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Analysis of Wind Turbine Driven PM Generator with Power Converters

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Abstract— **A Wind Generator System that employs a boost chopper and a permanent magnet synchronous generator is studied. By replacing the main circuit of generator and boost chopper with the equivalent circuit, the power and DC output voltage are obtained as a function of duty ratio of the boost chopper and generator rotational frequency. Maximum power from the generator characterized by the load and optimum duty ratio is theoretically determined. Results of MATLAB/ SIMULINK simulation are presented.**

Index Terms — **PMG, Rectifier, Chopper, Inverter, Wind Turbine**

NOMENCLATURE

ρ - air density
A - area swept by the blades
I_q, I_d – q - axis, d -axis current, respectively
X_q, X_d – Reactance of q -axis , d - axis, respectively
δ – Power Angle
θ – Power Factor Angle
p – Differential Operator (d/dt)
T_e – Electromagnetic Torque produced
V- Velocity of the Wind
λ - Tip Speed Ratio
ω_t –Turbine Speed
T_g – Generator Torque
V_{abc} – Phase Voltages
R_{abc} – Phase Resistances
λ_{abc} – Flux Linkages in the phases
β - Pitch Angle
K_S – Shaft-Compliance Coefficient
G - Gear ratio
C_p- Power Coefficient

I. INTRODUCTION

Consumption of energy based on fossil fuels is considered to be the major factor for global warming and environment degradation. The utilization of naturally occurring renewable energy sources as an alternative energy supply has been assuming more importance of less Power generation utilizing solar rays geothermal energy, wind force and wave force has became a reality.

Research on performance improvement of and cost reduction in such non–conventional energy conversion systems is being accorded the highest priority [7]. Wind power generation has a strong connection to rotating machinery and hence its practical application is most promising .Wind generator control methods have already been proposed to efficiently utilize the wind power which is prone to fluctuation every moment**.** The induction type machine has the advantages of robustness, low cost and maintenance-free operation. However, they have the drawbacks of low power factor and need for an AC excitation source. Permanent magnet generator is chosen so as to eliminate the drawbacks of induction generator. Boost chopper circuit with a single switching device is the choice for power control that provides an improved efficiency [8].

For analysis of the above wind generator system, the generator and boost chopper are represented by their equivalent circuits. Performance characteristics such as generated output power and DC output voltage are expressed as functions of the duty cycle of chopper and shaft speed of generator. The power generated varies with load with the peak occurring at certain load. Therefore, the optimum duty cycle for maximum power can be deduced by differentiating the output power with respect to duty cycle. The validity of the technique for arriving at the maximum power is confirmed in the simulation study. In the present analysis, the value of each part is calculated on the basis of the rotational speed observed by the rotation sensor. Considerations of the characteristics of the wind mill are not necessary, because the torque is a function of the generator speed and characteristics of the wind mill are reflected in the rotational speed [7].

II. COMPONENTS OF WIND ELECTRIC SYSTEMS

The basic components of a wind electric system analyzed herein are shown in Fig 1. A step-up gear box and a suitable coupling connect the wind turbine to the Permanent Magnet Synchronous Generator (PMSG). The generated power of continuously varying frequency is fed to local load through suitable power converters, to ensure constant voltage and constant frequency [4].

Since the wind power fluctuates with wind velocity, the generator output voltage and frequency vary continuously. The varying AC voltage is rectified into DC in a diode bridge and the dc voltage is then regulated to obtain constant voltage by controlling the duty ratio of a DC/DC boost converter. The DC voltage is inverted to get the desired AC voltage and frequency employing a PWM inverter [4]. The duty ratio, δ controls the Boost chopper output voltage.

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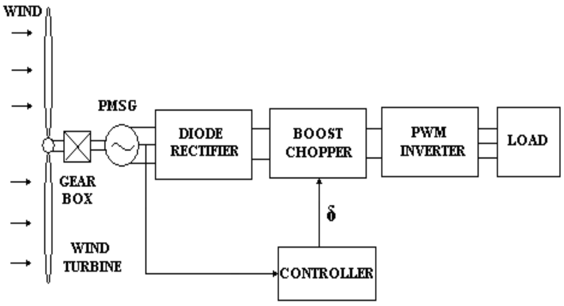

Fig 1. Block diagram of Wind Electric Generator system

can be fed to the power grid directly. A high level of overall efficiency can be achieved, while keeping the mechanical structure of the turbine simple [5].

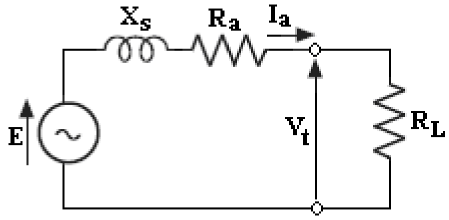

Fig 2. Equivalent circuit PM Generator for one phase

III. Theoretical Analysis

A. *Wind Turbine Model*

There are two types of wind turbines namely vertical axis and horizontal axis types. Horizontal axis wind turbines are preferred due to the advantages of ease in design and lesser cost particularly for higher power ratings [3].

The power captured by the wind turbine is obtained as

$$P=\frac{1}{2}\pi\rho R^3V^2C_p \quad (1)$$

where the power coefficient C_p is a nonlinear function of wind velocity and blade pitch angle and is highly dependent on the constructive features and characteristics of the turbine. It is represented as a function of the tip speed ratio λ given by

$$\lambda=\frac{R\omega_t}{V} \quad (2)$$

It is important to note that the aerodynamic efficiency is maximum at the optimum tip speed ratio. The torque value obtained by dividing the turbine power by turbine speed, is formed obtained as follows:

$$T_t(V,\omega_t)=\frac{1}{2}\pi\rho R^2C_t(\lambda)V^3 \quad (3)$$

where $C_t(\lambda)$ is the torque co-efficient of the turbine, given by

$$C_t(\lambda)=\frac{C_p(\lambda)}{\lambda} \quad (4)$$

The power co-efficient C_p is given by

$$C_p(\lambda)=\left(\frac{116}{\lambda 1}-(0.4*\beta)-5\right)0.5e^{\frac{-16.5}{\lambda 1}} \quad (5)$$

Where

$$\lambda_1=\frac{1}{\left(\frac{1}{(\lambda+0.089\beta)}-\frac{0.035}{\beta^3+1}\right)} \quad (6)$$

B. *Permanent Magnet Generator Model*

Permanent Magnet Generator provides an optimal solution for varying-speed wind turbines, of gearless or single-stage gear configuration[5]. This eliminates the need for separate base frames, gearboxes, couplings, shaft lines, and pre-assembly of the nacelle. The output of the generator

Generated emf / phase ,

$$E=V_t+I_a(R_a+jX_s)=V_t+I_aZ_s \quad (7)$$

where $Z_s=\sqrt{Ra^2+Xs^2}$

The rotor reference frames of the voltages are obtained as The rotor reference frames of the voltages are

$$V_q=-(R_S+L_qp)I_q-\omega_rL_dI_d+\omega_r\lambda_m \quad (8)$$

$$V_d=-(R_S+L_dp)I_d+\omega_rL_qI_q \quad (9)$$

The expression for the electromagnetic (EM) torque in the rotor is given by

$$T_e=\left(\frac{3}{2}\right)\left(\frac{P_n}{2}\right)\left[(L_d-L_q)I_qI_d-\lambda_mI_q\right] \quad (10)$$

The relationship between the angular frequency of the stator voltage (ω_r) and the mechanical angular velocity of the rotor (ω_m) is obtained as follows:

$$\omega_r=\frac{P_n}{2}\omega_mG \quad (11)$$

$$p\omega_r=\frac{P_n}{2J_g}(T_m-T_e) \quad (12)$$

$$p\theta=\omega_r \quad (13)$$

Torque developed by the turbine T_t released to the input to the generator T_m is expressed as

$$T_m=\frac{T_t}{G} \quad (14)$$

C. *Rectifier Model*

A three-phase diode bridge rectifier converts the AC generated output voltage, which will be varying in magnitude and also in frequency, into DC[9].

The average output voltage of the three phase diode rectifier is obtained as follows:

$$V_{dc}=(3*V_m)/\pi \quad (15)$$

and the average and RMS load current are given by:

$$I_{dc}=V_{dc}/R_L \quad (16)$$

$$I_{rms}=V_{rms}/R_L \quad (17)$$

D. Boost Chopper

The conversion of rectified DC voltage to any specified DC output voltage can be carried out employing a DC–DC converter or chopper circuit[9].

The boost chopper output voltage is obtained as

$$V_o=V_s(T/(T-T_{on})) \quad (18)$$

$$V_o=(V_s/(1-\delta)) \quad (19)$$

where δ=Duty ratio of the chopper

E. PWM Inverter Model

For providing electric power to industrial applications in the form of AC, the DC output of Boost Chopper is inverted in a three – phase inverter. Gating signals for PWM Inverter devices are generated employing a Sinusoidal Pulse Width Modulation Technique (SPWM), by comparing a sinusoidal reference signal with a triangular carrier wave. The frequency of reference signal f_r determines the inverter output frequency f_O and its peak amplitude controls the modulation index M and this in turn the rms output voltage, V_O[11].

If δ_m is the width of the m^{th} pulse and p is the number of pulses, then the rms output voltage is obtained as:

$$V_{ac} = V_{in}\left(\sum_{m=1}^{2pul} \frac{\delta_m}{\pi}\right)^{\frac{1}{2}} \quad (20)$$

IV. RESULTS

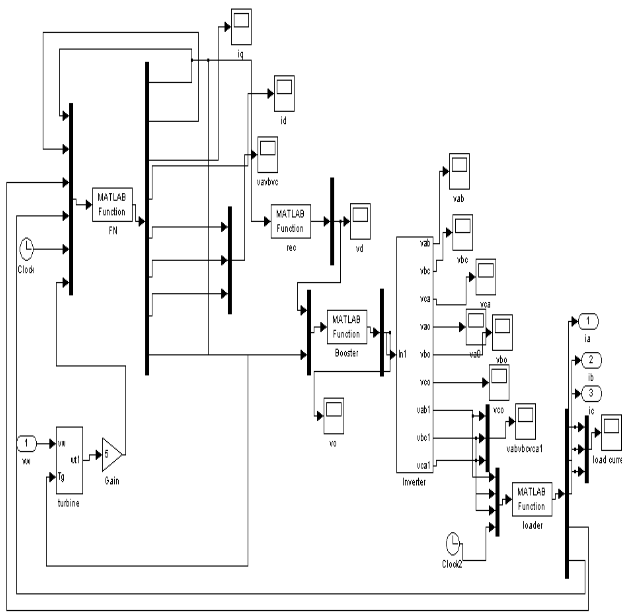

Fig 3.Simulation Model of Wind Generator System

Fig 3. shows the overall simulation model of Wind Electric Conversion System. This model is simulated for various wind velocities, see Fig. 4-to 10

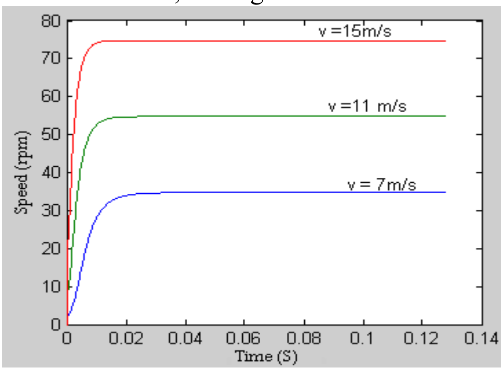

Fig 4. Wind Turbine Speed

Fig 4 shows the wind turbine speed in rpm for different values of wind velocity. Wind turbine reaches the steady state at t=3milliseconds at all wind velocities.

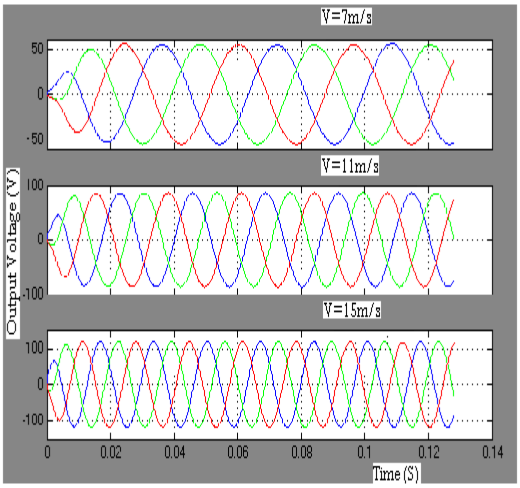

Fig 5. PMSG Output Voltage

Fig.5 shows the Permanent Magnet Generator output voltages for different values of wind velocities. The generated voltage reaches steady state at t=3milliseconds

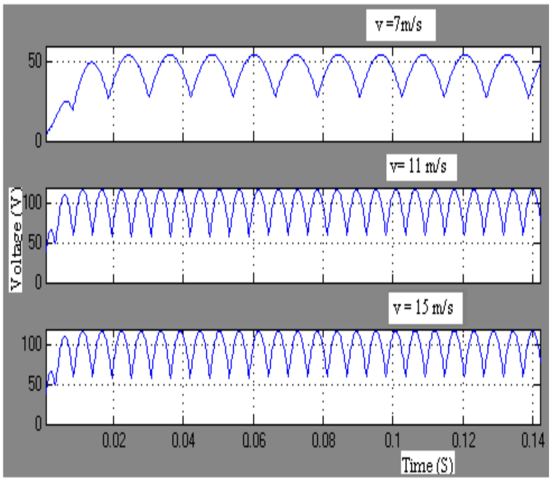

Fig 6. Rectifier Output Voltage

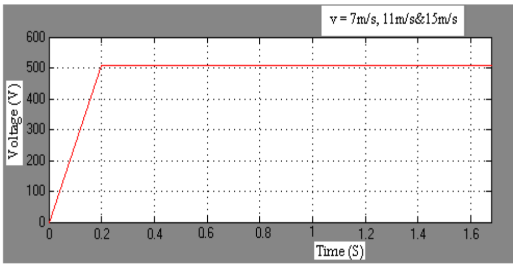

Fig 7 .Boost Chopper Output Voltage

Fig 6 shows the diode rectifier output voltage for various wind velocity. Fig 7 shows the boost chopper output voltage for different values of wind velocity. The chopper output voltage is 508volt constant. This is given to SPWM inverter.

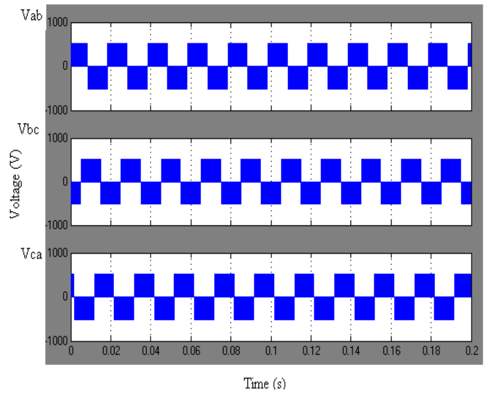

Fig 8. SPWM Inverter Output Voltage

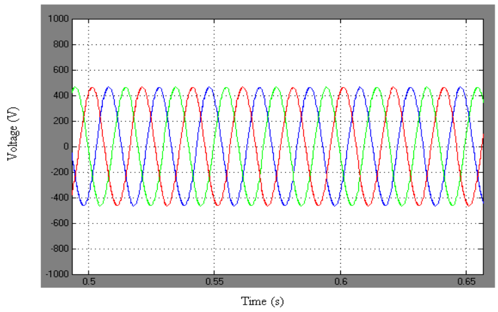

Fig 9 .Sinusoidal Output Voltage of SPWM Inverter

Fig 8 and 9 shows the inverter output voltage of 415Volt AC for different values of wind velocity, this is constant ac voltage is given to load.

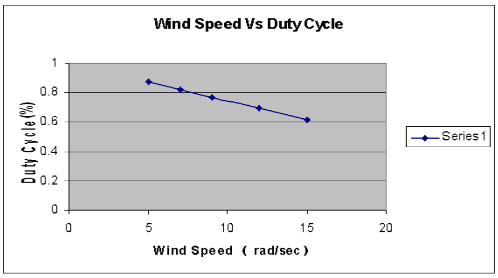

Fig 10. Wind Speed Vs Chopper Duty cycle

Fig 10. shows the Boost chopper Duty ratio for Maintain the dc voltage at desired level for various values of wind velocities

V. Conclusion

The wind turbine driven Permanent Magnet Generator is modeled using MATLAB/SIMULINK tool and analyzed for various input wind velocities. As the wind velocity varies the output voltage of PMSG also varies. The varying voltage is rectified into DC and is stepped up in a boost chopper producing a constant DC voltage irrespective of wind velocities. The constant DC voltage from the chopper is inverted in a Sinusoidal Pulse Width Modulated (SPWM) Inverter to obtain an AC output of constant voltage and constant frequency. Simulation study on a Wind Generated System employing MATLAB/SIMULINK model is the core coverage in this paper.

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