Review On Control Strategies For PMSG Based WECS

Vatsal J Patel [1]**, Dr. Jatin J Patel** [2]
[1, 2]Dept of Electrical Engineering
[1, 2]G.H. Patel College of Engg. & Tech. Anand, Gujarat

Abstract- *In a modern wind energy conversion system, the power electronics converter plays an important role for the reliable operation. This paper presents the mathematical modeling of wind turbine & Permanent magnet synchronous generator. This paper includes the control strategies of two power electronics converters, where one converter is connected to the Permanent magnet synchronous generator (PMSG) and other one has been connected with Grid side. Paper shows the control of Machine side converter (MSC) consist of four control strategies for maximum power point tracking (MPPT). The Grid side converter control consist of two different control strategies compared in this paper, first one is SVM base voltage oriented control (VOC) and second is Hysteresis current control (HCC).*

Keywords- PMSG,MPPT,Machine side converter control,Grid side converter control,Vector oriented control, Hysterisis control.

I. INTRODUCTION

In the current scenario, the renewable energy sources are gaining momentum at the distribution domain and with the application of power electronics converters with the same enhances the reliability and performance. Wind energy has been considered as an attractive energy source for electric power generation in the recent years. Because of the random and uncontrollable nature of wind speed variations, regulating the wind power captured by a wind turbine is complex and requires an accurate Mathematical model. This issue has been resolved by designing a variable speed wind turbine generator (WTG) system which is used to control the power captured over a wide range of wind speeds. Power electronics converters are important part of the Wind Turbine generation system for controlling the output voltage or current and consequently, its rotor speeds.

There are two types of wind turbine systems which are fixed and variable speed wind turbines. The variable speed wind turbine (VSWT) is most commonly used with the wind power systems in to maximize energy captured at various wind speed. The variable-speed wind turbine systems have a wide speed range of operation and provide 10%- 15% higher energy capture from the fixed speed types and reduce the load on the drive-train and tower structure. Recently, PMSG-based directly driven variable speed WECS are more popular than the doubly fed induction generator due to the elimination of gear box and no need of external excitation system. So, it can operate at lower wind velocity. There are several types of power electronics interfaces have been investigated for variable speed wind turbines. The control method to capture the maximum power from the wind turbines in the variable speed region is called a maximum power point tracking (MPPT) control. Due to the decoupling of the generator system from the grid, the grid support and fault ride through can be achieved easily. So, PMSG wind turbine is becoming more favored by the wind power industry.

This paper proposes a novel control strategy for grid interconnection of WECS and to solve the power quality problem at PCC. The system under consideration employs PMSG-based variable speed WECS consisting of two back-to-back converters with a common dc-link. The generator-side converter controls generator speed in order to achieve maximum power point tracking (MPPT). The grid-side inverter regulates dc-link voltage and injects the generated power into the grid. In addition to this, the grid side inverter is also utilised to compensate the reactive power and current harmonics generated by non-linear loads, if any, at PCC. This enables the grid to supply only sinusoidal current at unity power factor (UPF). The proposed control strategy utilises the grid-side inverter rating optimally which is always under utilised because of lower wind capacity factor [1]. According to the authors of [7–9], the expected wind output during peak is nearly 60% of rated output, and yet the annual capacity factor may be in the 20–30% range. Thus, the proposed strategy helps to achieve IEEE standard requirements with improved power quality at PCC. The simulation and experimental results are provided to validate the active power injection as well as the harmonics and reactive power compensation capabilities simultaneously.

The paper is structured as follows: the system under consideration is discussed in section 2, MPPT Algorithm in section 3.The proposed control strategy for generator side and grid-side converters is explained in Section 4 & 5 respectively and Section 6 concludes the paper.

II. SYSTEM DISCRIPTION

In wind energy conversion system, wind turbine is directly connected to the Permanent magnet synchronous generator. It converts the wind kinetic energy in to the mechanical energy. This mechanical energy than transfer to the PMSG and this generator the mechanical energy is transformed to electrical energy. PMSG is connected to the grid or load via back to back converter with dc link between the converters.

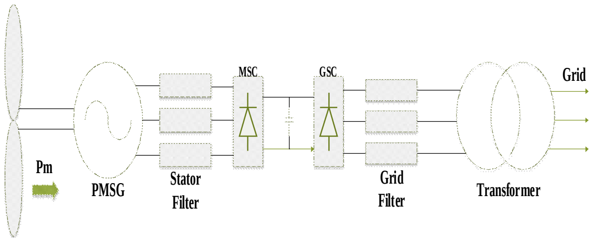

Figure 1 PMSG system with a back to back converter

The power electronics converter connected to the PMSG's stator windings is called machine side converter (MSC) and the power electronics converter connected to the grid is called grid side converter (GSC). The filter may be used in both side of converter to obtain the smooth current. The transformer can also be used for interconnection between wind turbine and grid.

Mathematical modeling of wind turbine

The extracted mechanical power from the wind is given by:

$$P_w = \frac{1}{2}\rho A C_p\left(\lambda,\beta\right)V_w{}^3 \tag{1}$$

Where, ρ is density of air A is the swept area of wind turbine, V_w is the wind speed, C_p is the power coefficient. and it is the function of the pitch angle β and the tip speed ratio λ.

The tip speed ratio is defined as :

$$\lambda = \frac{tipspeed}{windspeed} = \frac{\omega R}{v_w} \tag{2}$$

Where R is rotor radius (m) and ω is turbine angular speed (rad/s).

Here, the power coefficient $C_p = f\left(\lambda,\beta\right)$ is a function of both constraint. The different wind speed will require the optimal value of tip speed and pitch angle to achieve a highest C_p and give the highest power output at all available wind speed. As every optimal $C_{p,optimal}$ has one optimal value of tip speed ratio $\lambda_{optimal}$, it is necessary to control the tip speed ratio according to the wind speed. The MPPT is achieved by using power coefficient against tip speed ratio for different pitch angles of the turbine.

Mathematical modelindg of Permanent magnet synchronous generator

The dynamic model of PMSG is usually defined in the rotating reference frame *d-q* as follows:

$$V_q = R_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \lambda_m \tag{3}$$

$$V_d = R_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \tag{4}$$

The electromagnetic torque in the rotor can be described as

$$Te = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\left[\left(L_d - L_q\right)i_q i_d - \lambda_m i_q\right] \tag{5}$$

If i_d =0, the electromagnetic torque is given as:

$$Te = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right)\lambda_m i_q \tag{6}$$

Where, P is number of poles, λ_m is magnetic flux, L_d is direct-axis inductance, L_q is quadrature inductance, R_s is resistance and is ω_r rotor speed of generator.

Power electronic converter

The Ac output voltage from the wind generator is rectified by using bridge rectifier. This DC output voltage is fed to the DC-DC converter whose main function is to increase the variable dc voltage from rectifier to a constant DC voltage which is fed in to the inverter. The different control scheme is applied on the converter switch. The control scheme of the two converters will be described in detail in the following sections.

MPPT ALGORITHM

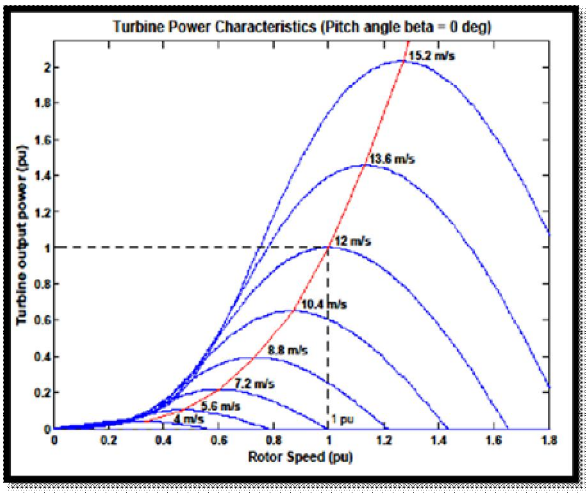

Figure 2 Wind turbine power Vs. Turbine rotor speed [3]

The maximum power point tracking, MPPT block generates reference speed which maximizes the power extracted from the turbine. At different wind speed maximum power corresponds to different generator speed shown in figure (2). So, look-up table is formed which gives the optimal generator speed according to given wind speed to maximize the power. Speed reference is obtained from look-up table to control the generator speed [3].

III. MACHINE SIDE CONVERTER CONTROL

The machine side converter is used to extract maximum power from the wind. The maximum power at different wind velocity is a cubic function of generator speed. So, the speed of generator is controlled by using the power-speed characteristic. There are four categories of the MPPT methods in the wind turbine system; power signal feedback control, perturbation and observation control, tip-speed ratio control and optimal torque control.

The dynamic machine model in the magnet flux reference system is as follow:

$$V_{qs} = -R_s I_{qs} - L_s \frac{d}{dt} I_{qs} + \omega_e L_s I_{ds} + \omega_e \psi \tag{7}$$

$$V_{ds} = -R_s I_{ds} - L_s \frac{d}{dt} I_{ds} + \omega_e L_s I_{qs} \tag{8}$$

Where, V_{qs} and V_{ds} are the stator phase voltages, I_{qs} and I_{ds} are stator phase current in *d-q* frame, L_s is the generator inductance and R_s is the generator resistance. The electromagnetic torque in d-q frame is given by,

$$T_e = \frac{3P}{2} I_{qs} \psi \tag{9}$$

The expression of the active and reactive power are

$$P = V_{ds} I_{ds} + V_{qs} I_{qs} \tag{10}$$

$$Q = V_{ds} I_{qs} - V_{qs} I_{ds} \tag{11}$$

The MPPT control of MSC consists of four strategies:

Tip Speed Ratio (TSR) control

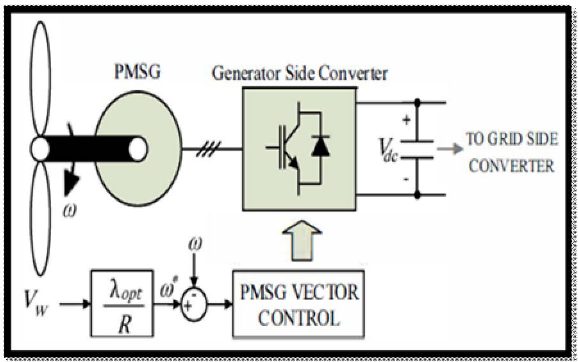

Figure 2 TSR Control Method [2]

The TSR control method regulates the rotational speed of the generator in order to maintain the TSR to an optimum value at which power extracted is maximum. This method requires both the wind speed and the turbine speed to be measured or estimated in addition to requiring the knowledge of optimum TSR of the turbine in order for the system to be able extract maximum possible power. Figure 2 shows the block diagram of a WECS with TSR control.

Power Signal Feedback (PSF) Control

In PSF control, it is required to knowledge of the wind turbine maximum power curve and track this curve through its control mechanisms. In this method reference power is generated either using a recorded maximum power curve or using the mechanical power equation of the wind turbine where the wind speed or the rotor speed is used as the input. Figure (3) shows the block diagram of a WECS with PSF controller for maximum power extraction.

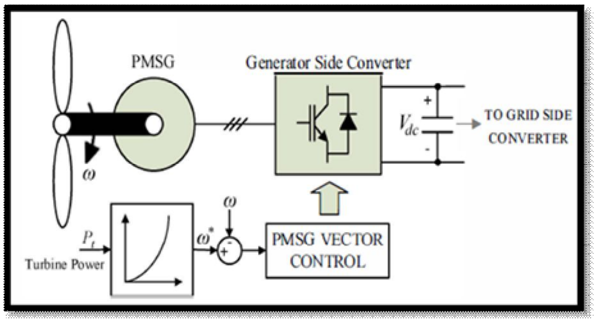

Figure 3 Block diagram of a PMSG based WECS with PSF method [2]

By measuring the turbine power allows calculating the speed reference which allows seeking the optimal operation. Following the optimum operation can be achieved after some iteration as shown in figure (4).

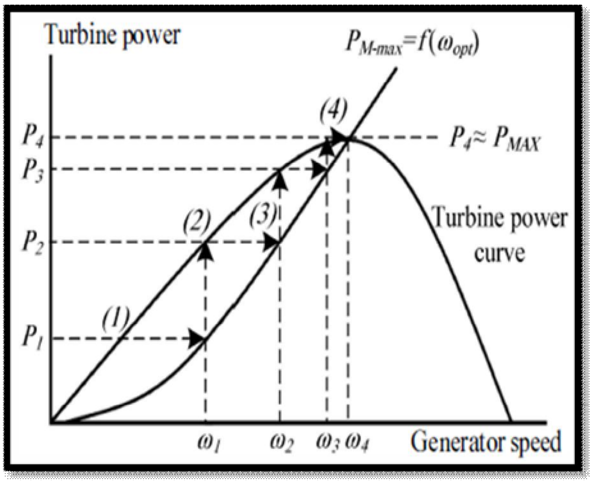

Figure 4 Convergence of the PSF method [2]

Optimal Torque Control (OTC)

In the OTC method when the wind speed changes, the generator torque is continuously controlled at the optimum operating point. The algorithm measures generator rotor speed and computes optimum torque T_{opt}, the torque which maximizes turbine power. This optimum torque is used as reference torque of a PMSG vector control method. The controller seeks the optimum operation point as expressed in Figure (6). Assuming the system is originally operating at point A, if the wind speed changes from V1 to V2, the turbine torque at point B becomes larger than the generator torque (Tg1), so, the turbine is accelerated up to the point C which the turbine torque and the generator torque are equal, so the WECS will work at a new operating point.

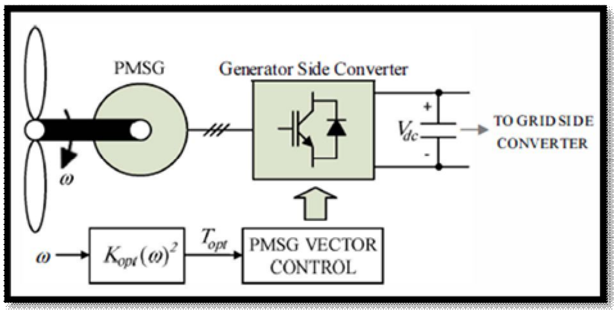

Figure 5 The block diagram of OTC method [2]

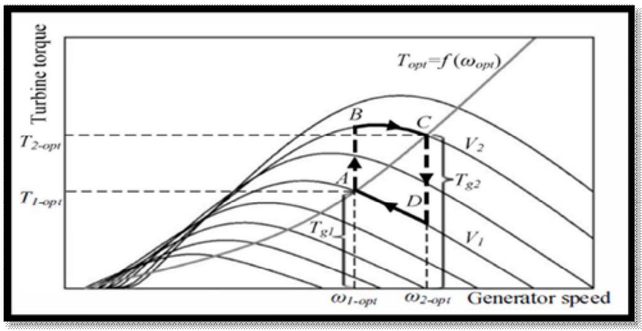

Figure 6 convergence of the OTC method [2]

Perturb and Observation Control

Hill climb search (HCS) methods are used for finding the peak point of the wind turbine power curve without any knowledge about wind turbine's maximum power curve or the information on wind velocity. Perturb and observation (P&O) technique is one of the WECS MPPT methods based on HCS algorithm. The fundamental principle of the P&O algorithm is to detect the change of wind turbine output power P[k]-P[k-l] after a generator speed perturbation ω[k]-ω[k-l] and decide the next generator speed perturbation $\Delta\omega$[k+1] according to the variation of P[k]-P[k-l].

First the generator speed is perturbed by a step change $\Delta\omega$[k] and then the variations of output power ΔP[k] is observed.

If the output power is increasing, the subsequent perturbation will be kept unchanged and the rotor speed will be increased until the optimal rotational speed of the rotor for a specific wind speed is reached and the WECS will operate at or around this point; otherwise the perturbation direction will be reversed. The principle of perturbation algorithm is illustrated in Fig.7.

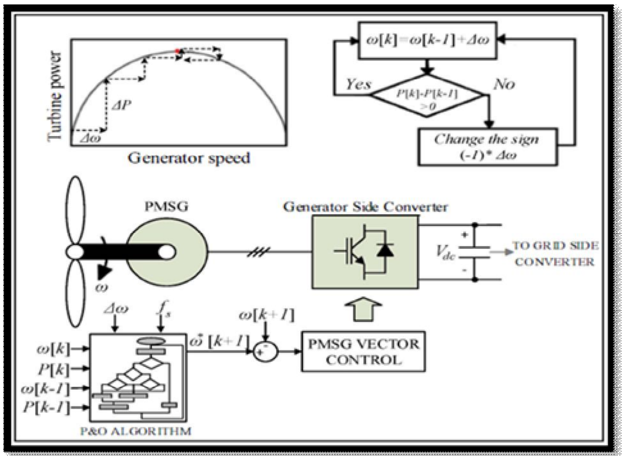

Figure 7.The block diagram of a PMSG based WECS with the P&O method [2]

Table 1 The comparison of MPPT methods in terms of dynamic response and efficiency [2]

MPPT Method	Response time (sec)	Recovery Time (sec)	Efficiency %
TSR	0.015	0.2	96.92
PSF	0.015	0.22	96.6
OTC	0	0.11	98.73
P&O	0.025	0.275	94

Table 2 Qualitative Comparison between different MPPT methods [2]

	TSR	PSF	OTC	P&O
Dynamic Response	Moderate	Moderate	Fast	Slow
Efficiency	Moderate	Moderate	High	Low
Torque Ripple	Moderate	Moderate	Low	High
Turbine characteristic Knowledge needed	Yes	Yes	Yes	No
Wind speed measurement needed	Yes	No	No	No
Appropriate power range	Small, Medium	Small, Medium	Small, Medium, high	Small

Grid side converter control

The dynamic model of the grid side converter connection, in reference fame rotating synchronously with the grid voltage is as follows:

$$V_q = R_s I_q + L_q \frac{d}{dt} I_q + \omega L_d I_d + 0 \quad (12)$$

$$V_d = R_s I_d + L_d \frac{d}{dt} I_d + \omega L_q I_q + E_s \quad (13)$$

Where V_d and I_d are the d-q axis output voltages of the inverter, ω is the grid frequency in rad/sec, L_d and L_q are the inductance in d-q axis which is equal to L_s and I_d and I_q are the d-q axis currents.

The equation of active and reactive power converted to grid are shown in equation (14), (15). It's shown that to control active power the d-axis current must be controlled and to control reactive power the q-axis current is needed to be

$$P = \frac{3}{2} E_s I_d \quad (14)$$

$$Q = \frac{3}{2} E_s I_q \quad (15)$$

The two different control strategies compared in this paper are

SVM base voltage oriented control (VOC)

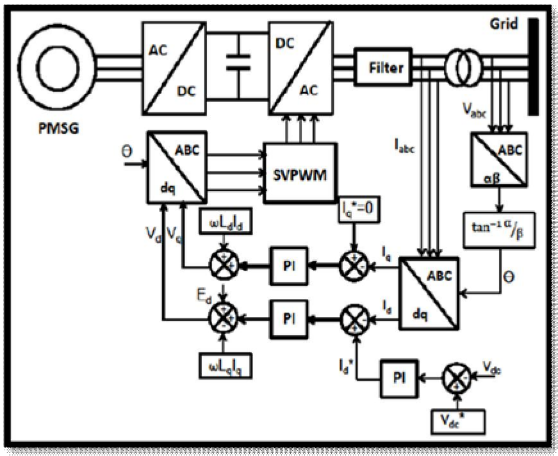

Figure 8 Voltage Oriented Control of grid side converter [3]

The aim of the control as shown in Figure (8) is to transfer all the active power produced by the wind turbine to the grid and also to produce no reactive power so that unity power factor is obtained, unless the grid operator requires reactive power compensation. In this control the phase locked loop (PLL) is used to synchronize the three phase voltage with the grid voltage.

DC-link voltage control loop: In order to transfer the active Power generated by the wind turbine to grid the DC-link voltage must remain constant. The outer loop of the control system regulates the DC bus voltage constant to be greater than the amplitude of the grid line to line voltage. In this control DC voltage is sensed and compared to its reference voltage and error signal is passes through PI controller which gives the reference of d-axis current.

Active power control loop: From Equations (14) it is clear that active power can be controlled by controlling the d-axis current. So d-axis current of grid is controlled by PI controller to its reference value which is generated by the voltage control loop.

Reactive Power control: Reactive power depends on the q current component as can be seen from Equation (15). So it can be controlled by controlling q-axis current. Reference q-axis current is set to be zero so that no reactive power flows into grid and obtain unity power factor. However in case of reactive power demand by grid under grid unbalance condition it can be changed.

A compensation terms will be added to improve the transient response of the system which can be concluded from Equations (12) and (13).

Hysteresis current control (HCC)

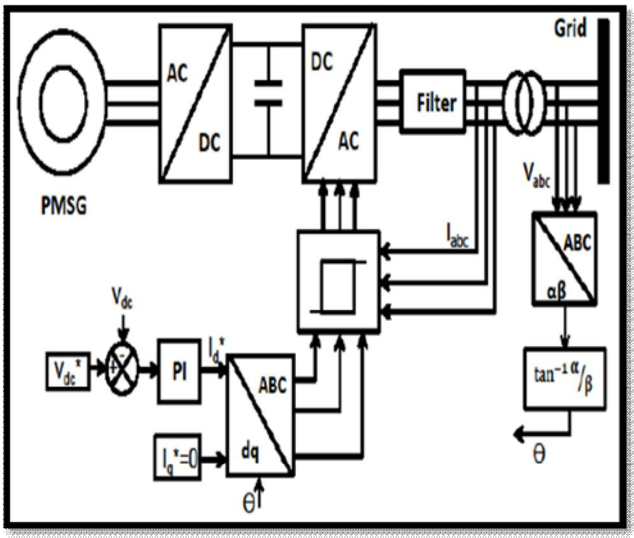

Figure 9 Grid-side Hysteresis Current Control [3]

The hysteresis current control system shown in figure (9) [15] is designed to maintain the DC-link voltage at a constant value. This DC-link voltage magnitude is adjusted by controlling the amount of current supplied to the electrical grid. The hysteresis controls the grid current by keeping the current wave in the range of the defined hysteresis band. When the current wave reached the band limits, the hysteresis controllers generate a control signal (0 or 1), which defines the PWM gate signal [14]. The current controllers adjust the output current Id, tracking the current reference Id∗. Comparing the instantaneous currents on the grid with the reference signal, the controller adjusts the duty cycle of the PWM of the converter. This leads to a reduced error signal (delta). In the system, The error between reference voltage and actual voltage feed the PI controller to produce a Id* and Iq* is set to be zero because it is responsible for reactive power. The output current then compared to the actual current supplied to the electrical grid. The error difference between the two signals is connected to the hysteresis current control, which produces the gate signal of the PWM. As the DC-link voltage increases, reference currents Id* produced also increase. When the current is lower than the reference current, the converter connects the positive side of the DC-link source to the load, thus the current Increases. On the contrary when the current is higher than the current reference the converter connects the negative side of the DC-link source to the load, which reduces the currents. With these two operations, the error of the current can be maintained within a certain fixed band.

Table 3 Observation [3]

Parameters	**Vector Oriented Control**	**Hysteresis current Control**
Settling time	0.02 sec	0.04 sec
Grid current THD	3.07 %	3.40 %
Current Fundamental value	16.29 A	16.33 A
Inverter voltage THD	35.8 %	40.08 %
Voltage Fundamental value	644.5 V	606.8 V

IV. CONCLUSION

The main MPPT methods for high power WECS are compared in terms of efficiency and Dynamic response. OTC method in tracking the MPP with the minimum possible time and the highest efficiency. It is followed by the PSF and TSR method which have similar characteristic from the efficiency and time response points of view although the TSR is a slightly better than the PSF. P&O method are less efficient and slowest recovery time, where the sum of response time and recovery time is three times of OTC one as per table 1. It can be seen that OTC method is one of the simplest and most efficient methods among MPPT methods for high power applications. The grid side control strategies are suitable to PMSG drives for wind turbines applications. However, with SVM based voltage oriented control techniques applied to the drive, it shows a better performance since lower current distortion higher overall efficiency is obtained. It is also observed that in than hysteresis current control peak overshoot is high as well as settling time is more.

REFERENCES

[1] Singh, M., V. Khadkikar, and Ambrish Chandra. "Grid synchronisation with harmonics and reactive power compensation capability of a permanent magnet synchronous generator-based variable speed wind energy conversion system." *IET Power Electronics* 4.1 (2011): 122-130.

[2] Heydari, Mojtaba, and Keyue Smedley. "Comparison of maximum power point tracking methods for medium to high power wind energy systems." *Electrical Power Distribution Networks Conference (EPDC), 2015 20th Conference on*. IEEE, 2015.

[3] Soni, R. K., et al. "Comparative study of SVM and hysteresis control strategies for grid side converter of PMSG." *India Conference (INDICON), 2014 Annual IEEE*. IEEE, 2014.

[4] Ackermann, Thomas, ed. *Wind power in power systems*. John Wiley & Sons, 2005.

[5] K.-H. Kim, T. 1. Van, D. Lee, S. Song, and E. Kim, "Maximum Output Power Tracking Control in Variable-Speed Wind Turbine Systems Considering Rotor Inertial Power," iEEE Transactions on industrial Electronics, vol. 60, no. 8, pp. 3207-3217, Aug. 2013.

[6] Y. Xia, K. H. Ahmed, S. Member, and B. W. Williams, "Wind Turbine Power Coefficient Analysis of a New Maximum Power Point Tracking Technique,", iEEE Transactions on industrial ElectroniCS, vol. 60, no. 3,pp.1122-1132,2013.

[7] Milligan, Michael R. *Measuring wind plant capacity value*. No. NREL/TP--441-20493. National Renewable Energy Lab., Golden, CO (United States), 1996.

[8] Boccard, Nicolas. "Capacity factor of wind power realized values vs. estimates." *energy policy* 37.7 (2009): 2679-2688.

[9] ‘Capacity factors at Kansas wind farms compared with total state electrical demand’, July 2007 to June 2008, http://www.kcc.state.ks.us/energy/charts/Wind Capacity Factors at Kansas Wind Farms Compared with Total State Electrical Demand.pdf

[10] KRAUSE P.C., WASYNCZUK O., SUDHOFF S.D.: ‘Analysis of electric machinery’ (IEEE Press, 1994)

[11] S. M. Dehghan, M. Mohamadian, and A. Y. Varjani, "A New VariableSpeed Wind Energy Conversion System Using Permanent-Magnet Synchronous Generator and Z-Source Inverter," iEEE Transactions on Energy ConverSion, vol. 24, no. 3, pp. 714-724, Sep. 2009.

[12] C. Liu, K. T. Chau, and X. Zhang, "An Efficient Wind-Photovoltaic Hybrid Generation System Using Doubly Excited Permanent-Magnet Brushless Machine," IEEE Transactions on industrial Electronics, vol. 5 7, no. 3, pp. 831-839, Mar. 2010.

[13] S. M. R. Kazmi, H. Goto, H.-J. Guo, and O. Ichinokura, "A Novel Algorithm for Fast and Efficient Speed-Sensorless Maximum Power Point Tracking in Wind Energy Conversion Systems," iEEE Transactions on industrial Electronics, vol. 5 8, pp. 29-36, Jan. 2011.

[14] Vazquez G., Rodriguez P., etc. *Adaptive Hysteresis Band Current Control for Transformerless Single- Phase PV Inverters*. IEEE 2009; p 178-182.

[15] Remli A., Aouzellag D., Ghedamsi K., *Study and Control of Wind Energy Conversion System based Permanent Magnet Synchronous Generator connected to the Grid*. Science Academy Publisher March 2011; Vol.1, No.1.