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Large Scale Wind Energy Conversion System Using Permanent Magnet Synchronous Generator

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***Abstract*—Renewable energy resources are getting increased attention from researchers because of depleting fossil resources, increasing fuel prices and the concern of climate change and global warming. In a country like India where long coastal line is available, offshore wind farms are one of the attractive options. Over last two decades the wind power penetration in to the grid is increasing at a very fast rate and therefore the wind farms are now required to participate actively in grid operation by an appropriate generation control. The advantage of using a Permanent Magnet Synchronous Generator for wind energy conversion systems is that its efficiency is higher compared to other variable speed WT configurations, its full scale converter allows full controllability, gearbox can be omitted by using higher number of poles of PMSG. This paper proposes the complete modeling and simulation, and analysis of a PMSG based WECS in terms of its power quality, range of wind speed that it can handle and the power balance when the machine is operating under varying wind velocity conditions. Vector control strategy is employed for both the converters connected, in cascade, between generator and the power grid. The WECS is analyzed under both partial and full-load regime. Generator control is applied for power optimization when wind speed is less than rated speed and pitch control is applied for speeds higher than rated speed but below cut-out speed.**

Keywords- Permanent Magnet Synchronous Generator (PMSG); Wind Energy Conversion System (WECS); Pitch Control; Vector Control; Voltage Source Converter (VSC).

I. Introduction

Wind energy is receiving enhanced interest and attention because of its inexhaustible potential, abundant supply, its increasingly competitive cost and environmental benefits. At the end of 2010, worldwide nameplate capacity of wind-powered generators was 318 GW. Wind power market penetration is expected to reach 8% by 2018. The wind generation has increased more than double in the past three years. Several countries have achieved relatively high capacity of wind power generation in 2013, such as China contributes 28.7% of the World wide wind power capacity, Unites States contributes 19.2%, Germany contributes 10.8%, Spain contributes 7.2% and India stands 5^{th} in this list contributing 6.3% [1]. As of 31 March 2014 the installed capacity of wind power in India was 21136.3MW. It is estimated that 6,000 MW of additional wind power capacity will be installed in India by the end of 2014.

The development of various wind turbine (WT) configurations in the last decade has been very dynamic. The main differences in the WECS configurations are in the electrical design and control. WECS can be mainly classified according to speed control and power control ability, leading to WT classes differentiated by the generating system (speed control) and the method employed for limiting the aerodynamic efficiency above the rated power (power control). Based on speed range, WTs can be fixed speed or variable speed type whereas the power control ability divides WECS into three categories namely; stall controlled, pitch controlled and active stall controlled WTs [2].

Significant developments in WECS technology have resulted in larger ratings and higher operating speed ranges. The development of high power WECS technology is more and more influenced by the grid connection requirements. The vast growth of the installed WECS and the planned increase of the wind power penetration level, bring more and more focus on WT control capabilities to make them function similar to conventional power plants.

PMSG based variable speed WECS with full scale power converter are emerging as a strong competitor to the other variable speed technologies. The power converter, whose rating is same as that of the generator, connected between PMSG and grid allows full controllability of the system. The PMSG is considered a good option, due to its self excitation property, allowing operation at higher power factor and efficiency. The efficiency of a PMSG based WECS is higher than other variable speed WT concepts. A multi-pole PMSG can operate at low speed, therefore gearbox can be eliminated. Since a gearbox causes higher weight, losses, cost and demands maintenance, a gearless construction using PMSG brings an efficient and robust solution [3, 4, 5].

A performance analysis on a 1.5MW PMSG based WECS has been attempted in this paper. Two voltage source converters connected back to back (B2B) are inserted between the stator of PMSG and the grid. The converters are able to control the power flow and unity power factor along with delivering good power quality at the point of grid connection. The generator control ensures maximum power extraction from the WT when it is operating in partial load regime (under rated wind speed) and the aerodynamic control ensures power limitation to the rated value when the WT is operating in full load regime (above rated wind speed). The paper includes five sections providing introduction, objectives of the present work, system configuration followed by simulation model developed in Simulink/ MATLAB, results and conclusion.

II. SYSTEM CONFIGURATION

The system configures a geared PMSG based WECS as illustrated in Figure 1. The stator of PMSG is connected to the grid through a pair of B2B connected VSCs and a transformer. The B2B arrangement of two VSC's with a DC bus in common, decouples the operation of two converters and allows an optimized operation. The two converters, namely, Machine side converter (MSC) and grid side converter (GSC), are controlled independently using vector control. In this work, the study is mainly focused on interaction between the WECS and the grid implementing control of active and reactive power and the effects of the implemented control over the power quality.

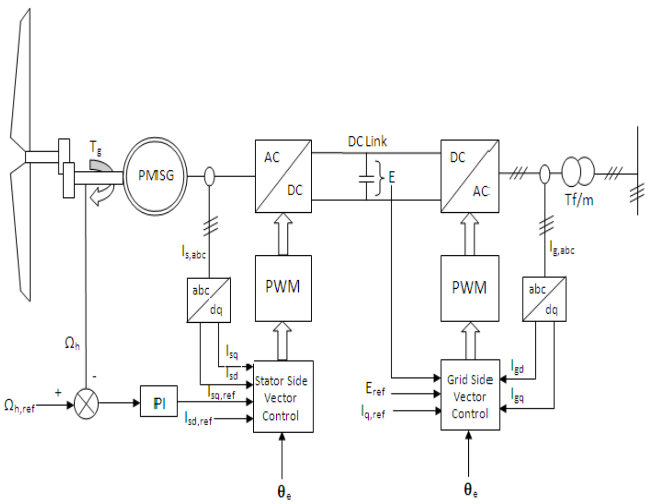

Figure. 1 Block diagram of WECS using PMSG

A. *Operation Strategy of WECS*

The power produced (P_{wt}) by a WT is

$$P_{wt} = ½\, \rho\, \pi\, R^2\, v^3\, C_p\, (\lambda, \beta) \qquad (1)$$

where ρ is the density of air, R is the length of blade, v is the wind velocity/speed and C_p is the efficiency of power extracted by WT. C_p is a function of β and λ, where β is the pitch angle and λ is the tip speed ratio (TSR) given by $\lambda = R\, \Omega_l / v$, here Ω_l is the turbine shaft speed. For a specific TSR, λ_{opt}, the power conversion efficiency yields its maximum value - $C_{p,max}$. When the WT is operating in the lower speed range (speed below cut-out), β is maintained at zero and the active power optimal control (or MPPT) is applied using a set point from the shaft rotational speed. Using expression of power extracted by WT, P_{wt} and TSR, λ, equation (2) may be derived as

$$P_{wt} = ½\, \rho\, \pi\, R^5\, \Omega_l^3\, \{C_p\, (\lambda) / \lambda^3\} \qquad (2)$$

Torque equation corresponding to this may be given as

$$T_{wt} = P_{wt} / \Omega_l = K\, \Omega_l^2 \qquad (3)$$

where $$K = ½\, \rho\, \pi\, R^5\, \{C_p\, (\lambda) / \lambda^3\} \qquad (4)$$

By maintaining the value of $\lambda = \lambda_{opt}$, $C_p\, (\lambda) = C_{p,max}$ and by operating the turbine at a variable speed, the optimum power can be extracted by the WT. For the considered WT, the WT attains a value of $C_{p,max} = 0.48$, for λ_{opt} equal to 8.1.

In addition to power coefficient (C_p) maximization, the proceeding constraints are also obtruded on the WECS so that power limitation during high wind speeds is ensured

$$P_{wt}\, (t) \leq P_{max} \qquad (5)$$

When the limitation in equation 5 is imposed, the system yields maximum power. To avoid acoustic disturbances, the following speed constraint is also imposed on WT

$$\Omega_l\, (t) \leq \Omega_{max} \qquad (6)$$

If speed limit is imposed first, then fulfilling the power constraint, (5) implicitly ensures that the following constraint for torque is achieved

$$T_{wt}\, (t) \leq T_{max} \qquad (7)$$

The mode of operation of WECS, considering the power, speed and torque constraints, is depicted through Fig. 2.

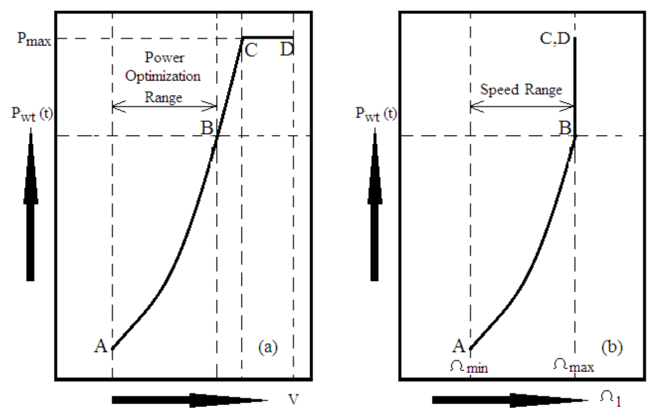

Figure. 2 Operation modes of WECS: (a) Wind power v/s Wind speed (b) Wind power v/s Turbine shaft rotational speed

The trajectory A-B in Figure 2 corresponds to the operation in below rated speeds. Below rated speeds, the operating point of the generator is set to harness optimum power. In this region, the WT operation is at variable speed whereas the pitch control is kept inactive [6].

At B, the speed constraint (6) is implemented and the speed is limited such that the generator runs on the rated speed. The trajectory, B-C (Figure 2) defines the rotational speed limitation operation. Once this constraint is achieved, the constraint for power is immediately imposed and the WT comes under power limiting mode. Segment C-D corresponds to the variable pitch, fixed speed operation where the speed is kept constant at rated and power is controlled to rated with the help of pitch control.

B. Control strategy for GSC

The converter at grid side is accountable for keeping a constant DC link voltage at its reference value. GSC is also responsible for operating the converter at the desired power factor. To achieve the independent control over active and reactive power flow, a vector control approach is implemented keeping the reference frame oriented along the grid voltage vector [7]. To regulate the DC link voltage, the direct axis component of current, I_d, is controlled and to transfer the reactive power, the quadrature axis component of current, I_q, is controlled. The control of GSC is illustrated in Figure 3.

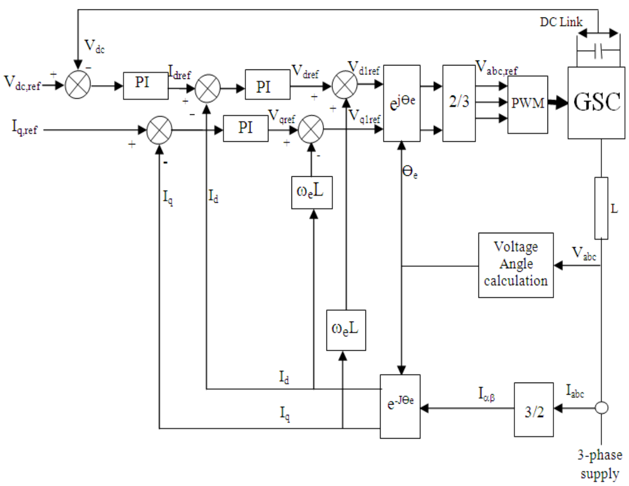

Figure. 3 Block diagram of Grid Side Converter (GSC)

The reactance L shown in the Figure 3 filters the high frequency ripple due to switching of the converter devices. The proceeding equations provide the basis for active and reactive power flow:

$$P = (V_d\, I_d + V_q\, I_q) \tag{8}$$

and

$$Q = (V_d\, I_q + V_q\, I_d) \tag{9}$$

V_d and I_d represents the direct axes components of grid voltages and currents and V_q and I_q represents the quadrature axes components of grid voltages and currents. The d-axis of the reference frame is aligned with the stator voltage position to make V_q equal to zero. It may be noticed that the direct axis of voltage V_d is constant because the supply voltage is kept constant. When V_q is zero and V_d is constant, the proportionality between active power & I_d and the reactive power & I_q becomes obvious from equations (8) and (9).

C. Control strategy for MSC

The system configuration for MSC control is depicted in Figure 4 where equations of the generator are projected on a reference coordinate system rotating synchronously with the magnetic flux. By aligning the d-axis of the reference frame with the stator flux vector, the q-axis stator flux is set to zero, ($\Phi_{sq} = 0$). Torque T may be written as

$$T = (3/2)\, P\, \Phi_m\, I_{sq} \tag{10}$$

where, P represents the pole pairs, Φ_m is the magnet flux and I_{sq} is the q-axis stator current. Equation (10) suggests that electromagnetic torque (or active power) is controlled by I_{sq}. The error between the generator speed and the reference speed (obtained from the wind speed – power optimal regime characteristics of the WT) is processed by a PI controller to yield the torque reference that further dictates the q axis reference current, $I_{sq,ref}$.

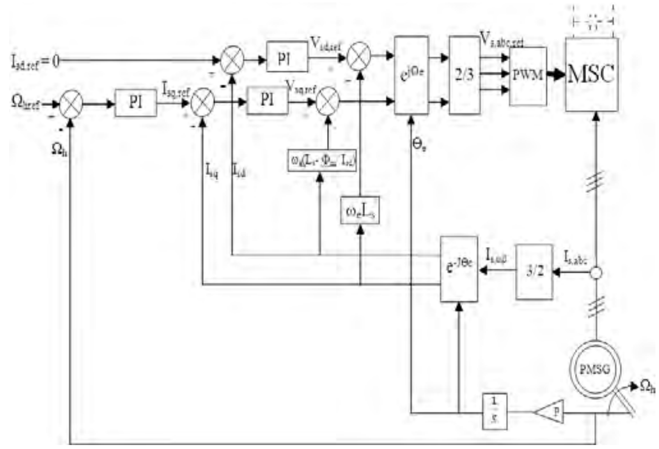

Figure. 4 Block diagram for Machine Side Converter (MSC)

The d-axis stator current, I_{sd} controls the reactive power trading with the grid. In the present work, the value of reference d-axis stator current $I_{sd,ref}$ is kept zero, to get the maximum possible torque at the rated flux value. The error between the reference and actual values of d and q axis stator currents are further processed through PI controllers to yield required dq voltages as shown in Figure 4. In order to control the currents independent one of each other, the compensation terms, $\omega_e L_s I_{sq}$ is added, and $(\omega_e L_s I_{sd} - \omega_e \Phi_m)$ is subtracted at the output of the PI controllers [7]. The decoupling factor is derived from the stator voltage equations in dq reference frame, given below:

$$V_{sq} = -R_s\, I_{sq} - L_s \frac{dI_{sq}}{dt} - L_s \omega I_{sd} + \omega \phi_m \tag{11}$$

$$V_{sd} = -R_s\, I_{sd} - L_s \frac{dI_{sd}}{dt} - L_s \omega I_{sq} \tag{12}$$

where, R_s and L_s are the generator resistance and inductance respectively, ω_e is the generator speed in electrical radians/sec.

III. Modeling And Simulation

The system illustrated in Figure 1 is modeled and simulated using Simulink/MATLAB. The simulink model is depicted in Figure 5. The stator of the PMSG is connected to 11 kV, 50 Hz grid through a pair of B2B connected converters and PMSG is rated at 1.5 MVA, 0.690 kV, 50Hz. The stator winding resistance is R_s=0.05Ω and the stator d-axis and q-axis inductances are L_d=L_q=0.515mH.

The system is operated at various wind velocities ranging from 7 m/s to 14 m/s. Initially the wind velocity is assumed to be 7 m/sec and later at every 2 sec, the wind speed is varied. Variation in wind speed is effected, when system reaches steady state for each of the specified wind speeds. Since WT is coupled to the generator via gearbox, the change in wind speed causes the change in generator speed. For wind speeds below 11 m/s, the generator speed is less than synchronous and the WT is operated in partial load regime.

The generator control acts according to the wind velocity and causes the rotor to rotate at the reference values provided by the optimal power control block. The error between the actual speed of the generator and the reference speed is fed to the PI controller yielding reference torque (or indirectly $I_{sq,ref}$) for the MSC. The reference current for the d-axis, $I_{sd,ref}$ is maintained at zero to achieve maximum torque (shown in Figure 6). The reference d- axis and q-axis voltages are obtained from two PI controllers as depicted in Figure 4. The compensation terms, $\omega_e L_s I_{sq}$ is added, and $(\omega_e L_s I_{sd} - \omega_e \Phi_m)$ is subtracted at the output of the PI controllers to control the currents independent of each other.

A wind speed of 11 m/s causes the speed of generator to reach its synchronous speed. At wind speeds greater than 11 m/s, the speed constraint is activated thereby limiting the generator speed to its rated value (1 pu). Here, the WT enters the full load regime and the pitch control is activated. Pitch control mechanism, reduces the power captured by the WT to its rated value, following power constraint given in (5). Once the speed constraint and power constraint are activated, the constraint given by (7) is automatically achieved.

The GSC is controlled to maintain the DC link voltage at constant. The real power demand of the MSC is met through the GSC control (Figure 7). The difference between the actual voltage at DC link and the reference voltage is fed to the PI controller that further yields the reference d-axis current, $I_{d,ref}$ for the converter at grid side. The reference current, $I_{q,ref}$, for q-axis, is kept zero to maintain the reactive power delivered by the inverter at zero.

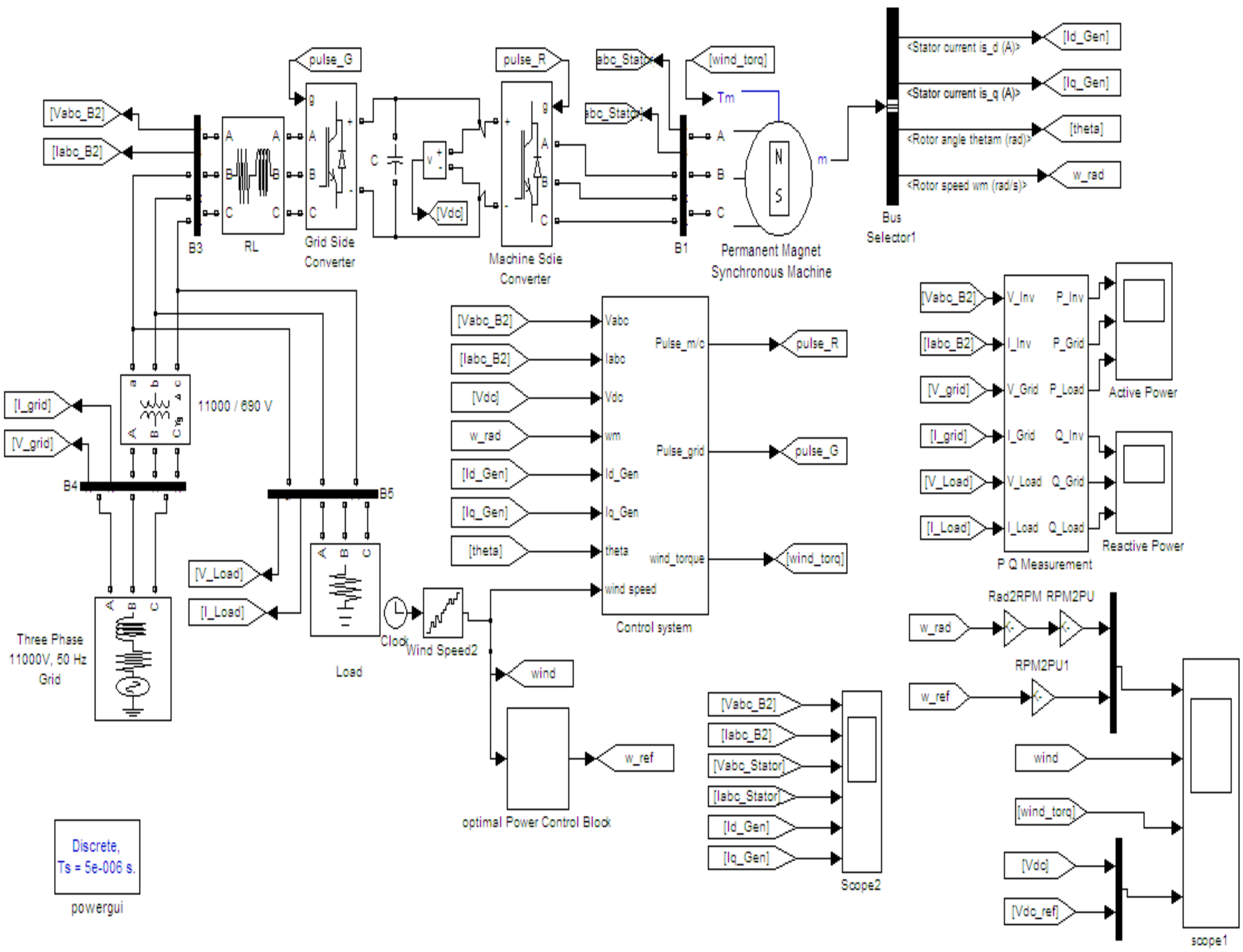

Figure. 5 MATLAB/Simulink model for 1.5MW WECS using PMSG

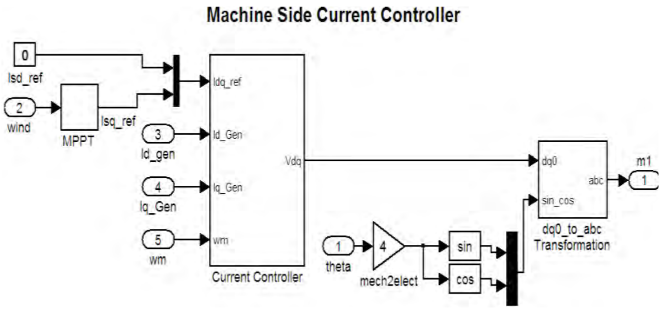

Figure. 6 MATLAB/Simulink model for Machine Side Converter (MSC)

The d-axis current component of MSC was set to zero for the same reason. A feedback controller is used in which the error between the desired and the reference d and q-axis currents is passed through a PI controller to generate V_{dref} and V_{qref}. The compensation terms are added and the resulting d-q voltages are converted into three-phase voltages, which serve as the modulating waves for the conventional sinusoidal PWM (SPWM) converter.

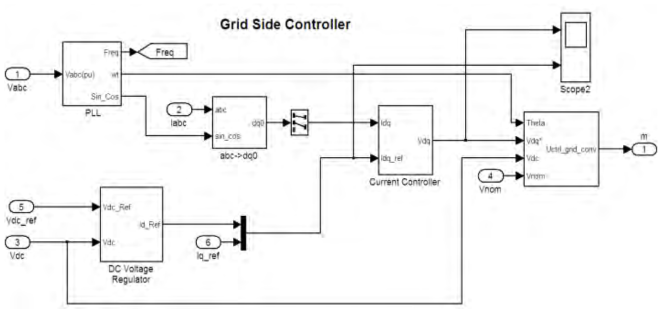

Figure. 7 MATLAB/Simulink model for Grid Side Converter (GSC)

IV. Results And Discussions

The Simulink/MATLAB model described above for the PMSG operation in a WECS is simulated for different wind velocities to check whether the system can successfully function in partial load and full load regime.

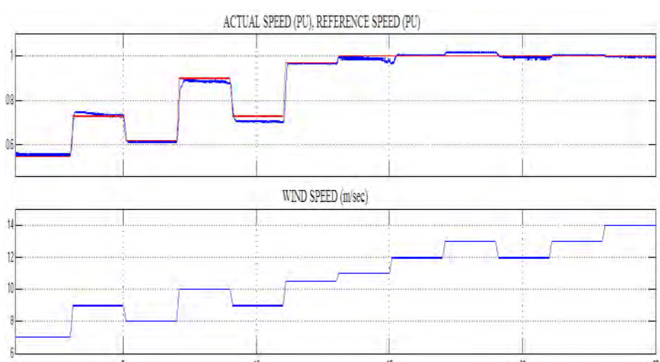

Figure. 8 Variation in generator speed with the variation in wind speed

Fig. 8 shows the variation in generator speed with the change in wind speed. It is very clear that the generator speed tracks the reference speed to harness maximum power for wind speeds below 11 m/s as per the wind-turbine characteristics. The speed is limited to 1 pu for wind speeds more than 11m/s indicating power limitation operation. The closeness of the actual generator speed to the reference speed reflects the performance of the control strategy implemented for the WECS control.

Fig. 9 shows the power delivered by the WECS for a load of 2MW connected between WECS and the grid. Load is receiving power from both, WECS and the grid. The power balance is well maintained, as all the power available from the WECS is supplied to the load and rest of the power is delivered by the grid at various wind speeds. It is observed that the magnitude of real power is changing with the change in wind speed whereas the direction is unchanged. The WECS is delivering a constant power, equal to rated power, for speeds more than 11 m/sec.

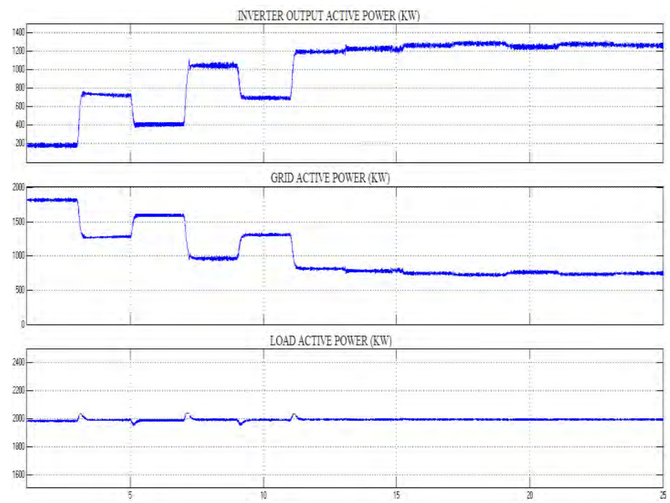

Figure. 9 Power balance in PMSG based WECS for various wind speeds.

The voltage at the point of grid connection is exactly sinusoidal as shown in Fig. 10. The total harmonic distortion (THD) is nearly 0.77%, indicating good power quality of the voltage fed to the grid.

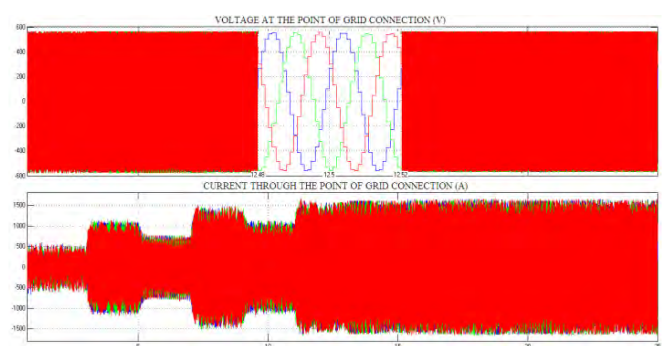

Figure. 10 Voltage and current waveforms at the point of interconnection between grid and PMSG based WECS.

The stator currents are not perfectly sinusoidal (Fig.10); the stator current is distorted because of the converter operation.

The increase in magnitude of currents supplied by the WECS is obvious with the increase in the wind speed. This increases the power fed to the grid at constant voltage and hence MPPT is achieved.

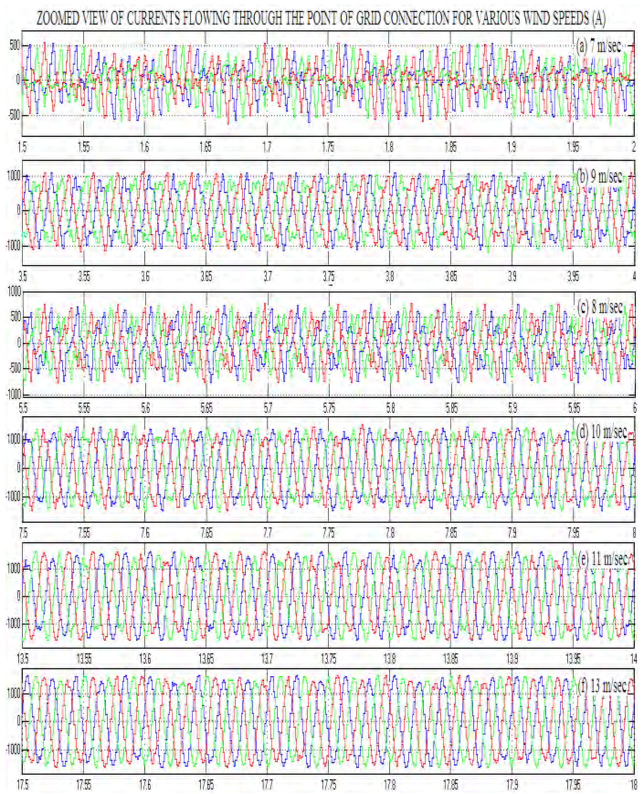

Figure. 11 Zoomed view of current waveforms at the point of interconnection between grid and PMSG based WECS.

The zoomed view for currents at various wind velocities is depicted in Fig. 11. The distortion of the currents supplied by WECS is more at low wind speeds. Table 1 shows the THD of current through the point of grid connection, calculated at various wind speeds ranging from 7 m/s to 14 m/s. It can be realized that power quality problems are encountered more at lower wind speeds.

TABLE I. TOTAL HARMONIC DISTORTION

Wind Speed (m/s)	7	8	9	10	11	12	13	14
THD (%)	10.89	4.61	3.01	2.63	2.15	1.88	2.37	2.26

The complete sets of waveforms indicate that the PMSG functions successfully in both partial load regime as well as in full load regime. The machine side controls work properly maintaining power quality, power balance and simultaneously allowing for maximum power being harnessed in partial load regime.

V. CONCLUSIONS

An analysis on grid connected PMSG based WECS is presented in this work/paper for varying wind velocity conditions. Simulink/MATLAB is used to develop the system model. Optimal power control of the system is implemented by implanting the wind turbine characteristics into the model. To limit the active power to its rated value in full load regime, pitch control is activated. PMSG model has been described based on the vectorized dynamic approach and this model is applicable to all types of PMSG configurations for steady state and transient analysis. However, the choice of reference frame will affect the waveforms of all d-q variables. The MSC is controlled for good power quality, optimal power control in partial load regime and power limitation in full load regime. The GSC is shown to control the DC-link voltage at the constant reference voltage. In all, this paper presents the implementation and control of a grid connected PMSG based WECS along with a comprehensive analysis on power harnessed and power quality.

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