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Control of a Grid Connected Wind Energy Conversion System By using Sliding Mode Control (SMC)

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***Abstract:** As the penetration of the wind energy is increased day by day in modern power systems all over the world, the Wind Farm Systems (WFS) are today required to participate actively in electric network operation by an appropriate generation control strategy. The paper deals with the extraction of maximum power using various techniques in permanent magnet wind energy conversion systems. The various techniques include PI control, SMC control and neural control to extract maximum power from the turbine. The d axis current is set to zero to reduce copper loss and the q axis current is varied to extract maximum power. Out of the two loops PI controllers are employed in current loop and the speed controller is varied according to the controller used. A sliding mode control strategy is used to regulate the output voltage and frequency of the grid. The active and reactive powers injected to the grid are controlled by controlling the d and q axis currents. Results are verified using Matlab/Simulink environment.*

***Keywords:** Permanent Magnet Synchronous Generator (PMSG), Model Reference Adaptive System (MRAS), estimated speed, optimum speed, Sliding Mode Control (SMC), PI Control, Neural Control, PMSG Power With Various Controllers.*

I. INTRODUCTION

In recent times, there has been a transfer to renewable energy resources (the wind, solar, biomass, hybrid, etc.) due to increasing awareness about global warming caused by the emission of carbon from conventional energy resources. So wind power has been an alternate to fossil fuels, which doesn't produce any flue gasses. According to World Wind Energy Association, the wind energy capacity has expanded to 500 GW by June 2015 and has reached around 5% of worldwide electricity usage [1]. Permanent Magnet Synchronous Generator is widely used in WECS as it has minimum inertia when connected to power converter gearbox can be eliminated, fast response, high power density, and high efficiency. When compared to Induction Generators PMSG is smaller, easy to control and more efficient. PMSG can operate at variable speeds so that maximum power could extract even when it is rotating at small or medium speeds.

In WECS, position and velocity are essential to achieving high performance on motor control, digital encoders, sine encoders, rotating transformers have been for sensing, which may damage and effect reliability. Sensor has causes drawbacks like requiring maintenance, complexity, increased cost, size and gross errors due to which system will be unstable. Several techniques are present for sensor-less control [2].In Digital phase-locked loop for sensor-less vector controls the frequency of output signal by a control signal that is proportional to the change in the output signal and the input signal. This technique doesn't work well when a machine runs at low speeds

II. WIND TURBINE MODEL

The turbine converts wind energy into mechanical torque. The mechanical torque can be obtained from mechanical power. The mathematical equation of wind turbine is given below. The output power of the wind turbine is given by

$$P_m = 0.5\rho\pi R^2 V_w^3 C_p(\lambda,\beta) \qquad (1)$$

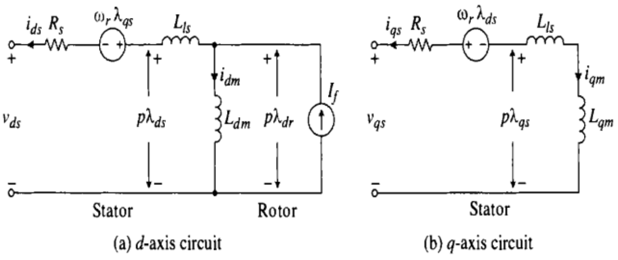
Where, P_m is a mechanical power of the wind turbine in watts, C_p is the power coefficient, ρ is the density of air in kg/m^3,V_m is the wind speed in m/sec. R is the blade radius in meters, β is the pitch angle, λ is the tip speed ratio. General equation to model coefficient of performance C_p is given by

$$C_P(\lambda,\beta) = C_1\left[\frac{C_2}{\lambda_i} - C_3\beta - C_4\right]e^{\frac{C_5}{\lambda_i}} + C_6\lambda \qquad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \qquad (3)$$

III. MODELLING OF PMSG

The proposed system consists of a wind turbine driving a PMSG fed through back to back PWM converters. The d and q axis circuit of permanent magnet generator is given below.



(a) *d*-axis circuit (b) *q*-axis circuit

Fig.1 Equivalent Circuit Diagram of PMSG

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The d axis and q axis voltage equations of PMSG are given below.

$$V_{ds} = R_S I_{ds} + L_S \frac{d_{Ids}}{dt} - \omega_r L_d I_{qs} \qquad (4)$$

$$V_{qs} = R_S I_{qs} + L_S \frac{d_{Iqs}}{dt} + \omega_r \lambda_f + \omega_r L_q I_{ds} \qquad (5)$$

Where V_{ds} and V_{qs} are the stator d and q axis voltages, I_{ds} and I_{qs} are the stator d and q axis currents. R_S denotes the stator resistance. $L_d$and $L_q$represents the d and q axis inductances. $\varphi_f$is the flux linkage.

IV. MODEL REFERENCE ADAPTIVE SYSTEM

The speed can be calculated by the model reference adaptive system, where the output of the reference model is compared with the output of an adaptive or adjustable model until the error between the two models reduces to zero. The speed observer used here is the model reference adaptive system. The reference and adaptive model is formed using relevant mathematical equations which are given below. The error between the reference model and the adaptive model is given to an adaptive mechanism which is basically a PI controller to reduce the error to zero so that the required parameter is estimated. The reference model is usually independent of the parameter to be estimated and the adaptive model is dependent of the parameter to be estimated[11] .In the proposed system sensor less control is achieved with the help of model reference adaptive system (MRAS) which is used to estimate the speed. The MRAS consists of two models namely the reference model and the adaptive model. Speed estimation by MRAS by comparing the stator currents was also proposed in the literature. The MRAS shown below uses two models to compute the stator flux of the PMSG. The reference model takes only the d and q axis currents as the inputs to estimate the stator flux whereas the adaptive model inputs include d and q axis currents and voltages and the parameter to be estimated which in this case is the speed of the generator.

A. Mras Design Equations

The adaptive model equations are taken with speed as the adjustable parameter. The equations governing the adaptive model is given below.

$$\varphi_{ds}{}^{*} = \int (V_{qs} + \omega^{*} L i_{qs} - R_s i_{ds}) dt + \varphi_f \qquad (6)$$

$$\varphi_{qs}{}^{*} = \int (V_{ds} + \omega^{*} L i_{ds} - R_s i_{qs} - \omega^{*} \varphi_f) dt \qquad (7)$$

The reference model equations are given by

$$\varphi_{ds} = L_d i_{ds} \qquad (8)$$

$$\varphi_{qs} = L_q i_{qs} \qquad (9)$$

The output of these models are compared and the error is given to an adaptive mechanism which in this case is a PI controller. The output speed is fed back to the adaptive model until the error is reduced to zero. Both the reference model and the adaptive model outputs the d and q axis stator flux. The error between the two is given to the adaptive mechanism which reduces the error to zero thereby estimating the speed of the generator.

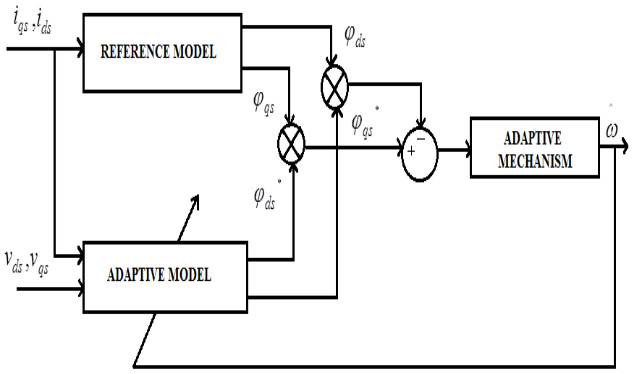

Fig.2 Basic MRAS Scheme

V. TYPES OF CONTROL TECHNIQUES

The Figure below shows the basic block diagram for MPPT using PI controller. The input to the PI controller is the error between the estimated speed and the optimum speed for MPPT. The speed of the Permanent magnet synchronous motor is estimated using a model reference adaptive system and the optimum speed is obtained using hill climbing search algorithm. The error is fed to a speed controller which is basically a PI controller to get the current reference. The reference current and the actual current are compared and the error is fed to a current controller and the pulses to the rectifier are given using any suitable pulse width modulation scheme [12-13]. The basic disadvantage of a PI controller scheme is that for a sudden change in wind speed the tracking is slow. To rectify this problem a feed forward neural network controller is employed.

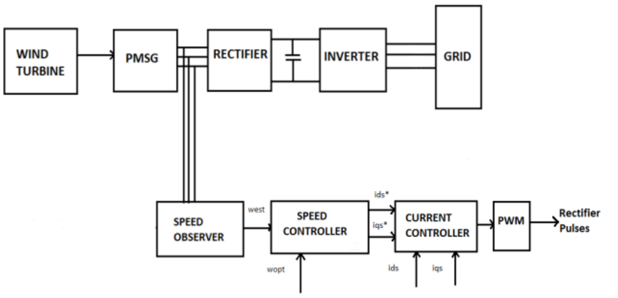

Fig. 3 Block Diagram of WECS system with PI Controller

The basic idea of the MPPT technique is to control the rectifier which will in turn vary the generator speed so as to obtain maximum power from the turbine. The circuit consist of a speed control loop and a current control loop. Both the controllers are PI controllers. The optimum speed of rotation is obtained by hill climbing search algorithm is used. The advantage of the hill climbing search is that it does not require prior knowledge of the wind speed. The only input required for the algorithm is the wind speed. The Algorithm outputs the maximum power for the given wind speed and the optimum speed of rotation is found out using the following relation.

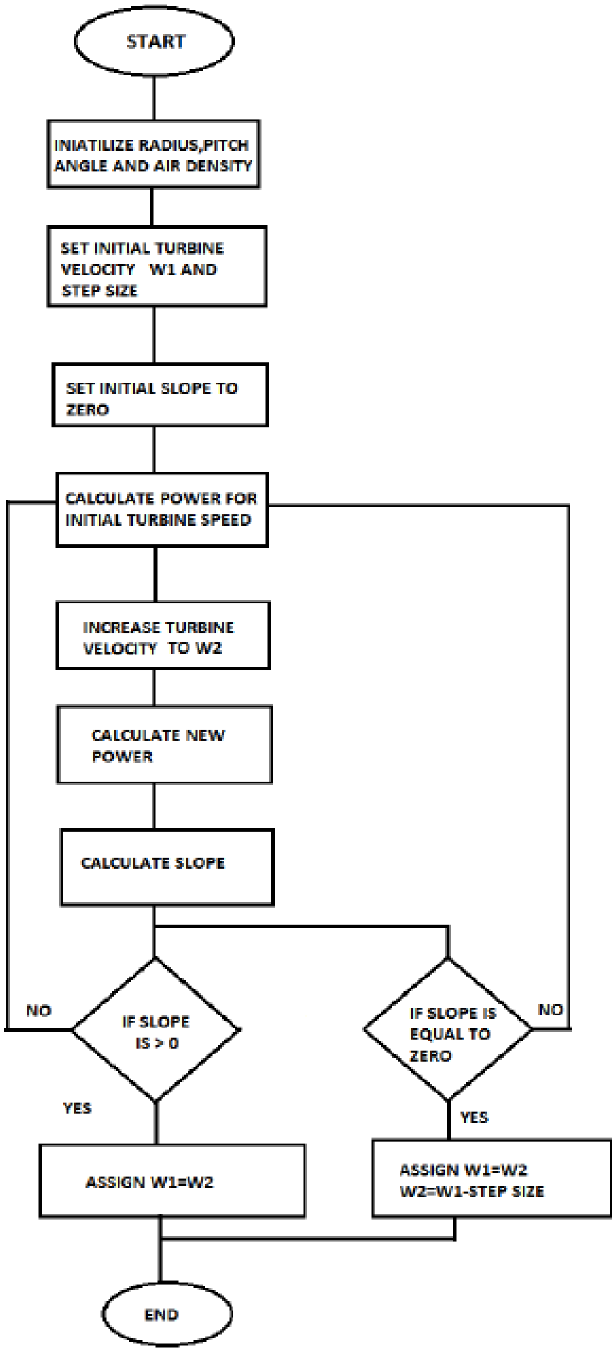

Fig.4 Flow chart for HCS Algorithm

$$\omega_{opt} = (\frac{P_{opt}}{K_{opt}})^{\frac{1}{3}} \qquad (10)$$

VI. PROPOSED TECHNIQUE WITH NEURAL CONTROLLER

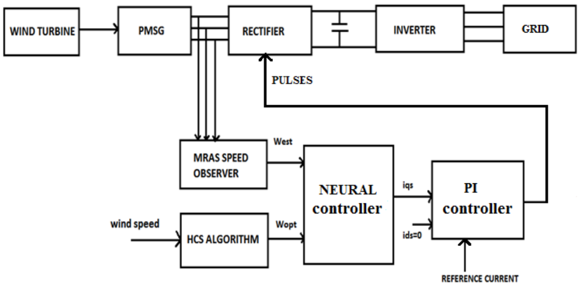

Fig-4: Block Diagram of WECS System with Neural Network Controller

The neural network controller is employed in the speed loop. Therefore the input to the neural network is the error between the actual speed and the optimum speed required for MPPT. The network with error as the input generates a reference q axis current at its output. The d axis current is set to zero to reduce the copper losses in the system. The reference q axis currents are compared with the actual q axis currents in a PI controller and the pulses are given to the rectifier using PWM technique.

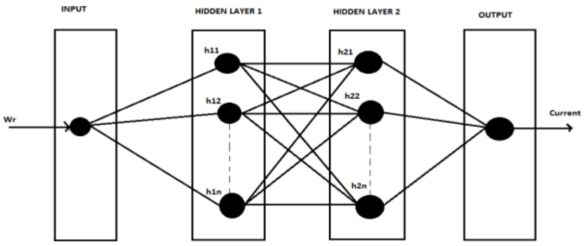

Fig-5: Neural Architecture Employed

To rectify the problems with PI controllers neural network is employed. Since the power output at a specific wind speed does not depend on the past wind speed we use a feed forward network. The network consists of two hidden layers with 10 neurons in one layer and 20 neurons in the second layer both having an activation function of log sigmoid. The output layer uses a linear activation function. The network is trained using Leven berg Marquardt Algorithm. The training data is obtained by running the simulation without the controller. The data is collected between the speed and current. The input to the neural controller is the error between the estimated speed and the optimum speed. The optimum speed is obtained by conventional hill climbing search algorithm. The speed of the PMSG is estimated using MRAS. The error is fed to the neural network controller and the controller generates the reference current. The reference d and q axis currents are compared with the actual currents using PI controller and the pulses are given to the rectifier. By proper control of the rectifier the speed of the generator is varied so as to obtain maximum power from the wind turbine.

VII. GRID SIDE CONTROL OF PMSG WECS

Most commercial wind turbines deliver the generated power to the electrical grid using power converters.

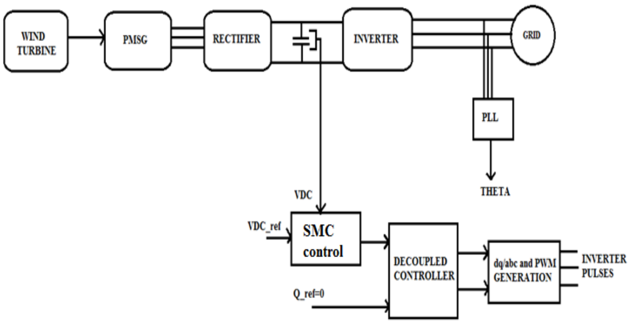

Fig-5: Grid side control with sliding mode control

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The dc link voltage control loop is used to maintain constant dc link voltage. Because of the cross coupling effect compensation terms are to be added to improve the dynamic response of the system. A phase locked loop is used to get the value of theta for coordinate transformation . The reference for reactive power can be set to zero for unity power factor operation, negative value for leading power factor and positive value for lagging power factor. The reference d-axis current represents the active power of the system, is generated by SMC controller for dc voltage control. When the inverter operates in steady state the dc voltage is kept constant at a value set by the reference voltage . The SMC controller generates the d axis current according to the operating conditions. Transforming the state equation of the grid circuit of the inverter from abc stationary to dq synchronous the following equations are obtained.

$$L_f \frac{d_{id}}{dt} = e_d - R_f i_d + \omega L_f i_q - V \qquad (11)$$

$$L_f \frac{d_{iq}}{dt} = e_q - R_f i_q - \omega L_f i_d \qquad (12)$$

The active and reactive powers are obtained as

$$P = \frac{3}{2} V i_d \qquad (13)$$

$$Q = \frac{3}{2} V i_q \qquad (14)$$

The d axis and q axis control voltages are then transformed to three phase using abc/dq transformations and then the pulses are given to the grid side inverter.

VIII.SIMULATION AND RESULTS

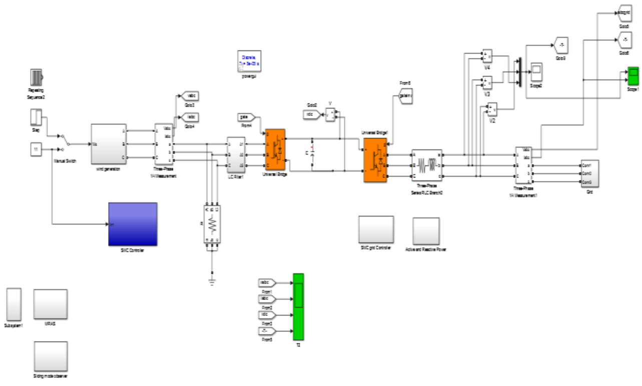

Fig-7: Matlab Circuit

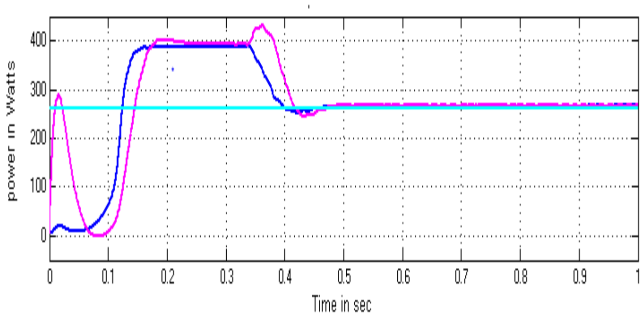

Fig-8: Speed estimation for different wind speeds

The effectiveness of the model reference adaptive system for speed estimation during varying wind conditions is shown below. Both the actual speed and the estimated speed coincides giving minimum error. The green line is the actual rotor speed and the blue line is the estimated speed from MRAS.

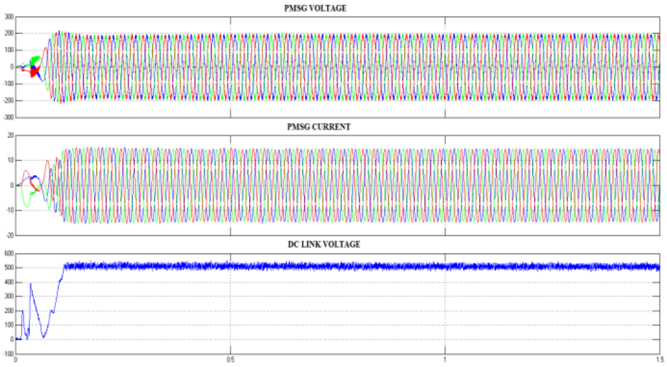

Fig-9: PMSG voltage current and dc link waveform

Voltage, current and dc link voltage waveform for a base wind speed of 10m/s is shown above. The dc link voltage is maintained at its reference of 500v by the grid side controller.

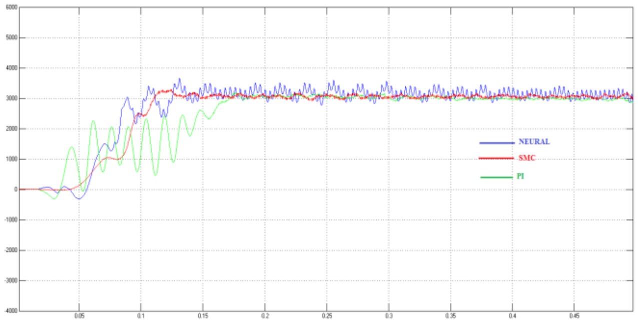

Fig-10: PMSG Power with various controllers

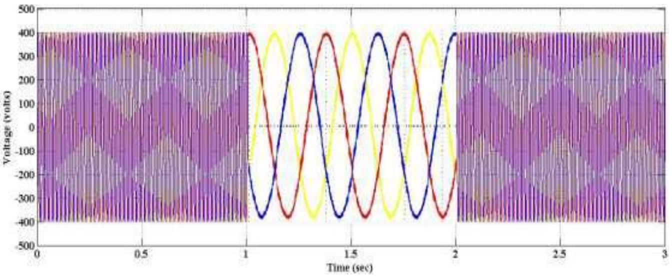

Fig-11: Grid voltage waveform

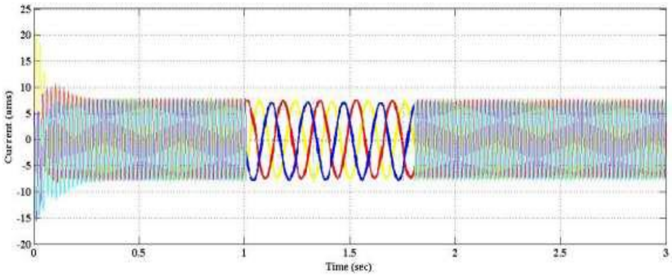

Fig-12: Grid current waveform

Figure shows the grid voltage and grid current using sliding mode control. The dynamic response of the sliding mode control can be seen from the above figure. The settling time for the grid current is around 0.1 sec.

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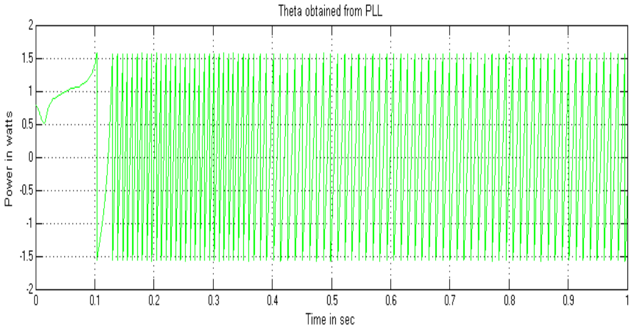

Fig-12: Theta obtained from PLL

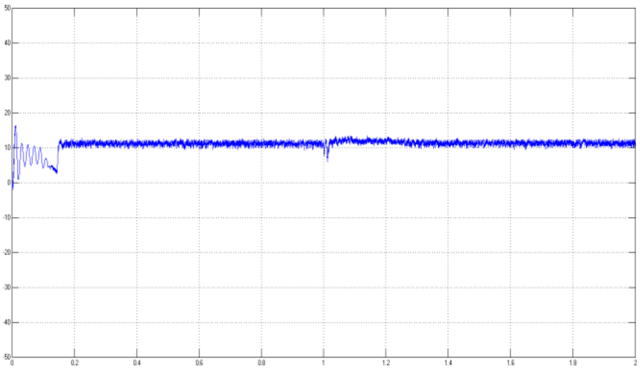

Fig-13: q- Axis Current Waveform

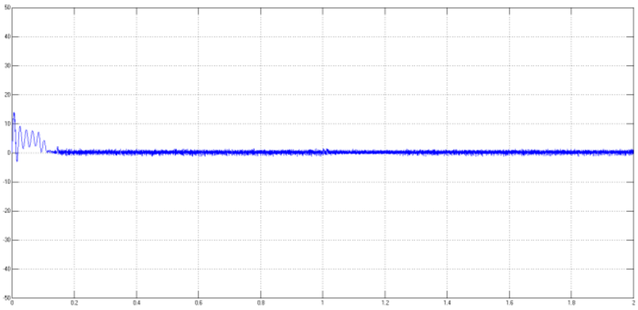

Fig-14: d- Axis Current Waveform

Figure shows the d and q axis currents for a step change in wind speed from 10m/s to12m/s. The q axis currents is maintained at zero by the SMC controller so that the reactive power is maintained at zero. Maintaining reactive power at zero also gives unity power factor operation. The d axis current is maintained at a constant value so that a constant active power is delivered to the grid and no reactive power is injected to the grid. The d axis currents are generated from the dc link voltage control where the dc link voltage maintained at 500 volts.

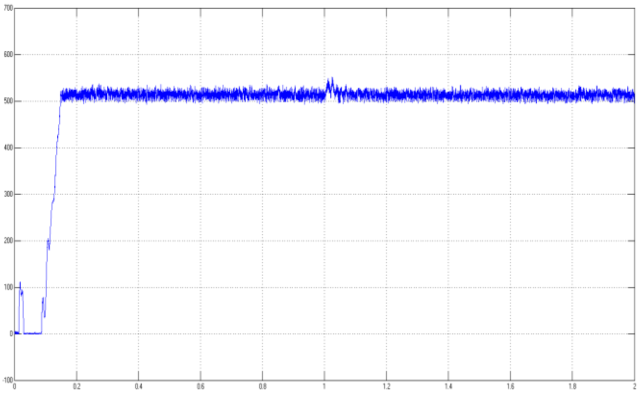

Fig-15: dc Link Voltage Waveform

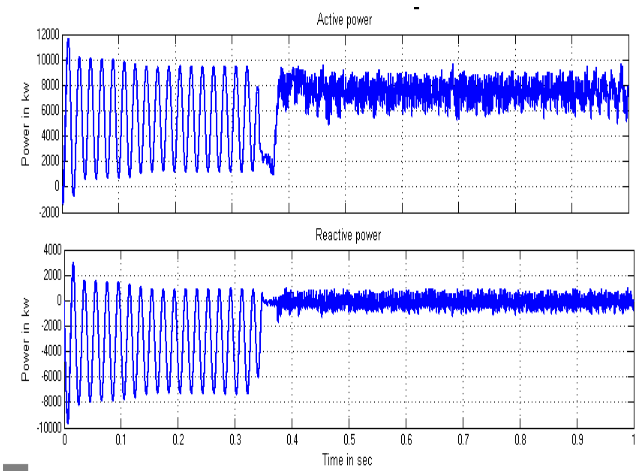

Fig-16: Active and reactive power

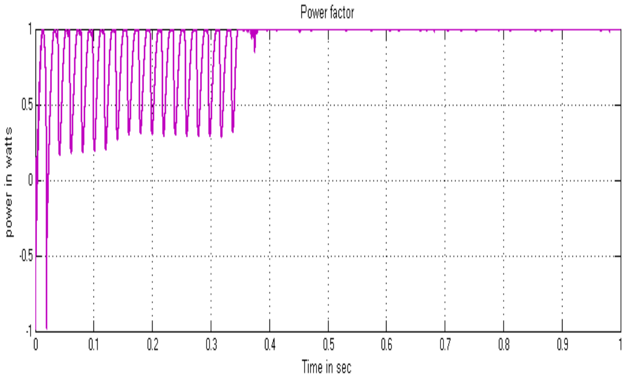

Fig-17: Power Factor

Figure shows the active and reactive power supplied to the grid. The reactive power reference is set to zero. The q axis component of current is controlled to be zero by the SMC controller so that reactive power is zero and unity power factor is obtained. Therefore the q axis voltage is zero. The reference q axis current is obtained from the equation given below.

$$i^{*}{}_{qg} = \frac{Q_{g^{*}}}{-1.5v_{dg}}$$

IX. CONCLUSION

This paper deals with a control strategy of the variable speed wind farm system based on the PMSG and connected to the distribution network. Various techniques like PI, SMC, Neural networks are used to implement the Maximum Power Point Tracking, DC link voltage regulation and unity power factor control. System performance with SMC and Neural have been compared and verified through simulations. The SMC and Neural controllers offer various advantages like perfect decoupling and better dynamic response. The neural controller shows slightly better dynamic response compared to sliding mode control. The grid side control strategy using sliding mode control is able to regulate both the total reactive and active power independently. Power factor at grid side is maintained unity by implementing Sliding Mode Controller. The performance of the system has been demonstrated for varying wind conditions.

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The simulation results demonstrate that the control strategy shows excellent dynamic and steady state performance and works very well for WF system based on the PMSG. It is finally shown that the results proved the effectiveness of the employed control methodologies.

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