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Review of Controller Designs for PMSG based Wind Energy Conversion System Tied to grid along with LCL Filter

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ABSTRACT: *A review of* ***design*** *and* ***analysis*** *of the* ***converter controller*** *is discussed in this paper for Permanent Magnet Synchronous Generator (PMSG) based variable speed wind turbinr which is connected to a grid alongwith LCL filter.* ***LCL filter*** *reduces the harmonics injected in grid system but also can lead to stability problem due to resonance at high frequency. Therefore the design parameters of the controllers should be planned considering the wearing down caused by various elements of LCL filter.*

The parameters of gain controller and damping resistance can be selected by using the bode diagram and step response. The proposed method has been implemented on the grid side controller design for 2.5 MW PMSG based variable speed wind generator. The simulation results show that the method is useful and good performance under wind speed variation of the control system can be achieved.

A model of directly driven PMSG based variable-speed WECS, along with dynamic model of the LCL filter is developed and in ***MATLAB/ SIMULINK*** *environment.*

Index Terms *- Wind energy, PMSG, model predictive control, maximum power point tracking (MPPT).*

1. INTRODUCTION

Global warming has pushed the environment to move from conventional to renewable distributed power generation systems. The distributed generations located close to load/ consumers and have merits such as: increase in availability of power with overall system reliability, lower costs, reduced emissions, and expanding energy options [1]. The wind power is one of the distributed resource but connecting wind turbine generator to distribution grid system results in stability problem. Therefore, it is important to study a suitable control design for wind generators connected to the grid with enhanced stability.

The VSWT-PMSG is planned to achieve maximum aerodynamic efficiency, increased energy capture, and reduce mechanical stress on WT [2]. Here, wind turbine is directly driving the PMSG generator. The VSWT-PMSG is, connected to the utility power system through the 3-ϕ BTB voltage source power converters. The converter permits very flexible control of active and reactive power flow to the grid. The converter decouples the PMSG and grid hence grid disturbances can not affect the generator. Converter operates at high switching frequencies (between 2-15 kHz) resulting high order harmonics, which disturb other devices, connected to the grid and generate the power losses [5], [6].
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In order to reduce harmonic currents injected to the grid, LCL filter is a solution with many advantages such as higher harmonic attenuation with smaller inductances compared with L-filter [7] but, resonance at high frequency by LCL filters result in stability issues. To avoid the resonance problem, a passive damping resistance is adopted in the LCL filter, although insertion of passive damping resistance reduces the filter effectiveness and increase losses [6]. Therefore, selection of a damping resistance and filter components should be taken into account of the controller design of VSC for their effectiveness and reduction in power losses.

In this review a controller for 2.5 MW class of the VSWT-PMSG connected to distribution network is studied, which shows the stability performance of current controlled grid side converter (GSC) connected to the grid through LCL filter. The controller is designed based on the synchronous d-q reference frame. A simple dynamic model for LCL filter including damping resistance is proposed as plant system. Simulation results prove that the controller system is very effective to control power delivered to the grid with small total harmonics distortion.

2. VSWT-PMSG MODELING SYSTEMS

The block diagram of control system for VSWT-PMSG is given below. It has following elements: a direct drive PMSG, 2L 3-ϕ BTB converter, a DC-link capacitor (**C_{dc}**), stator side controller (MSC), and grid side controller (GSC) with LCL filter.

The MSC is connected to the stator of PMSG, and it converts the 3-ϕ AC voltage generated by to DC voltage. The 3-ϕ voltage/ current sensors are connected on the stator terminal of PMSG. The rotor speed of PMSG is measured from the rotor of wind turbine/ PMSG.

The GSC is connected to the grid through LCL filter and a step up transformer. The grid current/ voltage sensors are connected on converter side and grid side of the LCL filter. The DC voltage (**V_{dc}**) across the DC capacitor is measured. The voltage reference of grid side voltage source converter for modulation is controlled by using the grid side controller.

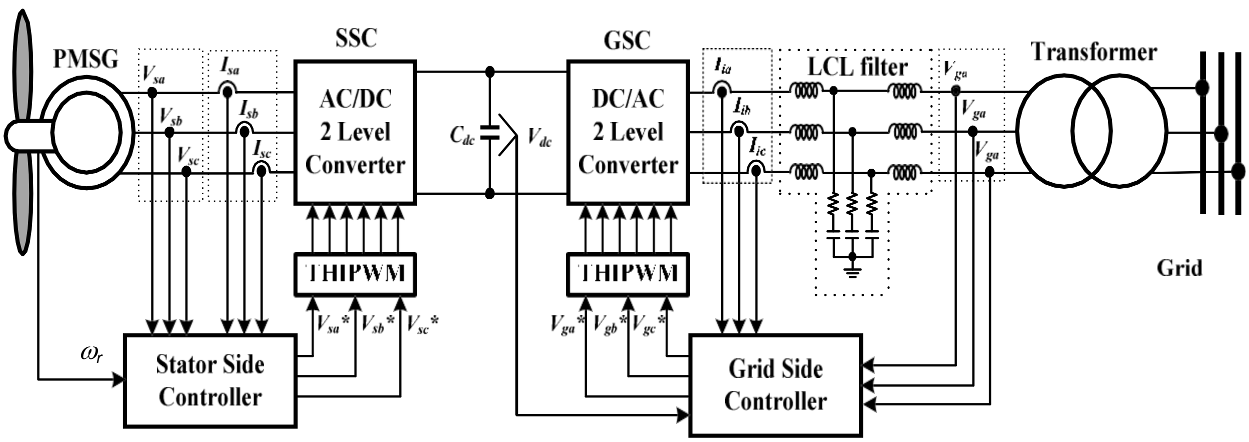


Fig. 1. Model and control system of PMSG based variable speed wind turbine

2.1.1 Wind Turbine Model

The mechanical power output of wind turbine is expressed as:

$$^{w}P_W = 0.5\rho\pi R^2 V^3 C_p(\lambda,\beta) \qquad (1)$$

Where, P_w is captured wind power (W), ρ is air density (Kg/m^3), R is radius of rotor blade (m), V_w is wind speed (m/s), and C_p is the power coefficient.

The value of C_p is dependent on tip speed ratio (λ) and blade pitch angle (β) based on the turbine features it can be expressed as a function as given below [9]:

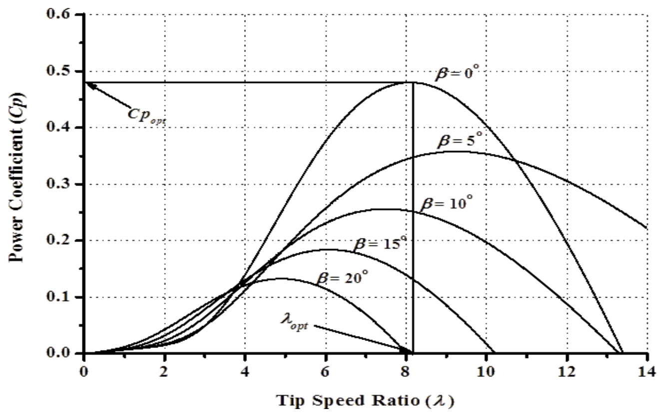
$$C_p(\lambda, \beta) = (C_1(C_2/\lambda_1) - C_3\beta - C_4))e^{-C3/\lambda 1} + C_6\lambda \qquad (2)$$

Where,

$$1/\lambda_1 = 1/(\lambda - 0.08\beta) - ((0.035/\beta^3)+1) \qquad (3)$$

Where C_1 to C_6 denote characteristic coefficients of wind turbine and have values as:

C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21 and $C0_6$=0.0068.



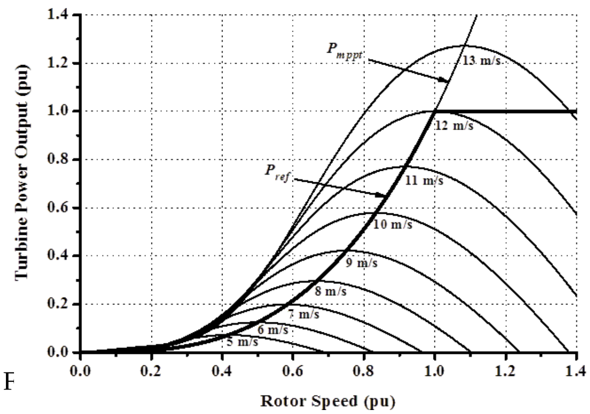


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Fig. 2 shows the Cp-λ chart for different values of β. The optimum value of C_p (**C_{popt} =0.48**) is obtained at **λ = 8.1** with **β = 0^0**. This value of λ is optimal value (**λ_{opt}**).

Fig. 3 gives the characteristic between the turbine power output and the rotor speed for different wind speeds where the blade pitch angle is set at 0 deg. **The maximum power output (1pu) of wind turbine is obtained at 12 m/sec of wind speed and 1pu of rotational speed**.

In VSWT system, the rotor speed of wind turbine (**ω_r**) is measured to determine the Maximum Power Point Tracking (MPPT). Due to the difficulty in accurate measurement wind speed and the cost of anemometer, maximum power (**P_{mppt}**) should be calculated without measuring the wind speed as expressed as under in Eq (4) [10] and the reference power (**P_{ref}**) is limited within the rated power of generator.

$$P_{mppt} = 0.5\ \rho\pi R^2(\omega_r R/\lambda^{opt})^3 C_{p\_opt} \quad (4)$$

2.1.2 **Dynamic Model of PMSG**

The dynamic model of PMSG in the d-q rotating reference frame is given in Eqns (5) & (6) [11].

$$d\psi sd/dt = -Vsd - Rs * Isd - \omega e * \varphi sd \quad (5)$$
$$D\psi sq/dt = -Vsq - Rs * Isq - \omega e * \varphi sq \quad (6)$$

With

$$\Psi sd = Lsd\ Isd + \Psi m \quad (7)$$
$$\Psi sq = Lsq\ Isq \quad (8)$$

Where V_{sd}/ V_{sq} are stator voltages, R_s is the stator winding resistance, I_{sd}/ I_{sq} are stator currents, ω_e is the generator rotational speed, ψ_{sd}/ ψ_{sq} are the stator flux linkages, L_{sd}/ L_{sq} are inductances of the stator winding (all in d-q reference frame), and ψ_m is the permanent magnet flux linkage. By using Eqn (5), (6), (7) and (8) the deferential equations of PMSG can be rewritten as under:

$$Lsd * \frac{dIsd}{dt} = -Vsd - Rs * Isd - \omega e * Lsq * Isq \quad (9)$$
$$Lsq * \frac{dIsq}{dt} = -Vsq - Rs * Isq - \omega e * Lsd * Isd + \omega e * \psi m \quad (10)$$

2.1.3 **Mathematical Model of LCL Filter**

As discussed, utilization of the LCL filter can lead to stability problem due to resonance at high frequency. To avoid resonance a **passive damping resistance (R_d) is placed in series with filter capacitor (C_f)**. However, using a **damping resistance can lead to power losses** and thus lead to decrease in filter efficiency. Therefore, in designing the voltage source converter controller system, **passive damping resistance should be part of plant system model**.

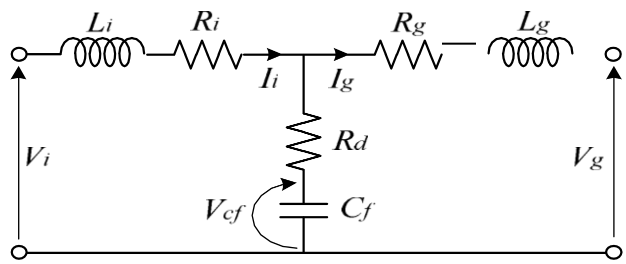

Fig. 4. Single phase LC filter equivalent circuit

Single phase LCL filter equivalent circuit is shown in Fig. 4. L_i/ R_i and L_g/ R_g are inverter/ grid side **inductance and its parasitic resistance**, C_f is filter capacitor, and R_d is a damping resistance. V_i/ I_i and V_g/ I_g are voltage and current on the converter and grid side of the LCL filter. V_{cf} is a voltage on the filter capacitor (C_f). The differential equation of LCL filter in stationary reference frame can be given as:

$$\mathbf{Li} * \frac{\mathbf{dIi}}{\mathbf{dt}} = \mathbf{Vi} - \mathbf{Vcf} - (\mathbf{Ri} + \mathbf{Rd})\mathbf{Ii} + \mathbf{Rd} * \mathbf{Ig} \quad (11)$$

$$\mathbf{Lg} * \frac{\mathbf{dIg}}{\mathbf{dt}} = \mathbf{Vcf} - \mathbf{Vg} - (\mathbf{Rg} + \mathbf{Rd})\mathbf{Ig} + \mathbf{Rd} * \mathbf{Ii} \quad (12)$$

$$\boldsymbol{Cf} * \frac{\mathbf{dVcf}}{\mathbf{dt}} = \mathbf{Ii} - \mathbf{Ig} \quad (13)$$

From (11), (12) and (13) the deferential equations in the d-q rotating reference frame can be given as:

$$\mathbf{Li} * \frac{\mathbf{dIid}}{\mathbf{dt}} = \mathbf{Vid} - \mathbf{Vcfd} - (\mathbf{Ri} + \mathbf{Rd})\mathbf{Iid} + \mathbf{Rd} * \mathbf{Igd} \quad (14)$$

$$\mathbf{Li} * \frac{\mathbf{dIiq}}{\mathbf{dt}} = \mathbf{Viq} - \mathbf{Vcfq} - (\mathbf{Ri} + \mathbf{Rd})\mathbf{Iiq} + \mathbf{Rd} * \mathbf{Igq} \quad (15)$$

$$\mathbf{Lg} * \frac{\mathbf{dIgd}}{\mathbf{dt}} = \mathbf{Vcfd} - \mathbf{Vgd} - (\mathbf{Rg} + \mathbf{Rd})\mathbf{Igd} + \mathbf{Rd} * \mathbf{Iid} \quad (16)$$

$$\mathbf{Lg} * \frac{\mathbf{dIgq}}{\mathbf{dt}} = \mathbf{Vcfq} - \mathbf{Vgq} - (\mathbf{Rg} + \mathbf{Rd})\mathbf{Igq} + \mathbf{Rd} * \mathbf{Iiq} \quad (17)$$

$$\boldsymbol{Cf} * \frac{\mathbf{dVcfd}}{\mathbf{dt}} = \mathbf{Iid} - \mathbf{Igd} + \boldsymbol{\omega} * \mathbf{Cf} * \mathbf{Vcfq} \quad (18)$$

$$\boldsymbol{Cf} * \frac{\mathbf{dVcfq}}{\mathbf{dt}} = \mathbf{Iiq} - \mathbf{Igq} - \boldsymbol{\omega} * \mathbf{Cf} * \mathbf{Vcfd} \quad (19)$$

The block diagram of the grid connected LC filter in the d-q rotating reference frame is shown in Fig. 6 (**s** is Laplace operator).

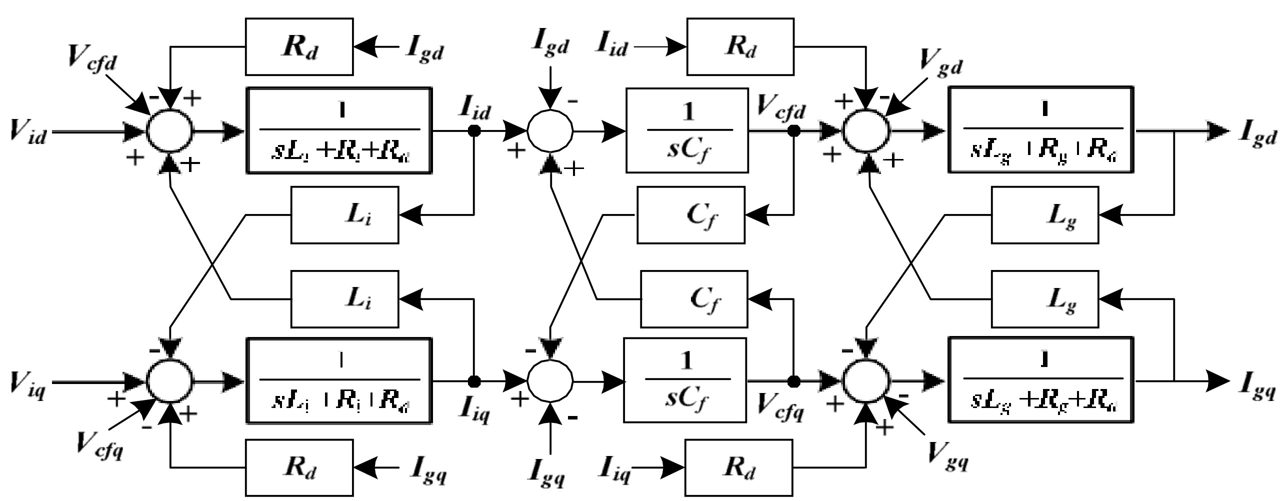

Fig. 6. Block diagram of LC filter in the d-q rotating reference frame

3. VSWT-PMSG CONTROLLER MODELING SYSTEMS

3.1 Machine Side Controller

Machine side controller system (MSC) is given in Fig. 7. Machine side controller controls active/ reactive power of the PMSG. The current control loop is designed in d-q rotating reference frame. The rotor angle position (θ_r) is obtained from the rotor speed of generator and the same is used to transformation between abc to dq or vice-a-versa. The active power (P_s) and reactive power (Q_s) of the generator are controlled by the d-axis current (I_{sd}) and the q-axis current (I_{sq}), respectively.

Reference active power (P_{ref}) is obtained from MPPT method of the wind turbine as given in Fig. 3. The reactive power reference (Q_s*) is set to zero for unity power factor operation. The cross couplings $I_{sd}\omega_e L_{sd}$ and $I_{sq}\omega_e L_{sq}$ are compensated at the output of the current controllers in order to improve tracking capability. In controller parameters, $1/(R+L_s s)$ is used as plant transfer function in d-q current loop and pole placement method is to tune the gain of the PI controllers.

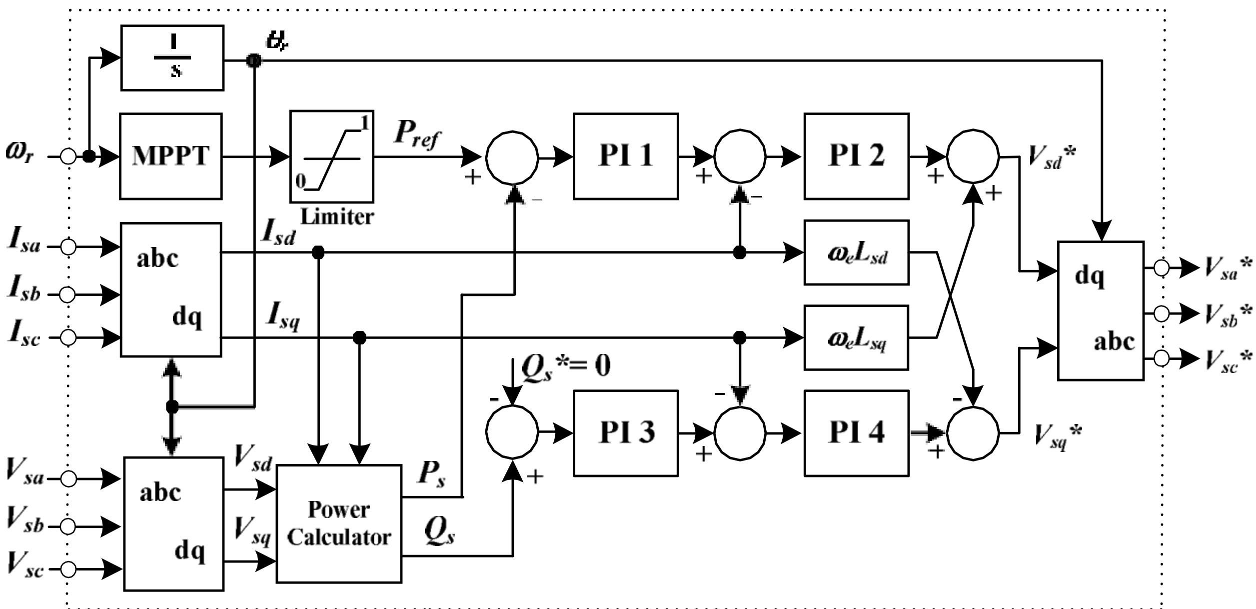

Fig. 7. Stator side controller system

3.2 Grid Side Controller

Grid side Controller is important in design of control system because it influence the performance of VSWT- PMSG connected to a grid. The aim of GSC control is to maintain DC link circuit voltage, control the reactive power exchange with the grid system and maintain the power factor to be unity [12]. This control method is based on the d-q rotating reference frame, which has same rotational speed as the grid voltage.

Grid side control system is given at Fig. 8. Phase Locked Loop (PLL) is used to obtain grid side phase angle (θ) for the d-q transformation. When grid voltages on the stationary reference frame are transformed into the d-q rotating reference frame, V_{gd} becomes constant and V_{gq} becomes zero. The active and reactive power delivered to the grid can be controlled separately by the d- axis current (I_{id}) and the q-axis current (I_{iq}), respectively.

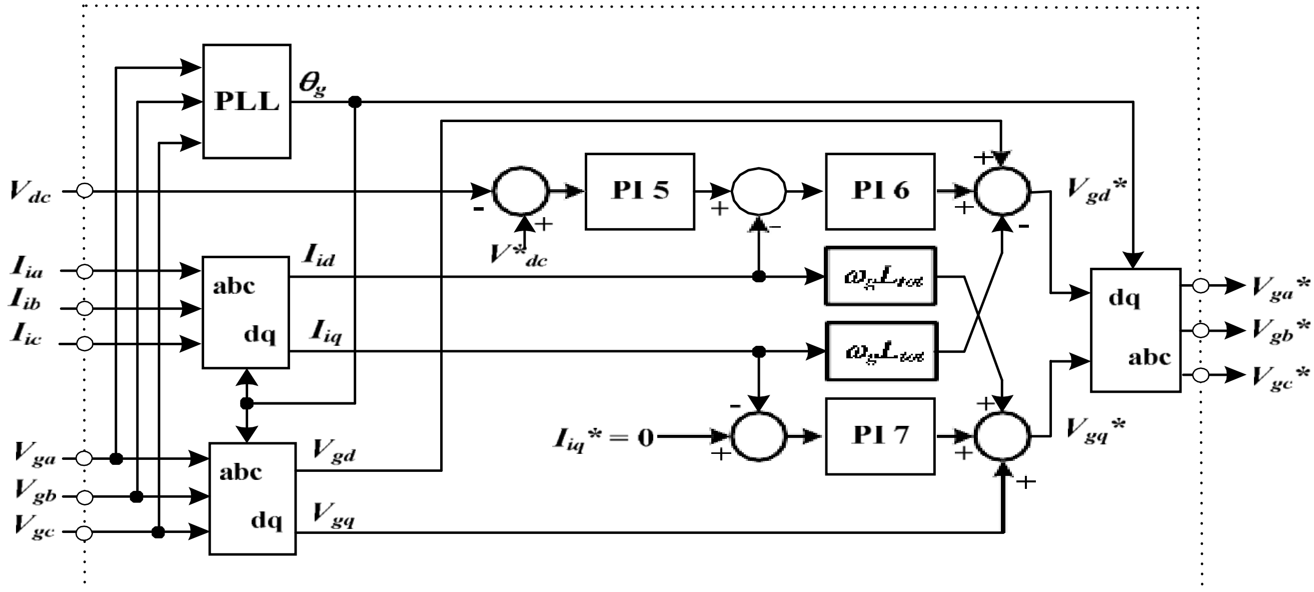

Fig. 8. Grid side controller system

For **smooth active power transfer** from **PMSG** to **grid**, the **DC- link capacitor voltage (V_{dc})** is kept **constant**. The d-axis current reference signal (I_{id}*) is obtained from output of the DC-voltage controller. For **unity power factor operation**, the q-axis **reference current (I_{iq}*) is set to zero**. To improve tracking capability of control system, the cross coupling terms can be canceled by adding ωL_{tot} at the output of the current controllers, where **L_{tot}** is **total series inductances of the filter and transformer**. The output of current controller (V_{gd}* and V_{gq}*) are transformed into the stationery reference frame (V_{ga}*, V_{gb}*, V_{gc}*) which are used as reference signal for pulse wave modulation to produce firing signal.

3.3 LCL Filter Parameters

LCL filter parameters of the system are shown in Table – I [6].

TABLE – I

System Parameters

Component	Parameter	Value
PMSG	Rating	2.5 MW
	Rs	0.01 (pu)
	Lsd	1.0 (pu)
	Lsq	0.7 (pu)
	ψ m	1.4 (pu)
	H	3.0 (sec)
AC/DC/AC Power Converter	SSC frequency Switching	1 kHz
	GSC frequency Switching	4 kHz
	Grid Frequency	50 Hz
	DC Link capacitor	25000 μF
	DC Link voltage	1.75 kV
Transformer	Total winding inductance (Lt)	0.040 pu
	Total winding resistance (Rt)	0.016 pu
	Converter side voltage	1.0 kV
	Grid side voltage	6.6 kV

Base impedance is taken as 0.4Ω, base inductance is 1.3mH, and base capacitance is 8000μF. Inductance of the inverter side (L_i) is 5.0% of base inductance. In calculation of grid side inductance (L_g), the transformer inductance (L_t) is also considered. 4% of base inductance has been considered as transformer inductance. Adding a small value of grid side inductance (L_g), total 4.1% of base inductance is considered as L_{tot}. The initial value for filter capacitor (C_f) is set to maximum of 5%. The resonance frequency of LCL filter is around 1.4 kHz.

4. SIMULATION RESULTS

Soundness of the design and analysis explained has been assessed and given using the model given at Fig. 9. A VSWT- PMSG rated at 2.5 MW is connected to 6.6 kV distribution system through converters, a LCL filter, a 1.0/6.6 kV step up transformer, and a double circuit transmission line. A local 1 MW load is installed near the wind generator. Impedances of the transmission line is in the form of R+jX, where R and X are the resistance and reactance, respectively. System base power is taken as 100 MVA.

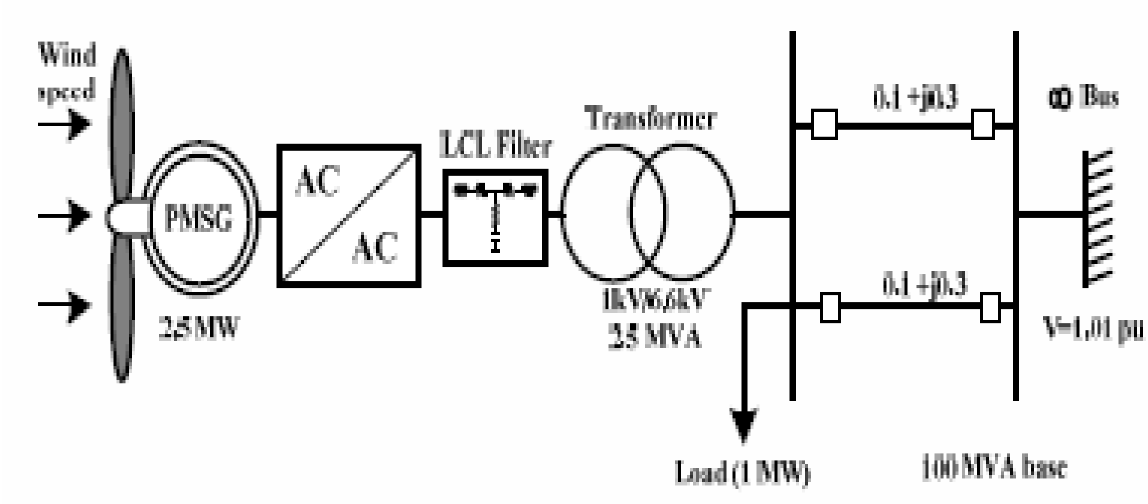

Fig. 9. Model system

Simulation is performed in MATLAB envioumment to evaluate the dynamic performances of the proposed system. Fig. 10 shows the pitch angle response of the VSWT-PMSG. The active power reference (P_{ref}), the active power output of PMSG (Ps), and the active power delivered to the grid (P_g) are also shown in Fig. 10. It is seen that P_S and P_g follow P_{ref} very well.

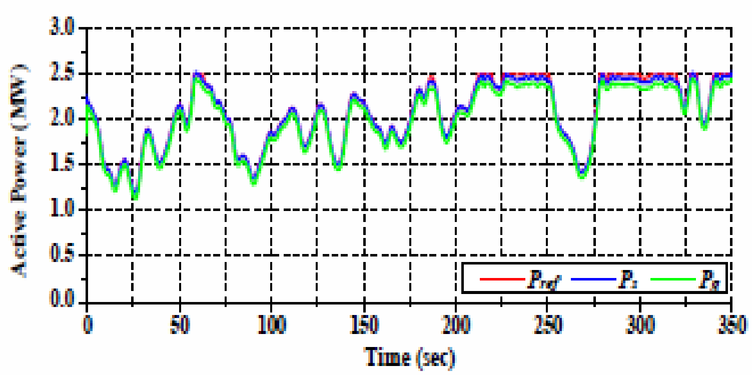

Fig. 10. Active Power Output

The reactive power outputs of the generator and the grid side converter are kept almost zero as shown in Fig 11.

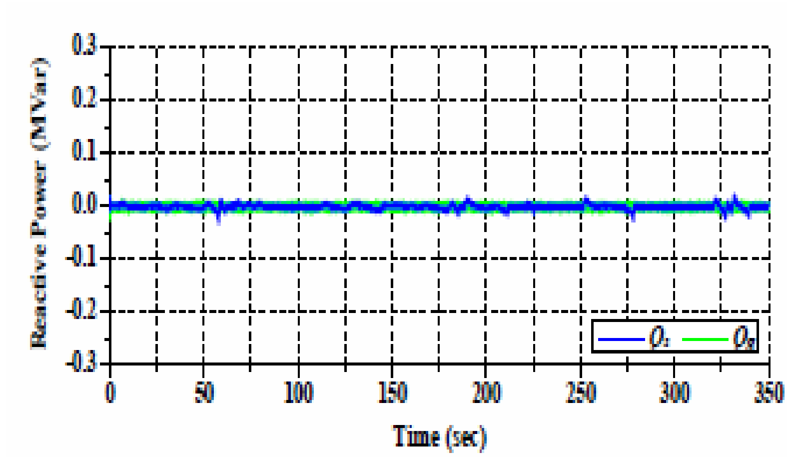

Fig. 11. Reactive Power Output

The response of the DC link voltage is shown in Fig. 12. It is seen that the DC voltage can also be maintained constant at rated value (1.75 kV).

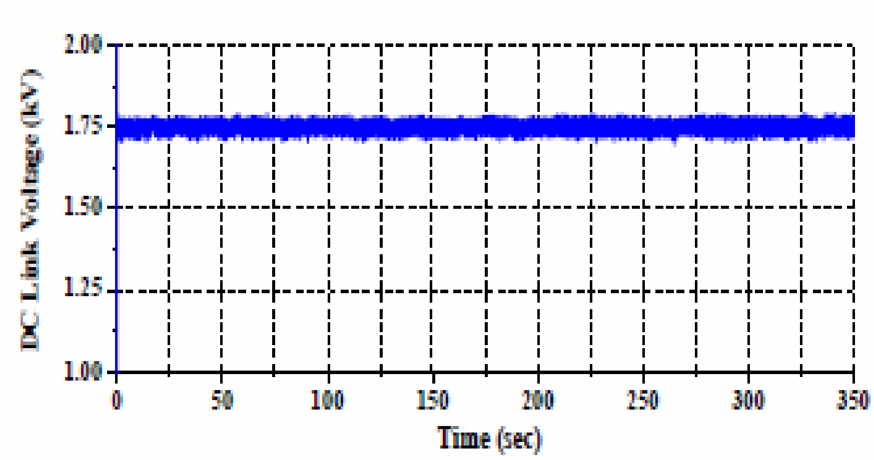

Fig. 12. DC Link Voltages

5. CONCLUSION

In this paper, design and analysis of the control system for 2.5 MW class of VSWT-PMSG connected to a distribution grid system through LCL filter is reviewed. Design and analysis of the grid side current controlled voltage source converter is mainly focused, in which passive damping resistance of the filter and gains of PI controllers of VSC are selected based on frequency response of the bode diagram and dynamic step response.

According to the simulation results, it can be concluded that the controller system is effective to control of active and reactive power supplied to the grid. Moreover, the LCL filter is very effective to reduce the effects of the harmonic distortions.

6. APPENDIX

PI controller parameters used for simulation are given in Table II. The parameters for PI 1 to PI 4 (PI controllers for the stator side controller) are obtained by using the pole placement method. The values for DC link voltage controller of the grid side controller (PI 5) can be selected same as those of PI 6 and PI 7.

TABLE – II

PI Controller Gains

PI Controller	K_p	T_i
PI 1	0.1	0.02
PI 2	0.4	0.05
PI 3	0.1	0.02
PI 4	0.4	0.0497
PI 5	0.2	0.0497
PI 6	0.2	0.0497
PI 7	0.2	0.0497

