

[6] Heier, "Grid Integration of Wind Energy Conversion System," Chicester, UK, *John Wiley & Sons Ltd*., 1998.

[7] B. Singh, Ram Niwas, and S.K. Dube, "Load Leveling and Voltage Control of Permanent Magnet Synchronous Generator-Based DG Set for Standalone Supply System," *IEEE Transactions on industrial informatics*, vol.10, no. 4, pp. 2034-2043, 2014.

[8] Ying ZHAO, Bo-wen SUN, "Research on STATCOM Principle and Control Technology," *International Conference on Consumer Electronics, Communications and Networks (CECNet)*, IEEE, pp. 1593-1596, 2011.

[9] Bhim Singh, Ram Niwas, and Sunil Kumar Dube, "Load Leveling and Voltage Control of Permanent Magnet Synchronous Generator-Based DG Set for Standalone Supply System," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2034-2043, 2014.

[10] S. M. Muyeen, R. Takahashi, T. Murata, J. Tamura and M. H. Ali, "Application of STATCOM/BESS for wind power smoothening and hydrogen generation," *Electric Power Systems Research*, vol. 79, no. 2, pp. 365-373.

[11] C. Banos, M. Aten, P. Cartwright, T.C. Green, "Benefits and control of STATCOM with energy storage in wind power generation," *IEEE International Conference on AC and DC Power Transmission*, pp. 230 – 235, 2006.

[12] G. Escobar, A.M. Stankovic, P. Mattavelli, "Reactive power, imbalance and harmonics compensation using DSTATCOM with a dissipativity-based controller," *IEEE Conference on Decision and Control*, pp. 3051-3055, 2000.

[13] Bhim Singh, Ram Niwas, and S.K. Dube, "Load Leveling and Voltage Control of Permanent Magnet Synchronous Generator-Based DG Set for Standalone Supply System," *IEEE Transactions on industrial informatics*, vol 10, no. 4, pp. 2034-2043, 2014.

[14] N. Mohan, "T.M. Undeland and W.P. Robbins, Power Electronics-Converters," *Applications and Design. John Wiley and Sons*, Third Edition, 2010.

[15] Daniel W. Hart, "Power Electronics," *Tata Mcgraw Hill Education ltd*., pp. 361 – 366, 2011.

[16] Soumik Sen, Kalyan Yenduri and Parthasarathi Sensarma, "Step-by-step Design and Control of LCL filter based Three Phase Grid-connected Inverter," *2014 IEEE International Conference on Industrial Technology (ICIT)*, IEEE, pp. 503-508, 2014.

[17] A.U. Lawan, Haider Abbas, J.G Khor Senior M., and A. Abdul Karim, "Dynamic Performance Improvement of MMC Inverter with STATCOM Capability interfacing PMSG Wind Turbines with Grid," *IEEE Conference on Energy Conversion (CENCON)*, IEEE, pp. 492-497, 2015.

[18] Lim S, Choi J., "LCL filter design for grid connected NPC type three-level inverter," *International Journal of Renewable Energy Research (IJRER)*, vol. 5, no. 1, pp. 45-53, 2015.

[19] Bhim Singh, Ambrish Chandra and Kamal Al-Haddad, "Power Quality: Problems and Mitigation Techniques," *A. John Wiley and amp; Sons ltd.*, 2015.

[20] ISC Committee, "IEEE standard for interconnecting distributed resources with electric power systems," *New York, NY: Institute of Electrical and Electronics Engineers*, 2003.