Analysis Of Transient Stability Of A Permanent Magnet Synchronous Generator Connected To Grid

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Abstract-The global energy consumption is rising and an increasing attention is being paid to alternative methods of electricity generation. The environmental impact of the renewable energy is very low and this makes them a very attractive solution for a growing demand. In this trend towards the diversification of the energy market, wind power is probably the most promising sustainable energy source, because of the relatively low capital cost involved and the short gestation period required. Induction generators used as wind generator are simple and easy to maintain. But the major drawback of this machine is its additional reactive burden on the system. Hence a variable speed wind generator such as a doubly fed induction generator or a permanent magnet synchronous generator (PMSG) is used. The fluctuating nature of wind causes the output of the variable speed PMSG to vary in amplitude and frequency, which is not suitable for use. Therefore in this work suitable control strategies are developed to produce a constant voltage and power and the transient stability analysis is carried out by simulating symmetrical and unsymmetrical fault as network disturbances. This is demonstrated using MATLAB simulations

Index Terms-Variable speed, Permanent Magnet Synchronous Generator, Transient Stability, AC/DC Converter, Renewable Energy, Grid, Fault.

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1. INTRODUCTION

RENEWABLE energy resources are also called sustainable or alternative energy. These energies are generated from natural resources such as wind, sunlight, tide, hydro, biomass and geothermal which are naturally replenished. Great attention is being paid to renewable energy sources due to increase in greenhouse gas emissions. The renewable energy has very low environmental impact and this makes them a very attractive solution for a growing demand. Energy crisis, climate changes such as atmosphere temperature rise due to the increase of greenhouse gases emission, coupled with high oil prices, limitation and depletion of fossil fuels reserves make renewable energies more attractive. The most important use of the renewable energies is to electrify remote villages and rural areas or rugged terrain located far away from power stations and distribution networks. The main drawback of the renewable energy system is its vulnerability to unpredictable climatic changes and dependency on weather conditions. Wind power is probably a good alternative because it is clean nonpolluting and low cost. It is estimated that by the end of 2003, the total installed capacity of the wind turbines has reached as much as 39.234 GW and will exceed 110 GW in the near future. [1]

Wind is produced due to the rotation of the earth and the irregularities on the earth's surface. The direction of the wind is dependent upon the earth's terrain, water bodies and vegetation. Hence the wind is fluctuating in nature and this fluctuating wind is used for the generation of electrical energy.

The wind is given as input to a constant speed or variable speed generators. Here a variable speed wind generator using a permanent magnet synchronous generator (PMSG) is used, whose magnetisation is provided by a permanent magnet pole system which has many advantages over electrically excited machines. Their efficiency is higher and no external supply is required for the excitation. These machines are more reliable and lighter due to the absence of slip rings. Moreover the thermal characteristics are better due to the absence of field losses. The disadvantages are they are costlier and the manufacturing is quite difficult. At higher temperatures the permanent magnets gets demagnetised quickly. In spite of these disadvantages these PMSG's are widely used. [2, 3]

Due to the fluctuating nature of wind the output of the variable speed PMSG is not suitable for use as it varies in amplitude and frequency A lot of efforts were made to interface renewable energy system to the grid and was achieved through a fully controlled power converter. The power convertor consists of generator side AC/DC convertor, DC link capacitor and grid side DC/AC inverter. [4]. The generator side converter controls the electromagnetic torque and therefore the extracted power while the grid side converter controls both the DC link voltage and the power factor. The simulation analysis is performed by using MATLAB, Simpower system.

Now the amount of power generated from wind energy is so high and hence it is quite necessary to analyse the fault ride through issues and the power quality problems. Recently most of the countries have developed grid codes for the safe operation of the power system. According to the US grid code requirement if the voltage does not fall below 15% of the nominal voltage and returns to 90% of the voltage with in 3s after the beginning of the voltage drop the turbine should not be disconnected from the grid. [5-7]

2. MODELING OF WIND TURBINE

The total power that is available to a wind turbine is equal to the product of the mass flow rate of the wind m_w, and $V^2/2$. Therefore,

Total wind power in Watts,

$$\begin{aligned} P_w &= (m_w V^2)/2 \\ &= (\rho A V^3)/2 \qquad (1) \end{aligned}$$

Where $m_w = \rho A V$, ρ is the density of the air in kg/m3, which depends upon the pressure, temperature, and relative humidity, A is the exposed area in m^2, and V is the velocity in m/s. From equation (1) it is seen that wind power varies as the cube of the wind velocity. [8,9]

The main function of a wind power system is to transform kinetic energy in the wind into electric energy. Wind energy forces an aerodynamic rotor to turn and thus the wind energy is transformed into mechanical energy. Mechanical energy, in a slow turning rotor shaft of wind blade, is geared up to a high-speed shaft which is connected to a generator. Inside the generator, the rotational mechanical energy is transformed into electrical energy. The electric power output is then connected to the grid.

The power extracted from the wind

$$P_w = C_p * \rho * A * V_w^3 / 2 \qquad (2)$$

Where C_p is the power coefficient. The amount of aerodynamic torque (τ_w) in Nm is given by the ratio between the power extracted from the wind (P_w) in W, and the turbine rotor speed (ω_w), in rad/s.

$$\tau_w = P_w / \omega_w \qquad (3)$$

Where ω_w is the angular velocity of rotor [rad/s].

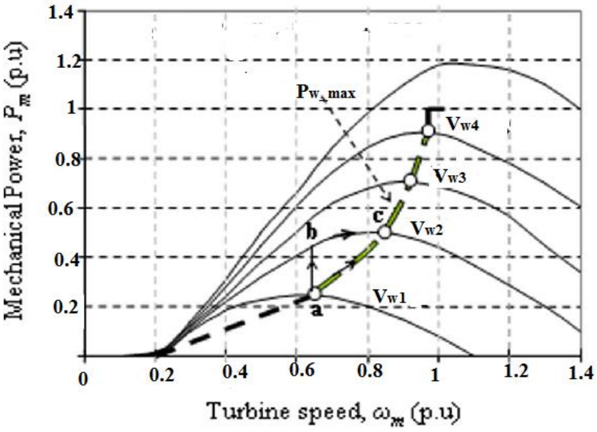

Figure 1 Mechanical power generated by the turbine as a function of the rotor speed for different wind speeds.

The maximum power is produced when the turbine operates at maximum C_p (i.e., at C_{p_max}). For C_p to be maximum rotor speed must be at an optimum value of the tip-speed ratio λ_{max}. For each variation of the wind speed, the rotor speed should be adjusted to follow the change. Therefore the target maximum power from a wind turbine can be written as

$$\begin{aligned} P_{w\_max} &= 0.5 \rho A C_{p\_max} [(\omega_{w\_max} R)/\lambda_{max})]^3 \\ &= K_{max} (\omega_{w\_max})^3 \qquad (4) \end{aligned}$$

Where

$$K_{max} = 0.5 \rho A C_{p\_max} (R/\lambda_{max})^3$$

The tip speed ratio is the ratio between the tip speed and the wind speed.

$$\lambda_{max} = \omega_{w\_max} * R / V_w \qquad (5)$$

$$\begin{aligned} \omega_{w\_max} &= \lambda_{max} V_w / R \\ &= K_\omega V_\omega \qquad (6) \end{aligned}$$

Therefore, the target optimum torque can be given by

$$T_{w\_max} = K_{max} (\omega_{m\_max})^2 . \qquad (7)$$

The mechanical rotor power generated by the turbine as a function of the rotor speed for different wind speed is shown in Fig.1. The maximum power curve (P_{max}) shows how maximum energy can be captured from the fluctuating wind. The function of the controller is to keep the turbine operating on this curve, as the wind velocity varies. [10] It is observed from this figure that there is always a matching rotor speed which produces optimum power for any wind speed. If the controller can properly follow the maximum power curve, the wind turbine will produce maximum power at any speed within the allowable range. The maximum torque can be calculated from the maximum power.

3. MODELING OF PMSG

The dynamic model of PMSG is derived from the two-phase synchronous reference frame in which the q-axis is 90° ahead of the d-axis with respect to the direction of rotation. The synchronization between the d q-rotating reference frame and the abc-three phase frame is maintained by a phase locked loop (PLL).The electrical model of PMSG in the synchronous reference frame is given in [11,12]

$$\frac{di_d}{dt} = \frac{1}{L_{ds}+L_{ls}}\left(-R_s i_d + \omega_e \left(L_{qs} + L_{ls}\right) i_q + u_d \qquad (8)$$

$$\frac{di_q}{dt} = \frac{1}{L_{qs}+L_{ls}}\left(-R_s i_q - \omega_e \left[\left(L_{ds} + L_{ls}\right) i_d + \psi_f\right] + u_q \qquad (9)$$

where d and q refer to the physical quantities that have been transformed into the d-q synchronous rotating reference frame, R_s, is the stator resistance [Ω], L_d and L_q are the inductances of the generator on the d and q axis, L_{ld} and L_{lq} are the leakage inductances of the generator on the d and q axis, respectively, Ψ_f is the permanent magnetic flux and ω_e is the electrical rotating speed.

The electromagnetic torque equation τe is given by

$$\tau_e = 1.5p((L_{ds}-L_{ls})i_d i_q + i_q \Psi \qquad (10)$$

The equivalent circuit of the PMSG in d-q synchronous rotating reference frame

4. MODELING OF MASS DRIVE TRAIN

In this study the two mass drive unit is considered. The mathematical equation is represented as [8]

$$2H_t \frac{d\omega_t}{dt} = T_m - T_{sh} \qquad (11)$$

$$\frac{1}{\omega_{elb}} \frac{d\theta_{tw}}{dt} = \omega_t - \omega_r \qquad (12)$$

$$2H_g \frac{d\omega_r}{dt} = T_{sh} - T_g \qquad (13)$$

Where H_t and H_g are the inertia constants of the turbine and the PMSG. θ_{tw} is the shaft twist angle, ω_t is the angular speed of the turbine in p.u, ω_t is the rotor speed of the PMSG in p.u, ω_{elb} is the base speed in electrical, and T_{sh} the shaft torque

$$T_{sh} = K_{sh}\,\theta_{tw} + D_t \frac{d\theta_{tw}}{dt} \qquad (14)$$

Where T_{sh} is the shaft stiffness and D_t is the damping coefficient.

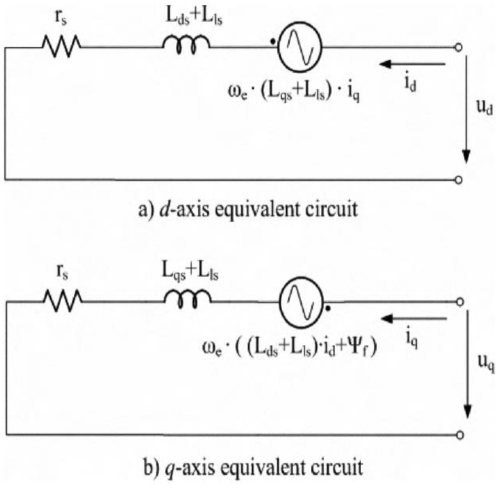

Figure 2 Equivalent circuit of the PMSG in the synchronous frame.

5. SIMULATION RESULTS

The model of the PMSG connected to the grid as shown in fig 3 is developed using a Matlab/Simpower simulation software. The subsystem used in the wind turbine is shown in Fig 4. The rated power of the PMSG is 50 kW and the speed of the machine is 500 rpm. The load connected to the system is 40kW. The fault is simulated for a time period of 1.2 to 1.4 secs. The simulations are done for Symmetrical fault (3LL), and Unsymmetrical fault (LG), (LL). The parameters of the PMSG used are given in Table1.

5.1 Transient stability analysis during a symmetrical fault condition

A balanced three phase fault is considered to occur on the transmission line during a time period of 1.2 to 1.4 secs. The simulation time period is 2sec. During the transient disturbance the grid side inverter provides the necessary reactive power so that the terminal voltage returns back to the prefault value itself. The Reactive power on the grid side is shown in Fig. 5 and the variation in terminal voltage in Fig 6. This is maintained by changing the rotor speed which is shown in Fig.7. The variation in electromagnetic torque and the electrical torque is shown in Fig 8. During the disturbance also there is not much difference between the mechanical and electromagnetic torque. The real power response is shown in Fig. 9. From the simulation results, it is clearly understood that the proposed system enhance the transient stability of variable speed permanent magnet under symmetrical fault condition.

5.2 Transient stability analysis during an unsymmetrical fault condition (LG)

In the second case a line to ground fault is assumed to occur on the transmission line and the simulations were carried out. The reactive power on the inverter side, the terminal voltage, rotor speed, mechanical and electromagnetic torque and the real power on the inverter side are shown in the Fig.10, Fig.11, Fig 12, Fig 13, and Fig.14. From the simulations it is seen that the disturbances are not severe as in the case of symmetrical fault. It is evident from the diagrams that the proposed control system can enhance the transient stability of VSWT-PMSG, when an LG fault occurs.

5.3 Transient stability analysis during an unsymmetrical fault condition (LG)

A LL fault is considered on the transmission line and the simulations were carried out. The response of the grid side inverter reactive power, terminal voltage, rotor speed, torque and the real power on the inverter side are shown in the Fig. 15. Fig. 16, Fig. 17, Fig. 18, Fig. 19.

Table 1 Parameters of PMSG

PMSG	
No. of poles	10
Rated Speed	500 rad/sec
Rated Current	12 A
Armature Resistance, R_s	0.425 Ω
Magnetic Flux Linkage	0.433 Wb
Stator inductance L_s	8.4mH
Rated Torque	80Nm
Rated power	50KW

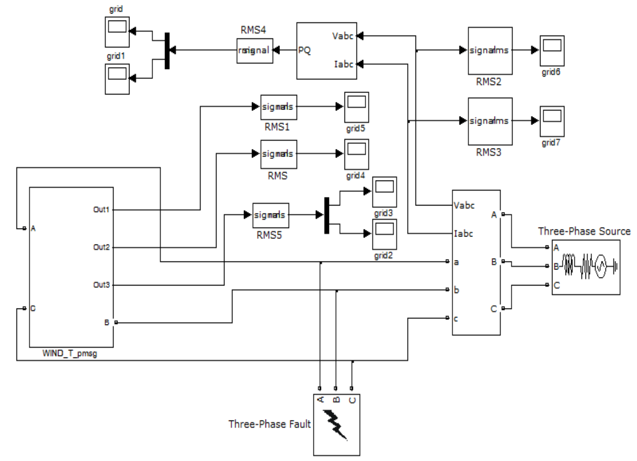

Figure 3 Simulink model of PMSG connected to grid

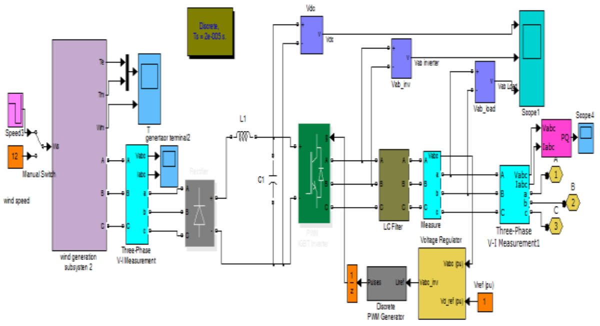

Figure 4 Subsystem used in the Simulink

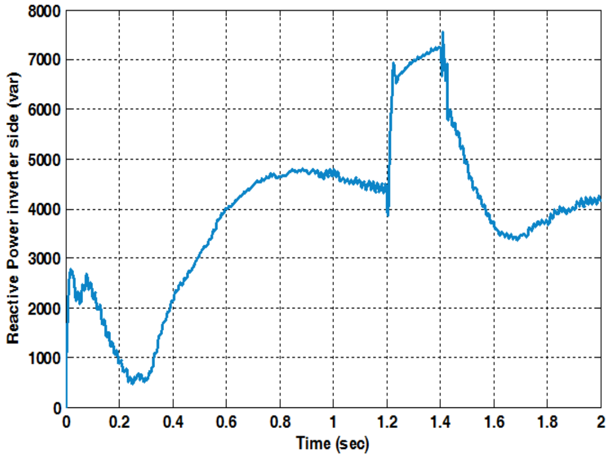

Figure 5 Reactive power inverter side (Symmetrical fault)

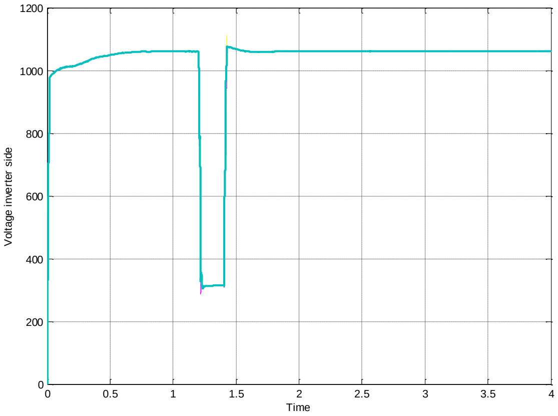

Figure .6 Voltage on the inverter side (symmetrical fault)

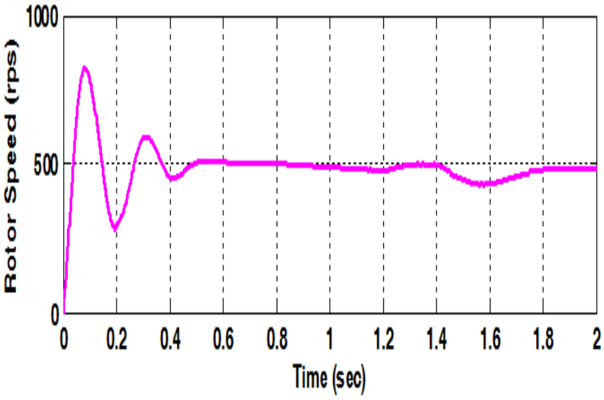

Figure 7. Rotor speed (Symmetrical fault)

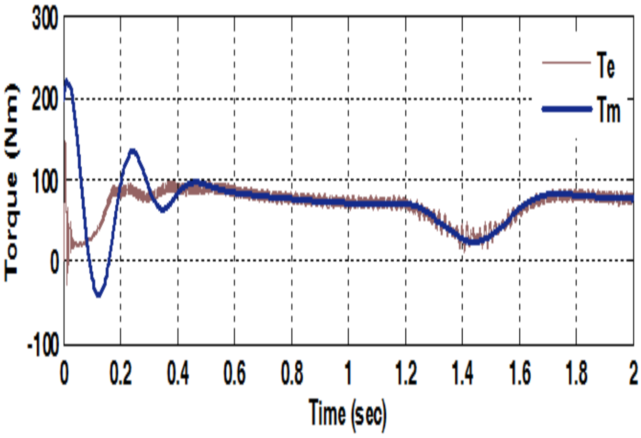

Figure 8 Te &Tm (symmetrical fault)

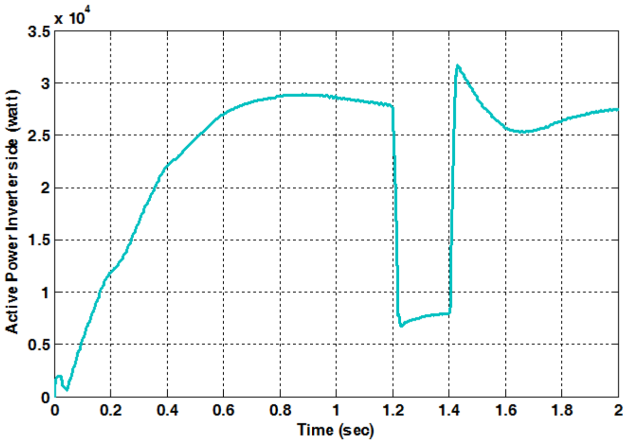

Figure. 9. Active power inverter side (symmetrical fault)

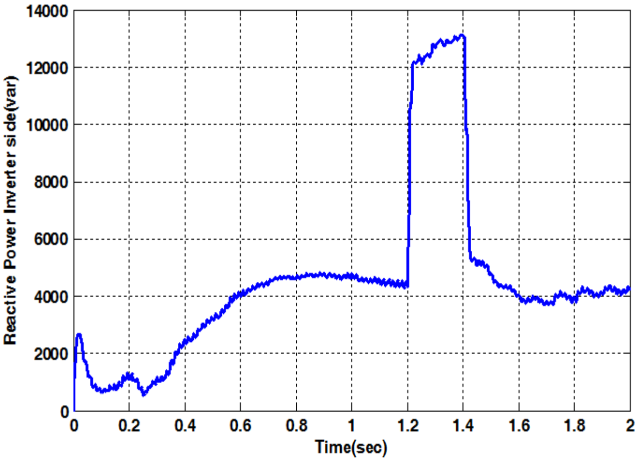

Figure 10 Reactive power inverter side (LG)

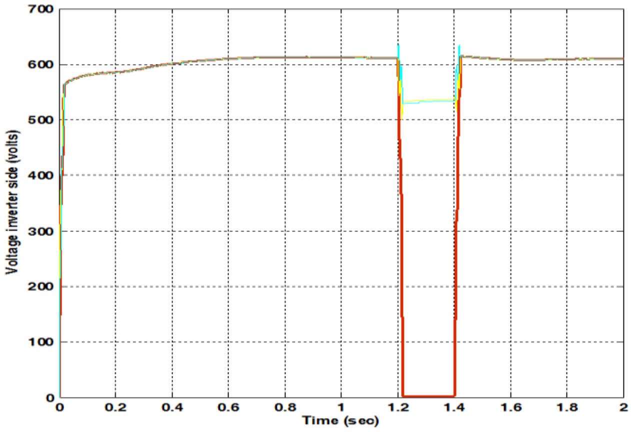

Figure 11. Voltage on the inverter side (LG)

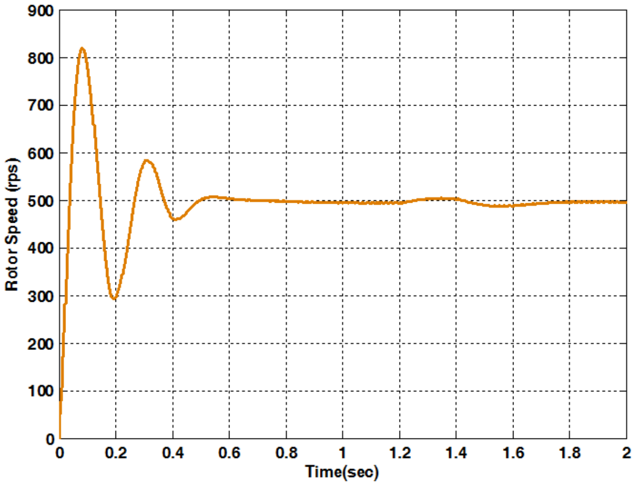

Figure.12 Rotor speed (LG)

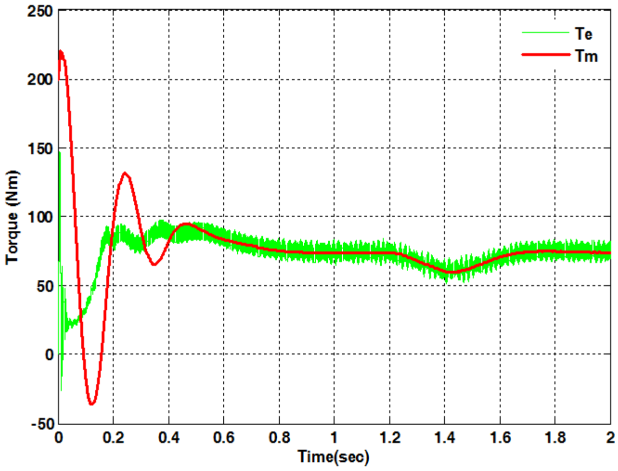

Fig 13 Variation of electromagnetic torque and mechanical torque (LG)

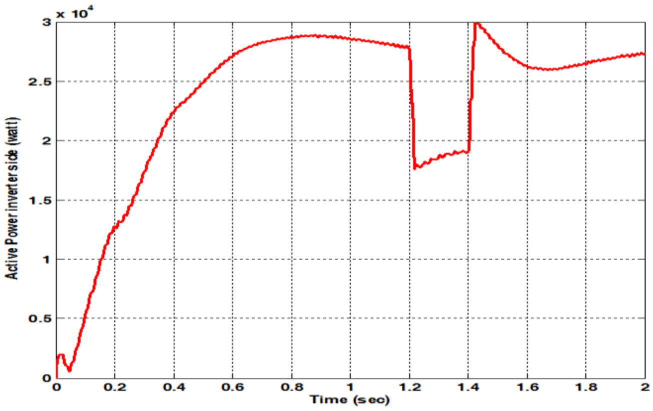

Figure. 14. Real power inverter side (LG)

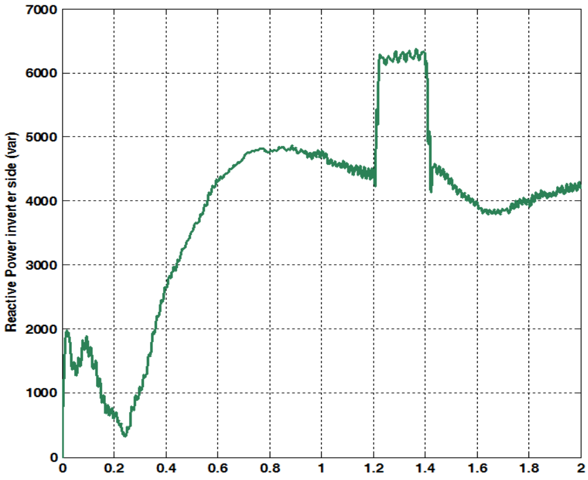

Figure 15 Reactive power inverter side (LL)

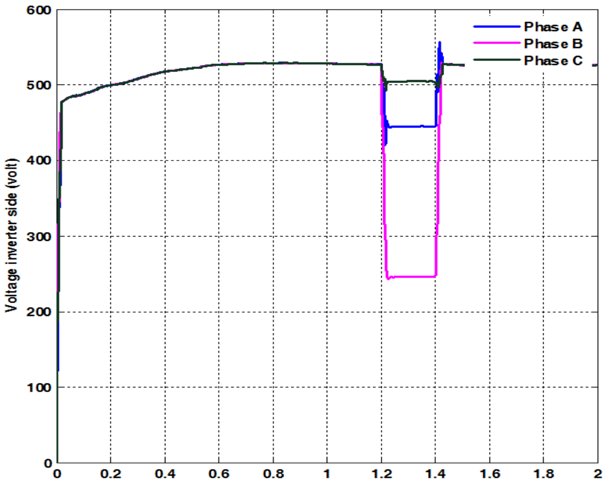

Figure 16. Voltage on the inverter side (LL)

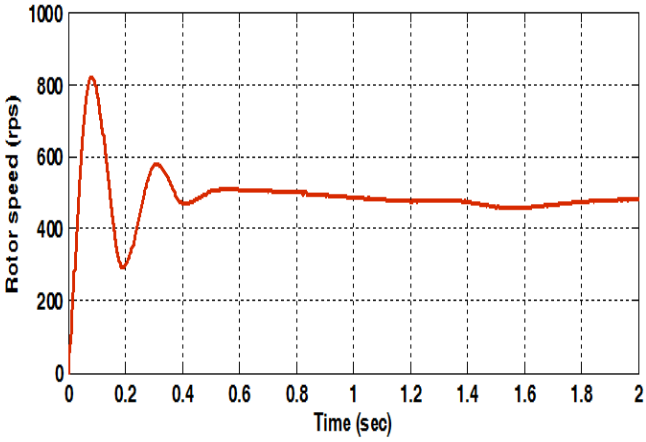

Fig.17 Rotor speed (LL)

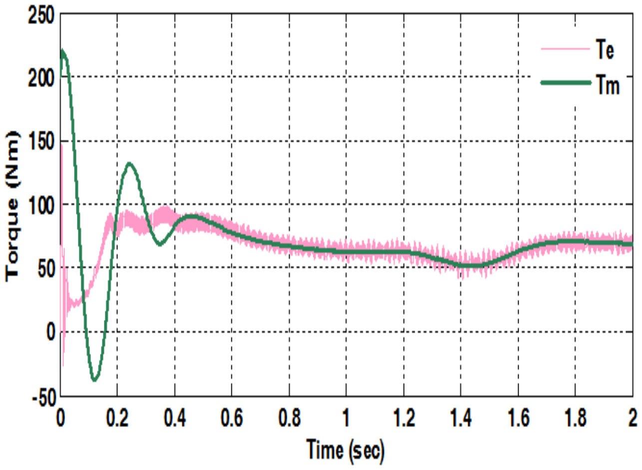

Fig 18 Variation of electromagnetic torque and mechanical torque (LL)

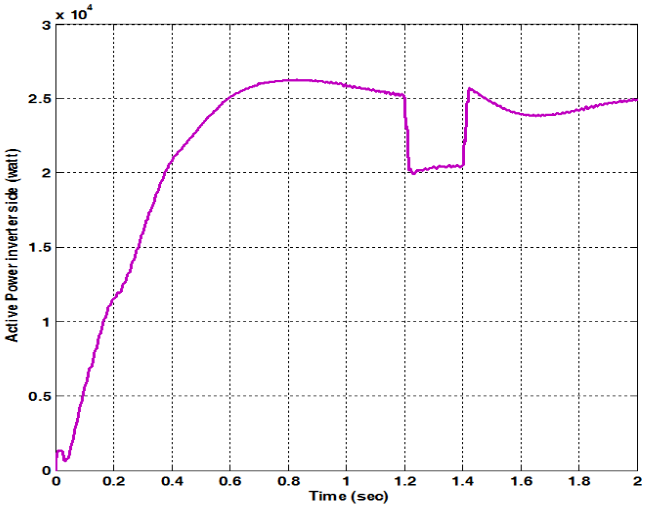

Figure. 19. Real power inverter side (LG)

6. CONCLUSIONS

The transient stability analysis of the variable speed permanent magnet synchronous generator has been studied during symmetrical and unsymmetrical fault. The output of the PMSG which is variable in amplitude and frequency is converted to constant voltage and frequency by using a two level AC-DC-AC converter inverter. Suitable control strategies provide maximum power to the grid and it also supplies the reactive power to maintain the terminal voltage of the grid to the pre fault value during the transient disturbance. During the simulation it has been found that the system is stable for both the symmetrical and unsymmetrical fault but is more severe in case of symmetrical fault Hence it can be concluded that the control system can well be used for enhancing the transient stability of the variable speed PMSG during the symmetrical and unsymmetrical fault. The simulation was done on Matlab using power Sim toolbox.

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