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Performance Analysis of Grid Connected Wind Energy Conversion System with a PMSG during Fault Conditions

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Abstract –Wind energy, among all of the renewable energy sources, has made rapid developments and significant inroads in electrical power systems. With the increased use of wind energy conversion systems (WECSs), several technologies have been developed. Since WECSs are more cost competitive, the comparison of different wind generator systems is the need of the hour. Permanent magnet generators employing these technologies have some significant advantages over conventional generators, such as no need of excitation, low volume and weight, high precision, and deletion of the gearbox. The aim of the paper is to analyse the performance of grid connected wind energy conversion system with a permanent magnet synchronous generator during fault conditions. The model includes a PMSG model, a pitch-angled controlled wind turbine model, power electronic converters and a power system model. A phase to phase fault is simulated on 132 KV bus of power system model and the measured results obtained from grid connection of the permanent magnet synchronous generator are presented followed by some conclusions.

Index Terms— Permanent Magnet Synchronous Generator, Power Electronic Converter.

Nomenclature

PMSG	Permanent Magnet Synchronous Generator
WECS	Wind Energy Conversion System
ω_B	Rotational speed of turbine
P_w	Power from the wind
P	Air density
R	Blade radius
V_ω	Wind speed
C_p	Power coefficient
λ	Tip speed ratio
β	Blade pitch angle
J	Moment of inertia
Pa	Accelerate mechanical power
u	Voltage
R	Resistance
i	Current
ω	Stator electrical frequency
s	Rotor slip
L_s	Stator leakage inductance
L_r	Rotor leakage inductance
M	Mutual inductance
T_e	Electromagnetic torque
T_m	Shaft Mechanic Torque

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I. INTRODUCTION

The renewable energy sources are one of the biggest concerns of our times. High prices of oil and global warming make the fossil fuels less and less attractive solutions. Wind power is a very important renewable energy source. It is free and not polluter unlike the traditional fossil energy sources. It obtains clean energy from the kinetic energy of the wind by means of the wind turbine. The wind turbine transforms the kinetic wind energy into mechanical energy through the drive train and then into electrical energy by means of the generator.

A growing proportion of energy is being met all over the world by electricity. This trend will be increasing day by day as the demand for electricity is increasing. This demand will have an increased impact on developing countries because their industrial progress will be based on modern technological developments in power generation. During recent years, due to the depletion of fossil fuels and the environmental problems caused by the use of fossil fuels, renewable energy sources have become the most sought resources. Wind is one of the sources of renewable energy [1-3]. Wind power is converted to electricity by wind turbine generators. Various technologies have been developed in wind energy conversion systems (WECSs) as the result of the effort to further improve WECSs based on the permanent magnet generator (PMG). Induction generators are most widely used in WECSs. Although they are robust and inexpensive, the space-consuming capacitors are bulky and expensive [4 & 5]. Induction generators with step-up gearboxes have low efficiency at low speeds [6]. When compared to conventional generators, the PMGs have the advantages of being robust in construction, very compact in size, not requiring an additional power supply for magnetic field excitation, and requiring less maintenance. A variable-speed WECS including a PMSG offers advantages over the constant-speed approach, such as maximum power-point tracking capability and reduced acoustic noise at lower wind speeds [7 & 8].

This paper describes the operation and control of permanent magnet synchronous wind generators. The generator is connected to the power network by means of a fully controlled frequency converter, which consists of three phase rectifier, an intermediate dc circuit, and a PWM inverter. The whole system is connected to AC grid and a phase to phase fault is simulated on 132 KV line. Simulations have been conducted with the software MATLAB/Simulink to validate the model and the control schemes [9-10].

II. MODELING OF WIND TURBINE WITH PMSG

The WECS considered for analysis consist of a PMSG driven by a wind turbine, three phase rectifier, an intermediate dc circuit, and a PWM inverter. Fig.1 shows a schematic of the power circuit topology of a variable speed wind turbine system that will be discussed in this paper. Since the wind is the intermitted source of energy, the output voltage and frequency from generator will vary for different wind velocities. The variable output ac power from the generator is first converted into dc using the rectifier. The available dc power is fed to the grid at the required constant voltage and frequency by regulating the modulation index of the inverter.

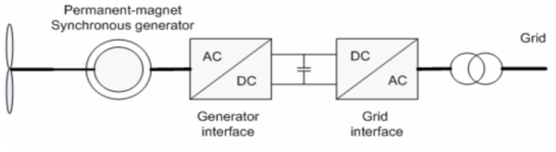

Fig. 1 Wind Energy Conversion System

The mechanical power available from a wind turbine

$$P_w = 0.5\rho\Pi R^2 V_\omega^3 C_p(\lambda,\beta) \quad (1)$$

$$C_p = \frac{1}{2}\times\left(\lambda - 0.022\times\beta^2 - 5.6\right)\times e^{-0.17\lambda} \quad (2)$$

$$\lambda = \frac{V_\omega}{\omega_B} \quad (3)$$

where P_w is the extracted power from the wind, ρ is the air density, R is the blade radius and V_ω is the wind speed. C_p is called the 'power coefficient' and is given as a nonlinear function of the parameters tip speed ratio λ and blade pitch angle β. The calculation of the performance coefficient requires the use of blade element theory. ω_B is the rotational speed of turbine. Usually C_p is approximated as [11]-[12],

$$C_p = \alpha\lambda + \beta\lambda^2 + \gamma\lambda^3 \quad (4)$$

where α, β and γ are constructive parameters for a given turbine. The torque developed by the windmill is

$$T_t = 0.5\mu\left(\frac{C_p}{\lambda}\right)\cdot V_\omega^3 u R^2 \quad (5)$$

The power coefficient Cp v/s Curves for various values of pitch angles increasing by step of 2 deg are shown in Fig.2. The dashed line represents Cp for pitch angle 0 degree. It is clear from Fig. 2 that as the value of λ increases, maximum value of Cp decreases. Fig.3 shows wind turbine characteristics for w=1p.u. and pitch angle increasing by step of 2 deg. It shows power P (pu), λ and Cp curves v/s wind speed in m/s. The total numbers of turbines were five.

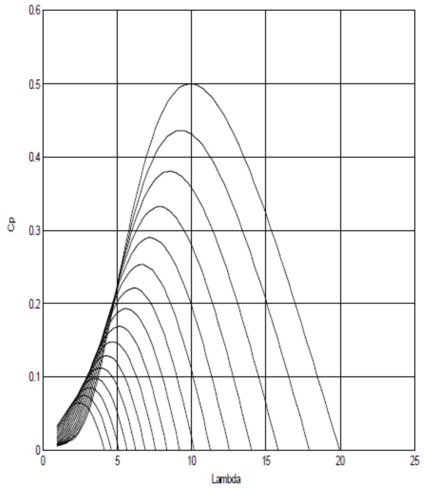

Fig. 2 Cp v/s λ Curves for Various Values of Pitch Angles

phase synchronous reference frame in which the q-axis is 90° ahead of the d-axis with respect to the direction of rotation.

The electrical model of PMSG in the synchronous reference frame is given as:

$$\frac{di_d}{dt} = \frac{v_d}{L_d} - \frac{Ri_d}{L_d} + \frac{L_q}{L_d} p w_r i_q \quad (6)$$

$$\frac{di_q}{dt} = \frac{v_q}{L_q} - \frac{Ri_q}{L_q} + \frac{L_d}{L_q} p w_r i_d - \frac{\lambda p w_r}{L_q} \quad (7)$$

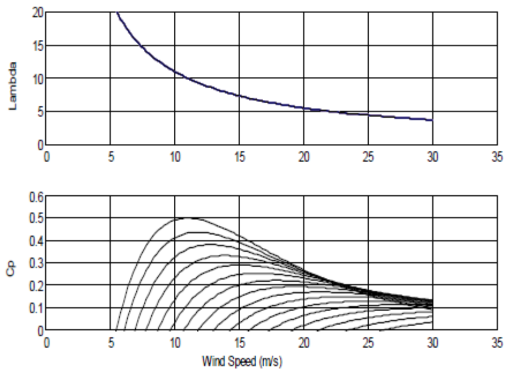

Fig. 3 Wind Turbine Characteristics

$$T_e = 1.5p\left[\lambda i_q + L_{dq} i_d i_q\right] \quad (8)$$

where all quantities in the rotor reference frame are referred to the stator.

L_q, L_d - q and d axis inductances
R - resistance of the stator windings
i_q, i_d - q and d axis currents
v_q, v_d - q and d axis voltages
ω_r - angular velocity of the rotor
λ - flux amplitude induced by the permanent magnets in the stator phases
p - number of pole pairs
T_e - electromagnetic torque.

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The L_q and L_d inductances represent the relation between the phase inductance and the rotor position due to the saliency of the rotor. The inductance measured between phase *a* and *b* (phase *c* is left open) L_{ab} is given by:

$$L_{ab} = L_d + L_q + (L_q - L_d)\cos\left(2\theta_e + \frac{\Pi}{3}\right) \qquad (9)$$

where θ_e represents the electrical angle. Mechanical system for the model is:

$$\frac{dw_r}{dr} = \frac{1}{J}(T_e - Fw_r - T_m) \qquad (10)$$

$$\frac{d\theta}{dt} = w_r \qquad (11)$$

where

J - combined inertia of rotor and load
F - combined viscous friction of rotor and load
θ - rotor angular position
T_m - Shaft mechanical torque.

Table 1. Design Parameters of PMSG

Design Parameters PMSG	
P_{nom}(VA)	2 x 10^6
X_d (p.u)	1.3050
X_d'' (p.u)	0.2520
Xq (p.u)	0.4740
X_q'' (p.u)	0.2430
T_d'' (p.u)	0.0681
T_q'' (p.u)	0.0513
R_r (p.u)	0.0060

Table 1 shows design parameters of PMSG. Fig.4 to Fig.7 shows PM synchronous generator characteristics. Fig.4 shows mechanical power applied to the Permanent Magnet generator.

Generator rotor speed is shown in Fig.5. Phasor currents I_a, I_b, I_c flowing into the stator terminals in pu based on the generator rating are shown in Fig.6.

Fig.7 presents phasor voltages (phase to ground) Va, Vb, Vc at the Wind Turbine Permanent magnet synchronous generator terminals in pu based on the generator rating.

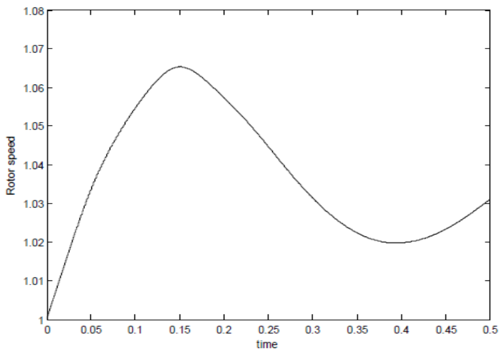

Fig. 5 Generator Rotor Speed

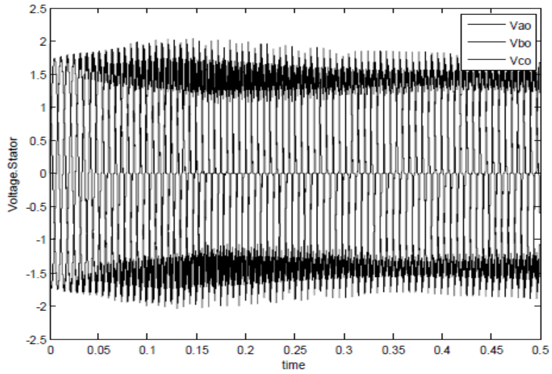

Fig. 6 Stator Phasor Currents I_{abc}

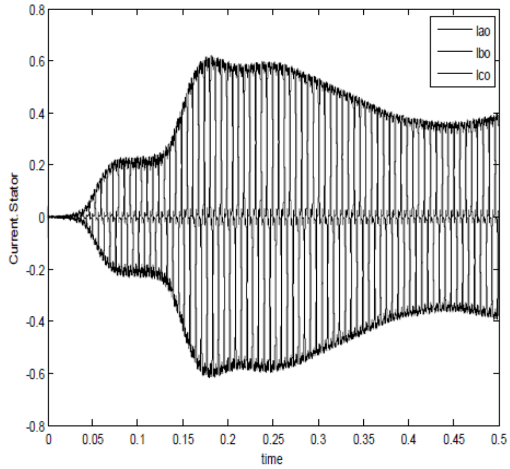

Fig. 7 Stator Phasor Voltage

III. POWER SYSTEM MODEL WITH CONVERTER CONTROL SYSTEM

A 10 MW wind farm is connected to a 33-kV distribution system exports power to a 220-kV grid [13], A-B fault at 104 ms for duration 50 ms is simulated at 132 KV line. The wind speed is maintained constant at 15 m/s. The control system of the DC-DC converter is used to maintain the speed at 1 pu. The reactive power produced by the wind turbine is regulated at 0 Mvar.

A. Grid-side Converter Control

The GSC is used to control the power flow in order to keep the DC-link voltage constant. The control strategy is based on the control of the DC bus voltage which kept constant and the control of line currents in order to regulate the power delivered by the stator circuits to the grid. For this, a filter was designed and implemented between the inverter and the grid.

Measurement systems measuring the d and q components of AC positive sequence currents to be controlled as well as the DC voltage V_{dc}. An outer regulation loop consisting of a DC voltage regulator. The output of the current I_{dgc_ref} for the current regulator (I_{dgc} = current in phase with grid voltage which controls active power flow). An inner current regulation loop consisting of a current regulator. The current regulatory controls the magnitude and phase of the voltage generated by converter C_{grid} (V_{gc}) from the I_{dgc_ref} produced by the DC voltage regulator and specified I_{q_ref} reference. The current regulator is assisted by feed forward terms which predict the C_{grid} output voltage.

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AC voltage regulator and VAR regulator is also there. The converters data for one turbine of Grid Side Coupling Inductor L= 0.15p.u., R= 0.003p.u., Line Filter Capacitor (Q=50) is 150000 var, Nominal DC Bus Voltage is 1100V, DC Bus Capacitor is 0.09F and Boost Converter Inductance L=0.0012H,R=0.005Ohm.

The maximum value of this current is limited to a value defined by the converter maximum power at nominal voltage. When I_{dgc_ref} and I_{q_ref} are such that the magnitude is higher than this maximum value the I_{q_ref} component is reduced in order to bring back the magnitude to its maximum value.

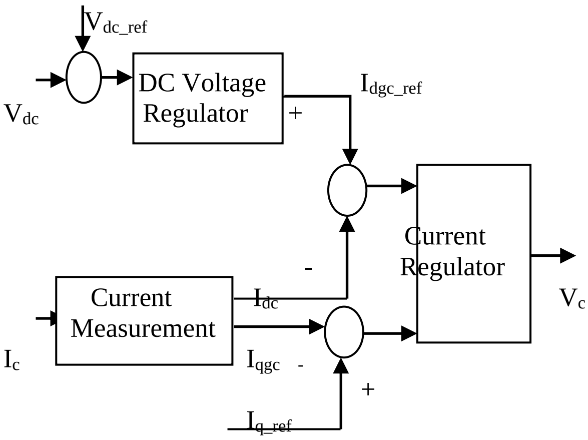

Fig. 8. Voltage and Current regulator of Converter

The control parameters for one turbine, DC Bus Voltage Regulator Gains K_p is 1.1 and ,K_i is 27.5, Grid Side Converter VAR Regulator gain [K_i] is 0.05, Grid Side Converter Voltage Regulator Gain [K_i] is 2, Grid Side Converter Current Regulator Gains K_p is 1and K_i is 50, Pitch Controller Gain [K_p] is 15, Pitch Compensation Gains K_p is 1.5 and K_i is 6, Maximum Pitch Angle is 27 deg and Maximum Rate of Change of Pitch Angle is 10 (deg/s).

The pitch angle is kept constant at zero degree until the speed w_r reaches desired speed of the tracking characteristic w_d. Beyond w_d, the pitch angle is proportional to the speed deviation from desired speed. The control system is illustrated in the Fig. 9.

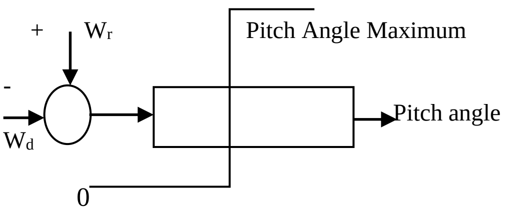

Fig. 9. Pitch Angle control system

IV. SIMULATION RESULTS

All the modeling is done in Matlab Simulink with simulation type discrete having sample time $2x10^{-6}$ secs. In this section the measurement results for the grid connection of the permanent magnet synchronous generator using the power electronic converter described above are presented. Phasor voltages V_a, V_b, V_c flowing into the grid-side converter in pu based on the generator rating are shown in Fig.10, while Fig.11 presents phasor currents I_a, I_b, I_c flowing into the grid-side converter in pu based on the generator rating. As shown in Fig.12, DC voltage oscillates at t=0.104 due to phase to phase fault on 132KV line. During the voltage sag the control systems try to regulate DC voltage system and DC voltage is recovered after sometime.

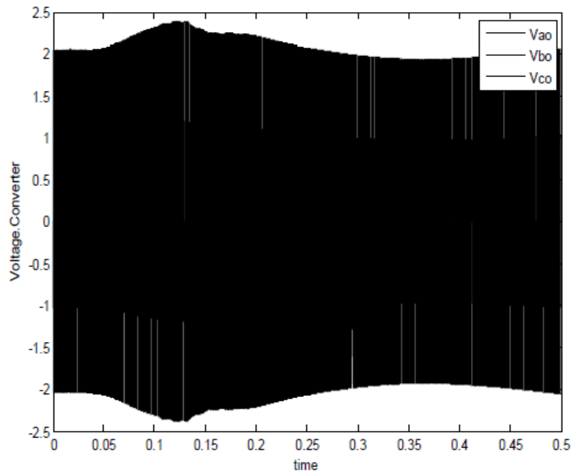

Fig. 10. Phasor Voltages at Grid Side Converter

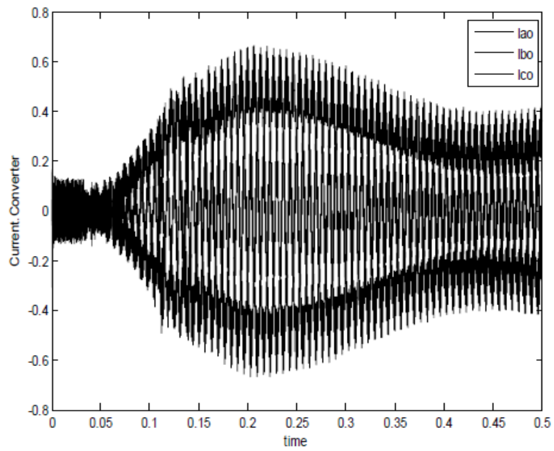

Fig. 11. Phasor Currents at Grid Side Converter

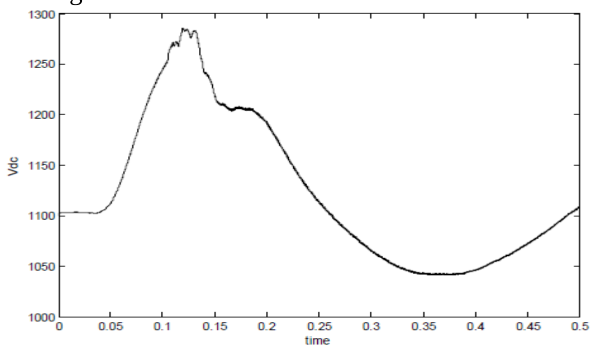

Fig. 12. DC Output Voltage

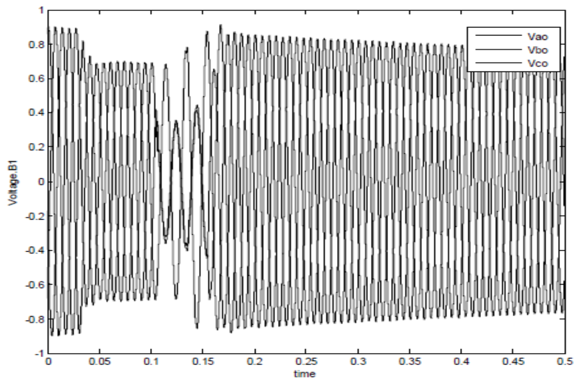

Fig. 13. Voltage at 440V Bus

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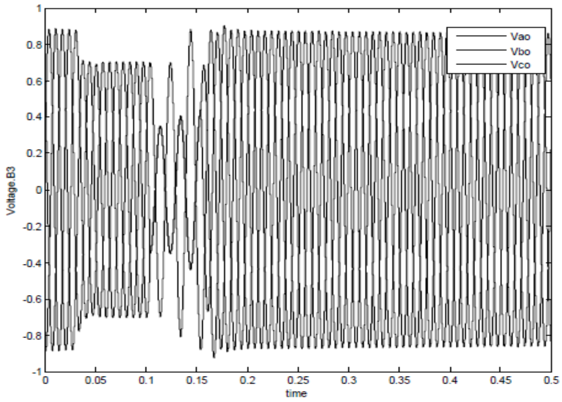

Fig. 14. Voltage at 132KV Bus

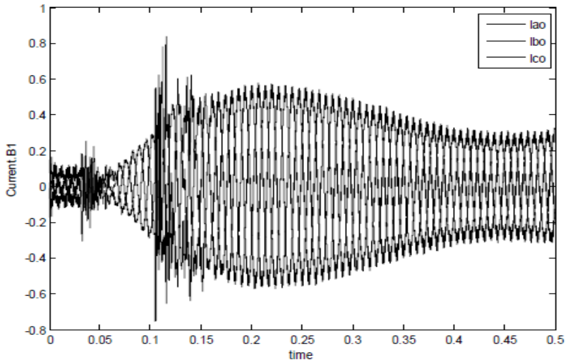

Fig. 15. Currents at 440V Bus

Voltages and current at different locations of power system are presented in Fig.13 to Fig.16. The system voltages and currents oscillate due to fault, but they return to their normal behavior quickly. The magnitude (%) relative to fundamental at various harmonic frequencies at different buses B1, B2, B3 and B4 is presented as bar graph in Fig. 17 to Fig. 20.

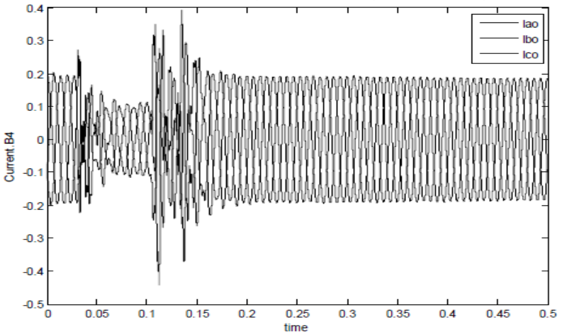

Fig. 16. Currents at 220KV Bus

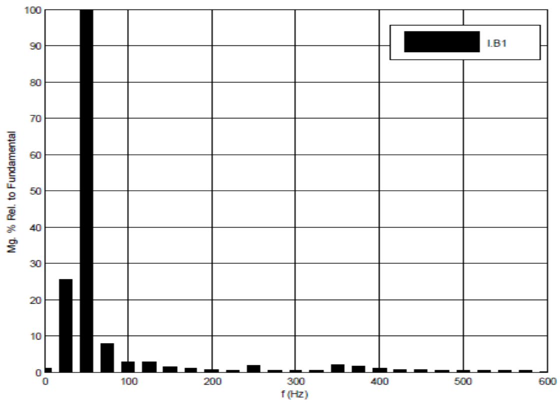

Fig. 17. Magnitude (%) Relative to Fundamental v/s frequency at Bus B1

Table 2 and Table 3 show voltage/current THDs at different buses B1, B2, B3 and B4. It is seen that values of THDs are much smaller. The wind turbine generator power is shown in Fig.21. The reactive power of wind turbine generator is presented in Fig.22. The control system regulates the reactive power to 0 MVAR.

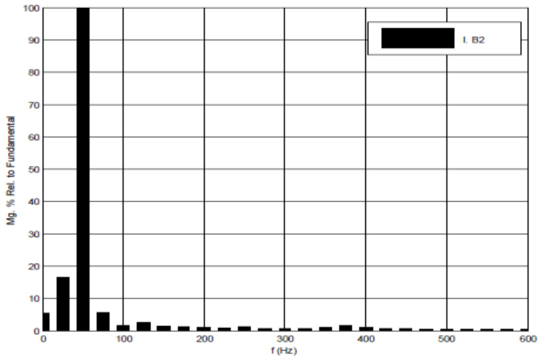

Fig. 18. Magnitude (%) Relative to Fundamental v/s frequency at Bus B2

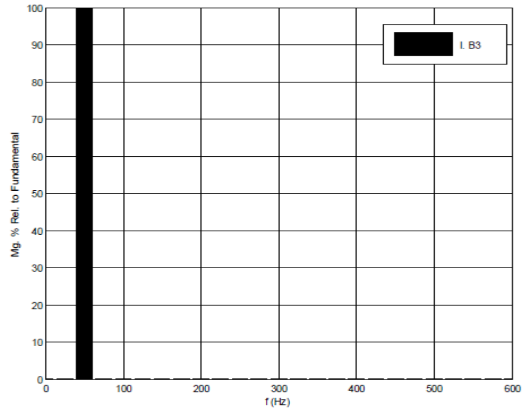

Fig. 19. Magnitude (%) Relative to Fundamental v/s frequency at Bus B3

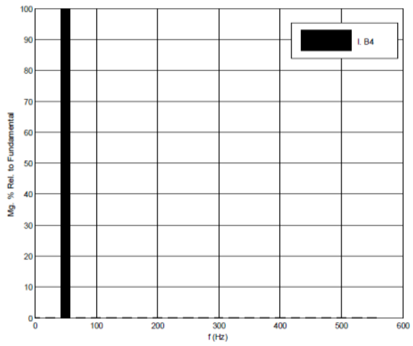

Fig. 20. Magnitude (%) Relative to Fundamental v/s frequency at Bus B4

Table 2. Voltage THDs at Different buses B1, B2, B3 and B4

Output Voltage	**THD (% Relative to Fundamental)**
B1	0.32
B2	0.065
B3	0.058
B4	0.01

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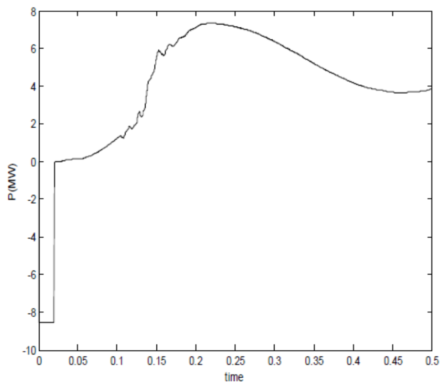

Fig. 21. Output Power

Table 3. Current THDs at Different buses B1, B2, B3 and B4

Output Current	THD (% Relative to Fundamental)
B1	4.33
B2	3.03
B3	0.09
B4	0.05

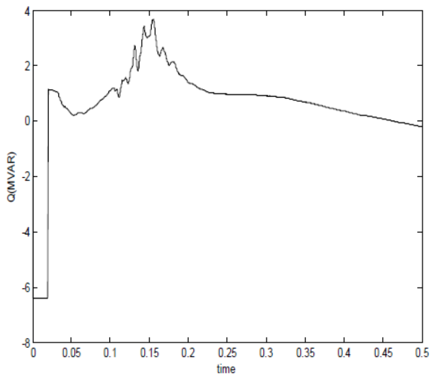

Fig. 22. Output Reactive Power

V. CONCLUSION

As the level of penetration of the wind power is increasing, it is necessary to analyze and evaluate the impacts of the wind power to the power system. Interconnecting wind power influences the performance of the power system in the light of stability, reliability, and quality. The paper presents the complete model of the variable speed wind turbine with PMSG connected to AC grid through converters with control system. At the same time, the paper addresses control schemes of the wind turbine in terms of pitch angle and AC and DC voltage regulation, VAR regulation and current regulation of converters. The pitch angle control is actuated in high wind speeds and uses wind speed signals and electric power as the inputs. The simulation results show that in event of transient fault, the output reactive power is regulated at 0 MVAR and the control system also brings DC voltage to 1100V. The results obtained indicate that the variations in currents and voltages at different locations in power system model. They return to normal behavior after experiencing oscillations for much less time.

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