Dynamic Analysis of Grid Connected Wind Turbine with a Permanent Magnet Synchronous Generator during Fault Conditions

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Abstract: - The use of wind turbines is increasing at very high rates in many countries around the world. Studies to evaluate the impact of connecting these new generation units to the existing power systems must be done. This paper proposes a wind energy conversion system for a grid connected permanent magnet synchronous generator (PMSG) and power electronic converter system. The model includes a PMSG model, a pitch-angled controlled wind turbine model, power electronic converters and a power system model. The control schemes in the paper include a pitch angle control for the wind turbine and voltage, var and current control for the power electronic converter. 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.

Key-Words: - Permanent Magnet, Synchronous Generator, Power Grid, Power Electronic Converter, Fault

1 Introduction

With its abundant, inexhaustible potential, it's increasingly cost competitive and environmentally clean wind energy is one of the best technologies available today to provide a sustainable supply to the world development. At the end of 2009, worldwide nameplate capacity of wind-powered generators was 159.2 GW [1]. By June 2010 the capacity had risen to 175 GW [1]. In depth understanding and investigation of wind energy related technologies, such as wind power generators, wind farm integration, grid code and etc., is very meaningful.

In terms of the generators for wind-power application, there are different concepts in use today. The major distinction among them is made between fixed speed and variable speed wind turbine generators. In the early stage of wind power development, fixed-speed wind turbines and induction generators were often used in wind farms. But the limitations of such generators, e.g. low efficiency and poor power quality, adversely influence their further applications. With large-scale exploration and integration of wind sources, variable speed wind turbine generators, such as doubly fed induction generators (DFIGs) and permanent magnetic synchronous generators (PMSGs) [1-3] are emerging as the preferred technology [4]. In contrast to their fixed-speed counterparts, the variable speed generators allow operating wind turbines at the optimum tip-speed ratio and hence at the optimum power efficient for a wide wind speed range.

Permanent magnets can be used to replace the excitation winding of synchronous machines because of magnet price reduction and magnetic material characteristic improvement. Permanent-magnet excitation allows us to use a smaller pole pitch than do conventional generators, so these machines can be designed to rotate at rated speeds of 20-200r/min, depending on the generator rated power. In addition, PMSG has the advantages of simple structure and high efficiency.

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 [5-6].

2 Modeling of Wind Turbine with PMSG

2.1 Wind Turbine Modeling

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.

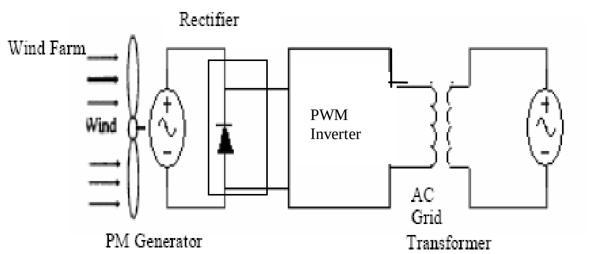

Fig. 1: Wind Energy Conversion System

The mechanical power available from a wind turbine

$$P_w = 0.5\, \rho\pi\, R^2\, {V_w}^3\, C_p(\lambda, \beta) \quad (1)$$

where P_w is the extracted power from the wind, ρ is the air density, R is the blade radius, and V_w 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 [7-8]. Here the following function will be used

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

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

where, ω_B is the rotational speed of turbine. Usually C_p is approximated as,

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

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

$$T_t = 0.5\, \rho \left(\frac{C_p}{\lambda}\right) {V_w}^3 \pi R^2 \quad (5)$$

The power coefficient C_p v/s $\boldsymbol{\lambda}$ Curves for various values of pitch angles increasing by step of 2 deg are shown in Fig.2. The dashed line represents C_p for pitch angle 0 degree. It is clear from Fig. 2 that as the value of λ increases, maximum value of C_p 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 C_p curves v/s wind speed in m/s. The total numbers of turbines were five.

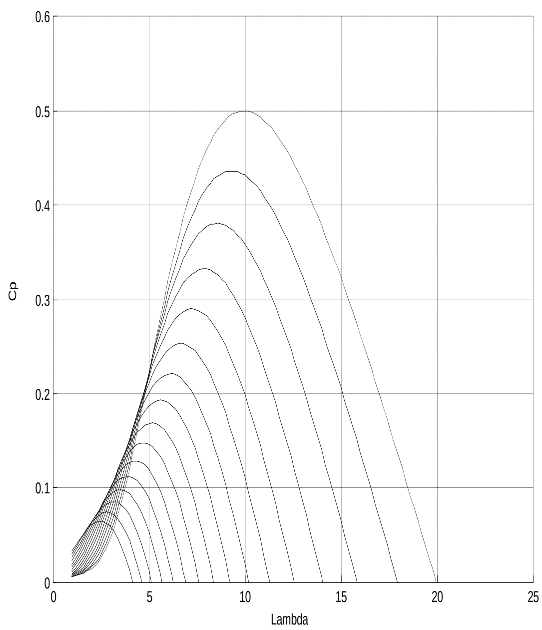

Fig. 2: C_p v/s λ Curves for Various Values of Pitch Angles

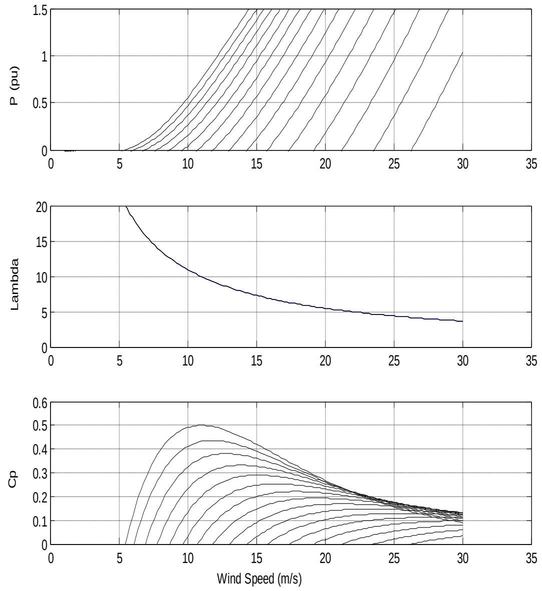

Fig. 3: Wind Turbine Characteristics

2.2 PMSG Modeling

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 electrical model of PMSG in the synchronous reference frame is given in [9-10].

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

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

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

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

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. For example, the inductance measured between phase a and b (phase c is left open) is given by:

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

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

$$\frac{dw_r}{dt} = \frac{1}{J}\left(T_e - Fw_r - T_m\right) \quad (10)$$

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

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 shows design parameters of PMSG. Fig.4 to Fig.7 shows PM synchronous generator characteristics. Fig.4 shows mechanical power applied to the PM generator. Generator rotor speed is shown in Fig.5.

TABLE 1 DESIGN PARAMETERS OF PMSG

Generator Data for One Turbine	
Nominal Electrical Power $P_{e,nom}$ (VA)	$2*10^6/0.9$
Nominal Frequency f (Hz)	50
Inductance L_d (p.u.)	0.00415
Inductance L_q (p.u.)	0.0015
Resistance R_s (p.u.)	0.006
Inertia Constant H(s)	0.62
Friction Factor F (p.u.)	0.01
Pairs of Poles p	1

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 and Fig.7 presents phasor voltages (phase to ground) V_a, V_b, V_c at the WTPMSG terminals in pu based on the generator rating. The variations in rotor speed are much less indicating the effectiveness of control system, which will be discussed in section IIIB.

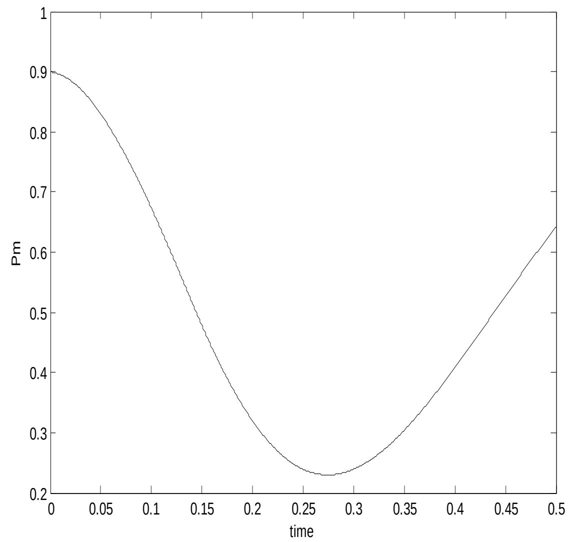

Fig. 4: Mechanical Torque Applied to PMSG

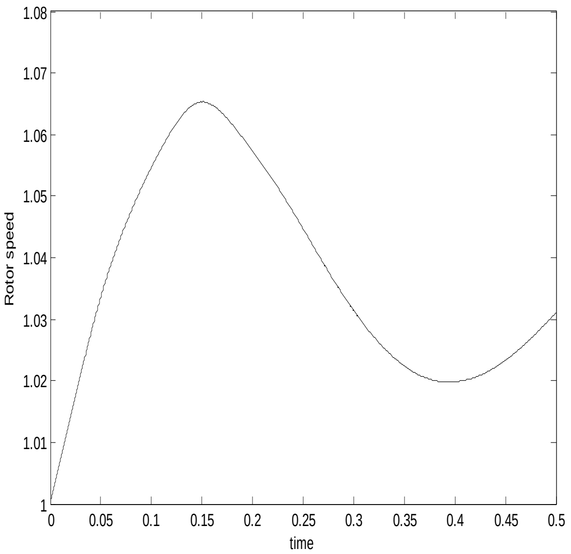

Fig. 5: Generator Rotor Speed

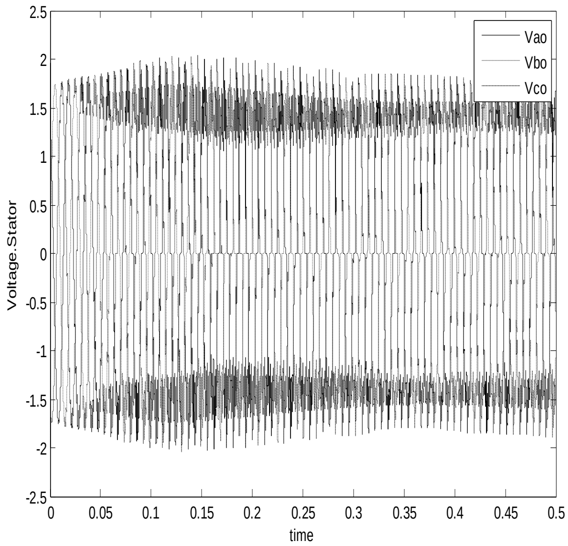

Fig. 6: Stator Phasor Currents I_{abc}

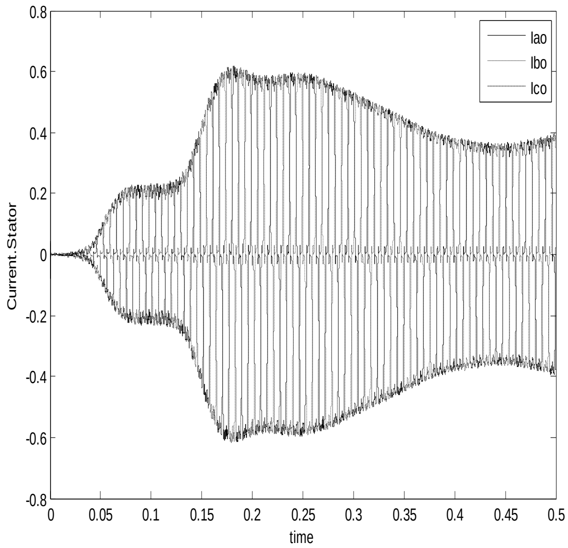

Fig. 7: Stator Phasor Voltages

3 Power System Model with Converter Control System

3.1 Power System Model

A 10 MW wind farm is connected to a 33-kV distribution system exports power to a 220-kV grid as shown in Fig.8. 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.

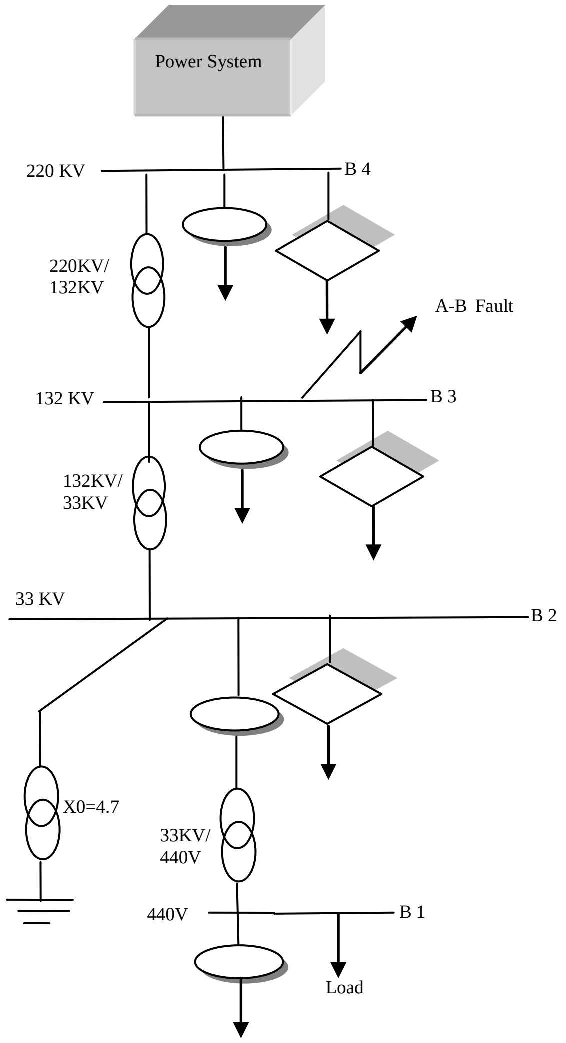

Fig. 8: Power System Model used in Paper

3.2 Grid-Side Converter Control System Model

The control system, illustrated in the Fig.9 and Fig.10, called Grid-Side Converter Control (GSC) System, consists of:

- 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 DC voltage regulator is the reference 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 regulator 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.

- AC voltage regulator and VAR regulator is also there.

The main converters data and control parameters for one wind turbine are given in tables 2 and 3. The magnitude of the reference grid converter current is equal to $\sqrt{I_{dgc\_ref}{}^2 + I_{q\_ref}{}^2}$. 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. 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.11.

TABLE 2 CONVERTERS DATA FOR ONE TURBINE

Grid Side Coupling Inductor (L(p.u.),R(p.u.))	0.15, 0.003
Line Filter Capacitor (Q=50) (var)	150000
Nominal DC Bus Voltage (V)	1100
DC Bus Capacitor (F)	0.09
Boost Converter Inductance (L(H), R(Ohm))	0.0012, 0.005

TABLE 3 CONTROL PARAMETERS FOR ONE TURBINE

DC Bus Voltage Regulator Gains [Kp,Ki]	1.1, 27.5
Grid Side Converter VAR Regulator gain [Ki]	0.05
Grid Side Converter Voltage Regulator Gain [Ki]	2
Grid Side Converter Current Regulator Gains [Kp, Ki]	1, 50
Pitch Controller Gain [Kp]	15
Pitch Compensation Gains [Kp, Ki]	1.5, 6
Maximum Pitch Angle (deg)	27
Maximum Rate of Change of Pitch Angle (deg/s)	10

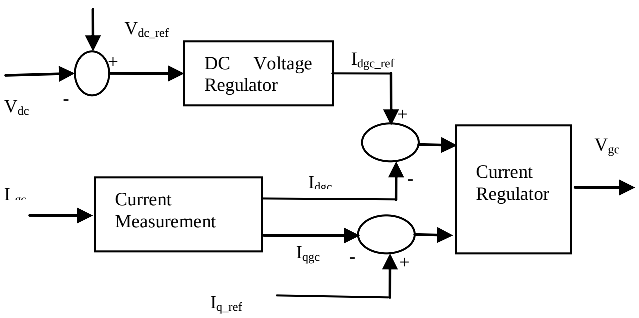

Fig. 9: DC Voltage Regulator and Current Regulator

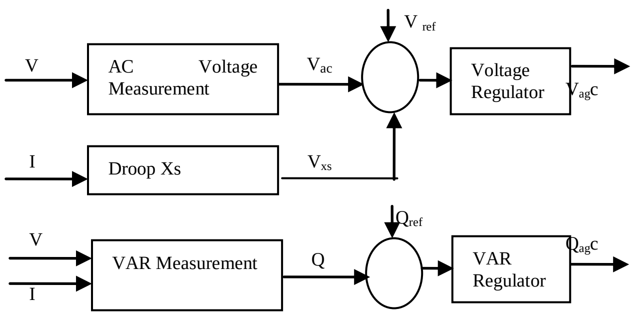

Fig. 10: AC Voltage Regulator and VAR Regulator

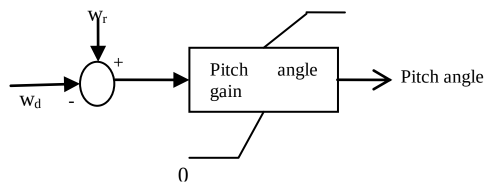

Fig. 11: Pitch Control System

4 Results and Discussions

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.12, while Fig.13 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.14, 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. Voltages and current at different locations of power system are presented in Fig.15 to Fig.18. 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 bargraph in Fig. 19 to Fig. 22.

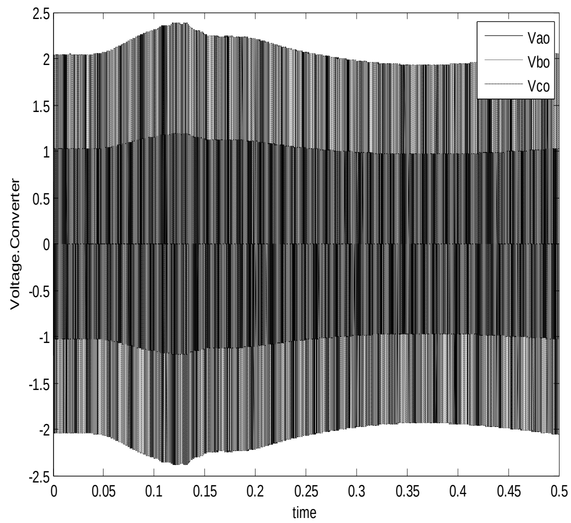

Fig. 12: Phasor Voltages in Grid Side Converter

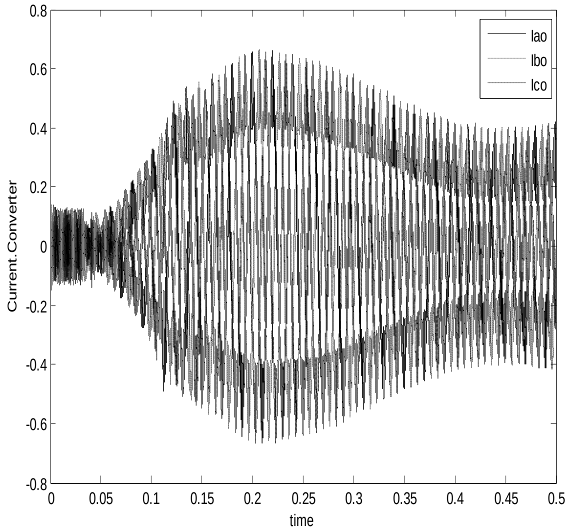

Fig. 13: Phasor Currents in Grid Side Converter

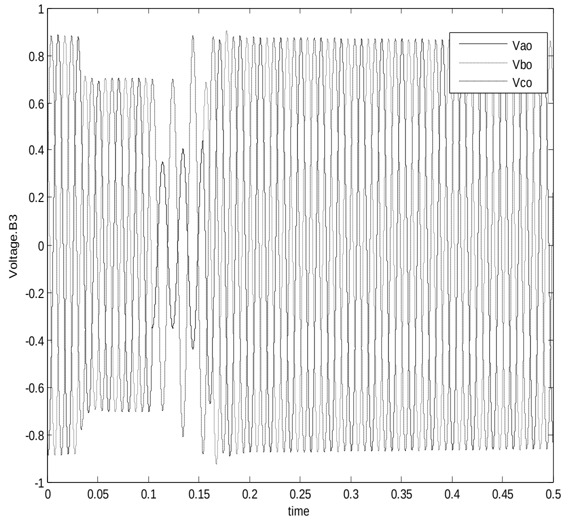

Fig. 16: Voltages at 132KV Bus

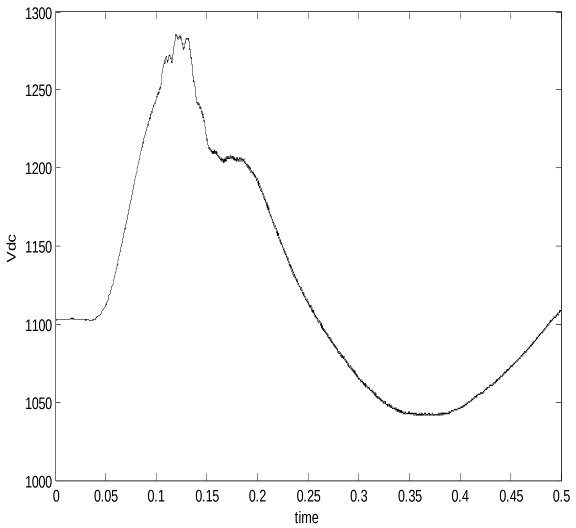

Fig. 14: DC Output Voltage

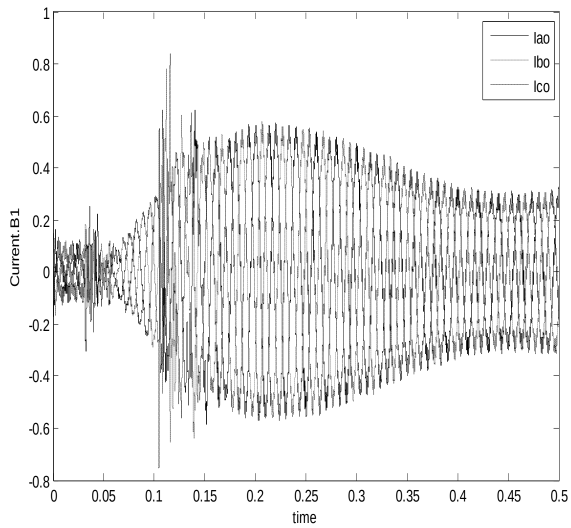

Fig. 17: Currents at 440V Bus

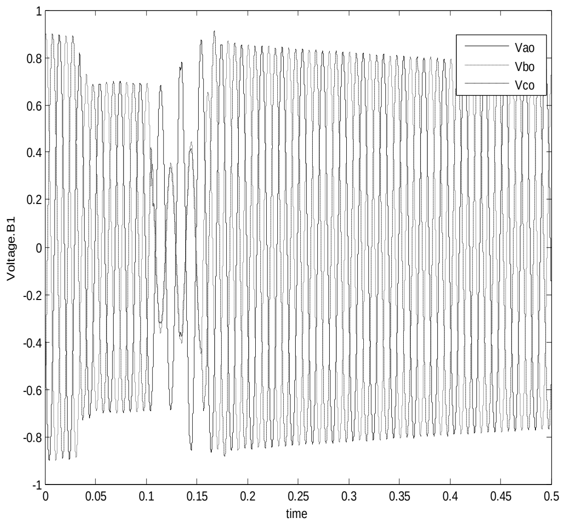

Fig. 15: Voltages at 440V Bus

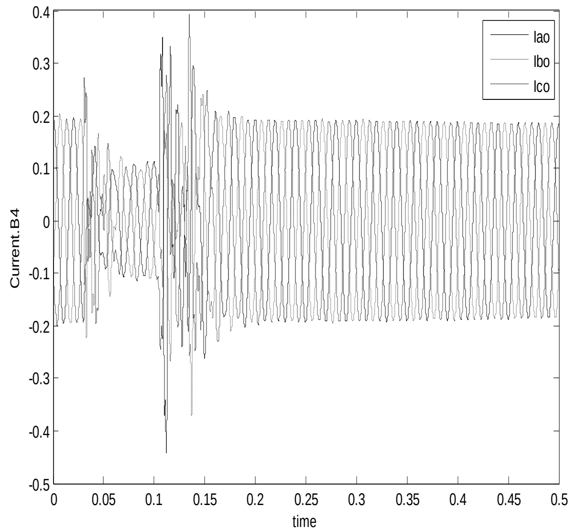

Fig. 18: Currents at 220KV Bus

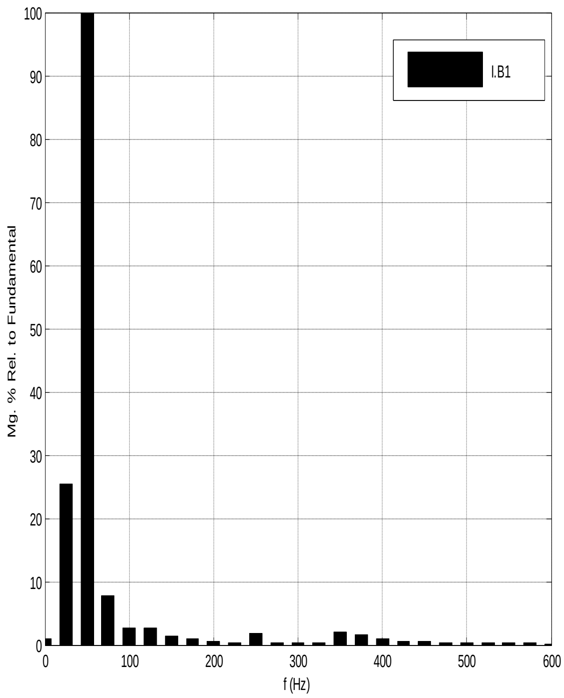

Fig. 19: Magnitude (%) Relative to Fundamental v/s frequency at Bus B1

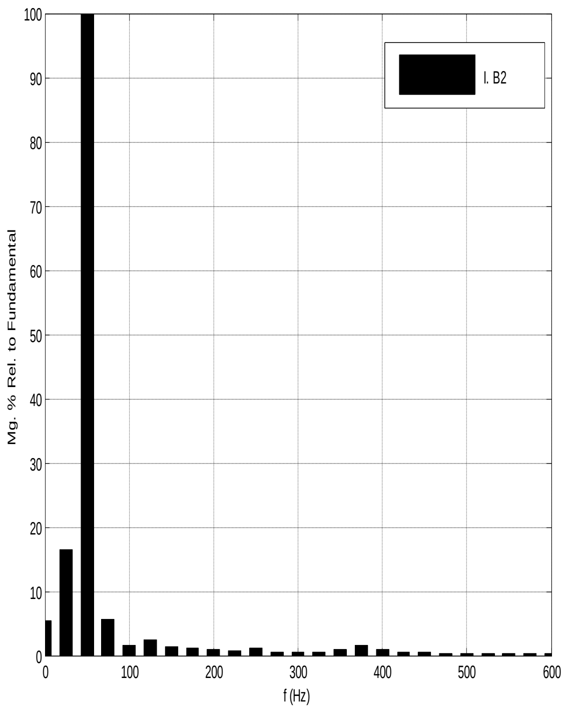

Fig. 20: Magnitude (%) Relative to Fundamental v/s frequency at Bus B2

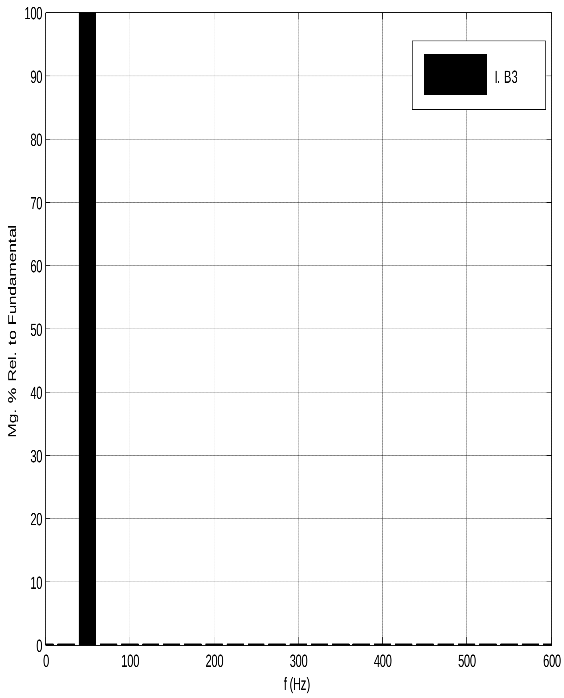

Fig. 21: Magnitude (%) Relative to Fundamental v/s frequency at Bus B3

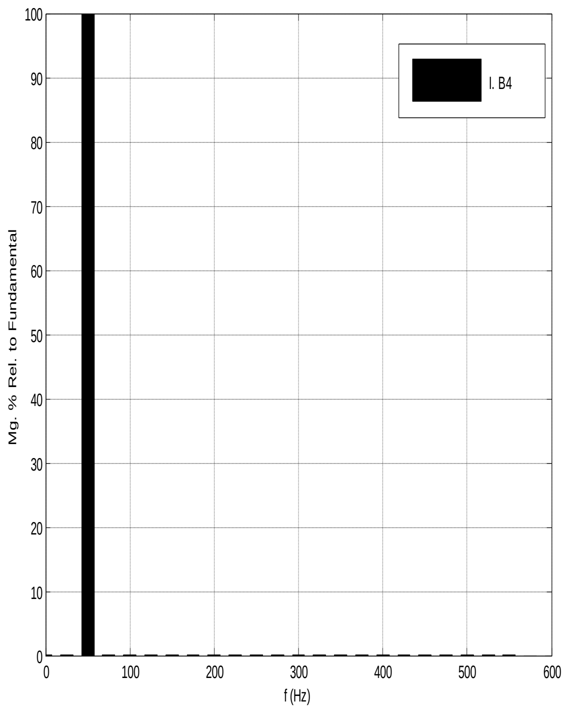

Fig. 22: Magnitude (%) Relative to Fundamental v/s frequency at Bus B4

Table 4 shows 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.23. The reactive power of wind turbine generator is presented in Fig.24. The control system regulates the reactive power to 0 MVAR.

TABLE 4 VOLTAGE/CURRENT THDS AT DIFFERENT BUSES B1, B2, B3 AND B4

S.No.	Quantity	THD (% Relative to Fundamental)
1.	O/P V_{B1}	0.33%
2.	O/P V_{B2}	0.07%
3.	O/P V_{B3}	0.05%
4.	O/P V_{B4}	0.01%
5.	O/P I_{B1}	4.26%
6.	O/P I_{B2}	3.15%
7.	O/P I_{B3}	0.09%
8.	O/P I_{B4}	0.05%

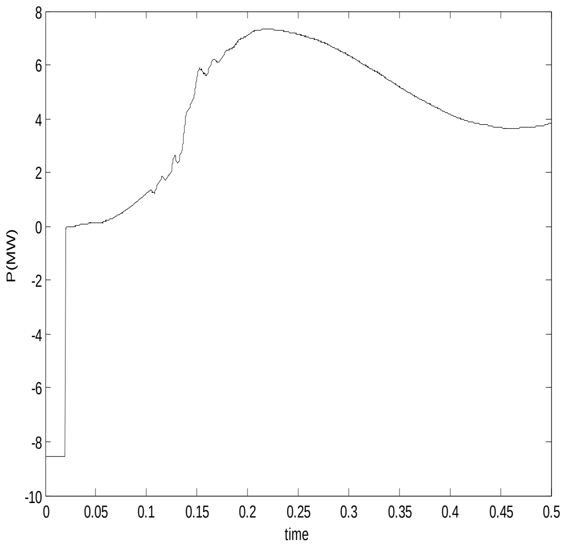

Fig. 23: WTPMSG Output Power

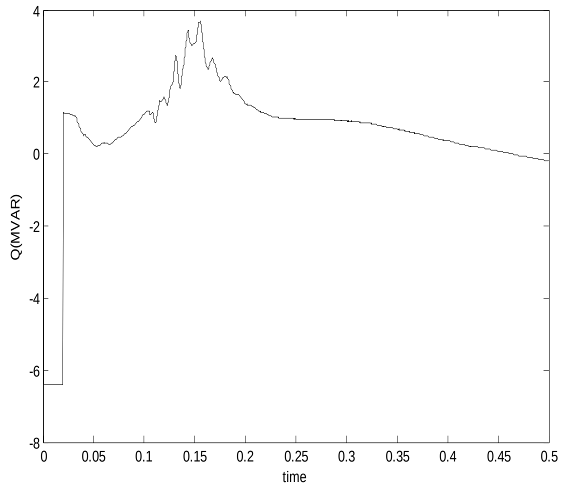

Fig. 24: WTPMSG Output Reactive Power

5 Conclusions

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 currents and voltages at different locations in power system model as well as converters return to normal behaviour after experiencing oscillations.

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Biographies

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