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
\( \omega_B \) Rotational speed of turbine
\( P_w \) Power from the wind
\( P \) Air density
\( R \) Blade radius
\( V_w \) Wind speed
\( C_p \) Power coefficient
\( \lambda \) Tip speed ratio
\( \beta \) Blade pitch angle
\( J \) Moment of inertia
\( Pa \) Accelerate mechanical power
\( u \) Voltage
\( R \) Resistance
\( i \) Current
\( \omega \) Stator electrical frequency
\( s \) Rotor slip
\( L_m \) Stator leakage inductance
\( L_r \) Rotor leakage inductance
\( M \) Mutual inductance
\( T_e \) Electromagnetic torque
\( T_m \) Shaft Mechanic Torque

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 mostly 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

\[
P_w = 0.5 \rho \pi R^2 \frac{V_m^3}{\alpha} C_p(\lambda, \beta) \quad (1)
\]

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

\[
\dot{\lambda} = \frac{V_m}{\omega_r} \quad (3)
\]

where \( P_w \) is the extracted power from the wind, \( \rho \) is the air density, \( R \) is the blade radius and \( V_m \) is the wind speed. \( C_p \) is called the ‘power coefficient’ and is given as a nonlinear function of the parameters tip speed ratio \( \lambda \) and blade pitch angle \( \beta \). The calculation of the performance coefficient requires the use of blade element theory. \( \omega_r \) 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 \( \alpha, \beta \) and \( \gamma \) are constructive parameters for a given turbine. The torque developed by the windmill is

\[
T_e = 0.5 \mu \left( \frac{C_p}{\lambda} \right) V_m^3 uR^2 \quad (5)
\]

The power coefficient \( C_p \) v/s 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 \( \lambda \) increases, maximum value of \( C_p \) decreases. Fig. 3 shows wind turbine characteristics for \( w=1 \) p.u. and pitch angle increasing by step of 2 deg. It shows power \( P \) (pu), \( \lambda \) and \( C_p \) curves v/s wind speed in m/s. The total numbers of turbines were five.

**Fig. 2 \( C_p \) v/s \( \lambda \) Curves for Various Values of Pitch Angles**

\[
\frac{di_d}{dt} = \frac{v_d}{L_d} - \frac{R_i_d}{L_d} + \frac{L_q}{L_d} p_w i_q \quad (6)
\]

\[
\frac{di_q}{dt} = \frac{v_q}{L_q} - \frac{R_i_q}{L_q} + \frac{L_d}{L_q} p_w i_d - \frac{\lambda p_w}{L_q} \quad (7)
\]

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

\[
L_d, L_q \quad - \quad q \text{ and } d \text{ axis inductances}
\]

\[
R \quad - \quad \text{resistance of the stator windings}
\]

\[
i_q, i_d \quad - \quad q \text{ and } d \text{ axis currents}
\]

\[
v_q, v_d \quad - \quad q \text{ and } d \text{ axis voltages}
\]

\[
\omega_r \quad - \quad \text{angular velocity of the rotor}
\]

\[
\lambda \quad - \quad \text{flux amplitude induced by the permanent magnets in the stator phases}
\]

\[
p \quad - \quad \text{number of pole pairs}
\]

\[
T_e \quad - \quad \text{electromagnetic torque}.
\]

The \( L_d \) and \( L_q \) 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:

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

where \( \theta_r \) represents the electrical angle. Mechanical system for the model is:

\[
\frac{dw_r}{dr} = \frac{1}{J} \left( T_e - Fw_r - T_m \right) \quad (10)
\]

\[
\frac{d\theta_r}{dt} = w_r \quad (11)
\]

where

\[
J \quad - \quad \text{combined inertia of rotor and load}
\]

\[
F \quad - \quad \text{combined viscous friction of rotor and load}
\]

\[
\theta \quad - \quad \text{rotor angular position}
\]

\[
T_m \quad - \quad \text{Shaft mechanical torque}.
\]
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 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) $V_a$, $V_b$, $V_c$ at the Wind Turbine Permanent magnet synchronous generator terminals in pu based on the generator rating.

### Table 1. Design Parameters of PMSG

<table>
<thead>
<tr>
<th>Design Parameters PMSG</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{nom}$ (VA)</td>
<td>$2 \times 10^6$</td>
</tr>
<tr>
<td>$X_d$ (p.u)</td>
<td>1.3050</td>
</tr>
<tr>
<td>$X_q$ (p.u)</td>
<td>0.2520</td>
</tr>
<tr>
<td>$X_q$ (p.u)</td>
<td>0.4740</td>
</tr>
<tr>
<td>$X_q$ (p.u)</td>
<td>0.2430</td>
</tr>
<tr>
<td>$T_d$ (p.u)</td>
<td>0.0681</td>
</tr>
<tr>
<td>$T_q$ (p.u)</td>
<td>0.0513</td>
</tr>
<tr>
<td>$R_e$ (p.u)</td>
<td>0.0060</td>
</tr>
</tbody>
</table>

The control parameters for one turbine, DC Bus Voltage Regulator Gains $K_q$ is 1.1 and $K_v$ is 27.5, Grid Side Converter VAR Regulator gain $[K_e]$ is 0.05, Grid Side Converter Voltage Regulator Gain $[K_u]$ is 2, Grid Side Converter Current Regulator Gains $K_p$ is 1 and $K_v$ is 50, Pitch Controller Gain $[K_p]$ is 15, Pitch Compensation Gains $K_q$ is 1.5 and $K_v$ is 6,

### 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 $I_{gs_{-}ref}$ for the current regulator ($I_{gs} =$ 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 $C_{grid}(V_{dc})$ from the $I_{gs_{-}ref}$ produced by the DC voltage regulator and specified $I_{gs_{-}ref}$ 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 converters data for one turbine of Grid Side Coupling Inductor $L= 0.15$p.u., $R=0.003$p.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 $L=0.0012$H,$R=0.005$Ohm.

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

![Pitch Angle control system](image)

**IV. SIMULATION RESULTS**

All the modeling is done in Matlab Simulink with simulation type discrete having sample time \( 2 \times 10^{-6} \) 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.

![Phasor Voltages at Grid Side Converter](image)

![Phasor Currents at Grid Side Converter](image)

Volatges 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.
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.

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

<table>
<thead>
<tr>
<th>Output Voltage</th>
<th>THD (% Relative to Fundamental)</th>
</tr>
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<tbody>
<tr>
<td>B1</td>
<td>0.32</td>
</tr>
<tr>
<td>B2</td>
<td>0.065</td>
</tr>
<tr>
<td>B3</td>
<td>0.058</td>
</tr>
<tr>
<td>B4</td>
<td>0.01</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Output Current</th>
<th>THD (% Relative to Fundamental)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>4.33</td>
</tr>
<tr>
<td>B2</td>
<td>3.03</td>
</tr>
<tr>
<td>B3</td>
<td>0.09</td>
</tr>
<tr>
<td>B4</td>
<td>0.05</td>
</tr>
</tbody>
</table>
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.

REFERENCES


