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MATLAB Simulation of Power Electronic Converter for PMSG Based Wind Energy Conversion System

A.Bharathi sankar[1], Dr.R.Seyezhai[2]

Research Scholar, Department of EEE, SSN College of Engineering, Chennai, India [1]

Associate Professor, Department of EEE, SSN College of Engineering, Chennai, India [2]

Abstract: This paper presents the simulation of power electronic converter for Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion System (WECS). The modeling of wind turbine and PMSG is carried out in MATLAB to determine its parameters. An Active Diode clamped multilevel inverter (ADCMLI) with a novel double carrier pulse width modulation (DCPWM) has been proposed for the wind energy system. Performance parameters are evaluated for the proposed converter and the results are verified.

Keywords: Permanent Magnet Synchronous Generator, Wind Energy Conversion System, Active Diode clamped multilevel inverter, double carrier pulse width modulation.

I. INTRODUCTION

Fig.1 shows the schematic representation of a power converter for wind energy conversion system. This paper focuses on the modeling and simulation of variable speed wind turbine coupled with Permanent Magnet Synchronous Generator. The PMSG based WECS can connect to the turbine without using gearbox. This reduces the cost of maintenance and moreover, it will reduce the weight of nacelle [1-3]. Initially, the wind turbine and the PMSG are modelled for extracting its parameter. A suitable AC-DC power converter is designed for wind energy systems. An active diode clamped multilevel inverter has been proposed which solves the unbalanced power loss distribution among the devices that occurs in the conventional diode clamped multilevel inverter. For the proposed MLI, a novel double carrier pulse width modulation technique with inverted sine has been implemented which improves the spectral quality of the output voltage. Simulation studies are carried out in MATLAB/SIMULINK and the results are verified.

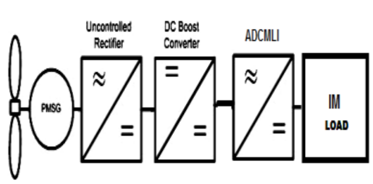

Fig .1 Schematic representation of modelled ADCMLI fed PMSG

II. WIND TURBINE MODEL

Wind turbine is used to convert the wind energy to mechanical torque. The mechanical torque of turbine can be calculated from wind turbine extracted from wind power. The power contained in wind is given by the kinetic energy of the flowing air mass per unit time.

Wind turbine is described by following equation

$$\lambda = \frac{\omega_M R}{V_{wind}} \quad \text{....... (1)}$$

$$P_M = \frac{1}{2} * \rho * \pi * R^2 * C_p * V_{wind}^3 \quad \text{.....(2)}$$

$$P_M = \frac{1}{2} * \rho * \pi * R^2 * C_p * \frac{\omega_m^3}{\lambda^3} \quad \text{........(3)}$$

$$T_m = \frac{P_M}{\omega_M} \quad \text{.......(4)}$$

λ = Tip speed ratio
M= Blade angular speed (mechanical rad/s)
R=blade radius [m]
V_{wind}=Wind speed (m/s)
P_M Mechanical power from the wind blade (KW)
ρ=Air density (kg/m^3)
Cp= Power coefficient
$T_{M=}$ Mechanical torque from wind blade [N/m]
The power coefficient of a wind energy converter is given by

$$C_p = (0.44 - 0.0167\beta)\sin\frac{\pi\,(\lambda-2)}{13-0.3\beta} - 0.00184(\lambda-2)\beta.(5)$$

Where
β is the blade pitch angle. For a fixed pitch type the value of β is set to a constant value.

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Vol. 1, Issue 8, November 2013

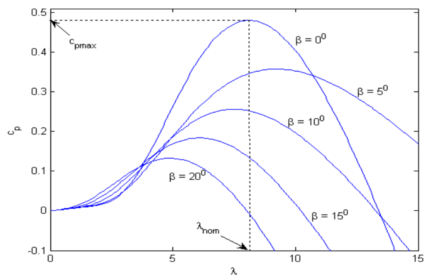


Fig 2. C_p (λ, β) characteristic for different value of the pitch angle.

The cp-λ a characteristic is shown in fig 2, for different values of the pitch angle β, is illustrated below. The maximum value of C_p (C_p max = 0.48) is achieved for β = 0 degree and for λ = 8.1. The value of tip speed ratio is defined as the nominal value (λ nom) [4].Table 1.shows the parameter of wind turbine.

Table 1.Parameter of Wind Turbine

Base power	1 KW
Base wind speed	8 m/s
Max power at base wind speed pu	0.73
Base rotational speed pu	1.2

The torque developed by the wind turbine depends on the wind velocity as shown in Figures 3 & 4. The power captured by the wind turbine is maximum when the wind velocity is 4 m/s to 16 m/s.

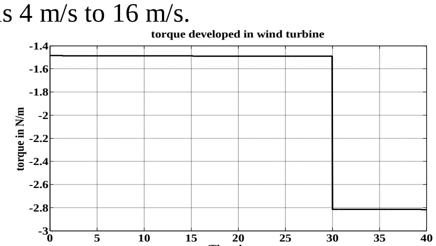


Fig .3: Generated torque

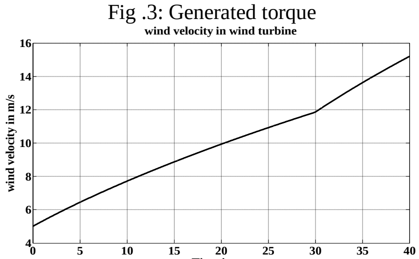
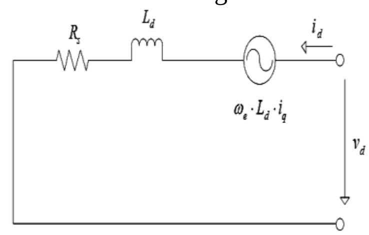


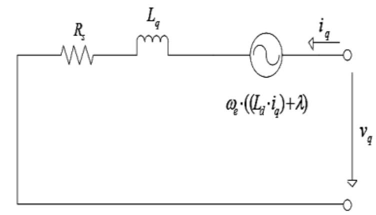
Fig .4: Wind velocity for Wind Turbine

III. PERMANENT MAGNET SYNCHRONOUS GENERATOR

This paper presents the dynamic model of permanent magnet synchronous generator based on wind energy conversion system. The Mat lab/Simulink provides a fully developed Permanent Magnet Synchronous Generator model, which is based on generalized machine theory. The Permanent Magnet Synchronous Generator is a direct drive type with low speed and a high number of poles, the wind turbine and the generator are rotating at the same mechanical speed via the same shaft [5]. Consider the equivalent circuit of PMSG based on WECS in Figure.5. The modeling of PMSG is established in the *d-q* synchronous reference frame equivalent circuit as shown in Fig 5A & 5B respectively.



5A. d – axis equivalent circuit



5B. q – axis equivalent circuit

Fig .5 Equivalent circuit of PMSG in *d-q* reference frame.

The voltage and torque equations of PMSG are given by

$$\frac{d}{dt} * i_d = \frac{1}{L_d} * v_d - \frac{R}{L_d} * i_d + \frac{L_q}{L_d} * p\omega_r i_q \quad \ldots\ldots. (6)$$

$$\frac{d}{dt} * i_q = \frac{1}{L_q} * v_q - \frac{R}{L_q} * i_q - \frac{L_d}{L_q} * p\omega_r i_q - \frac{\lambda p \omega_r}{L_q} \quad \ldots(7)$$

$$T_e = 1.5\, \rho\, [\lambda i_q + (L_d - L_q)\, i_d\, i_q] \quad \ldots\ldots. (8)$$

Where

L_q = q axis inductance
L_d = d axis inductance
R = resistance of the stator windings
I_q = q axis current
I_d = d axis current
V_q = q axis voltage
V_d= d axis voltage
ω_r = angular velocity of the rotor
λ= amplitude of flux induced
P = the number of pole pairs
The dynamic equations are given by

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m) \quad \ldots\ldots\ldots (9)$$

$$\frac{d}{dt}\theta = \omega_r \quad \ldots\ldots\ldots (10)$$

Where

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Vol. 1, Issue 8, November 2013

J = inertia of rotor
F = friction of rotor
θ = rotor angular

Table 2.PMSG PARAMETERS

Line-line rated voltage	24 Volts
Rated power	1KW
Supply frequency	50 Hz
D-axis inductance	3.21mH
Q-axis inductance	0.971mH
Stator leakage inductance	0.308 mH
Stator resistance	2.90 mΩ

Table.2 shows the parameter of PMSG. The simulation result of the constant output power at variable wind speed is simulated. The output of wind energy system generated voltage and generated current is shown in Figure 6 and 7 respectively.

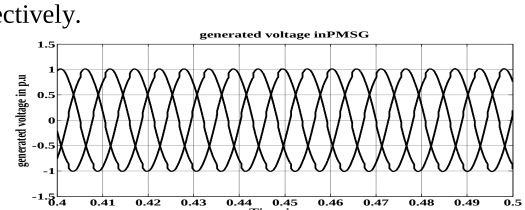

Fig.6.Generated voltage for PMSG

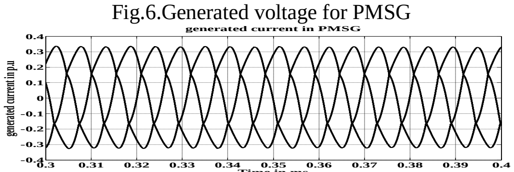

Fig .7.Generated current for PMSG

The power developed from the PMSG based wind energy conversion system is a voltage of 24V,1KW,50Hz then voltage is stepped up to a 50V,50Hz and the generated rectified output voltage is obtained 50V DC is shown in Figure 8.

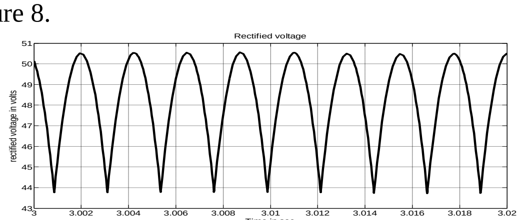

Fig .8.Rectified voltage for PMSG

IV. DC - DC BOOST CONVERTER

The step-up dc-dc converter is known as boost converter. It's mainly used to the regulated dc power supplies. The average output voltage of converter is always greater than the input voltage. The output voltage of converter is controlled by the switching duty cycle. When the switch is ON condition, the diode is reverse biased, and hence isolates the output stage of converter. During the switch ON condition the inductor gets the energy from the source and stores it. During switch OFF condition, the diode is forward biased and the output side receives the energy from the inductor as well as the input. Thus the energy transferred to the output from input is always greater in a given switching cycle. The ratio of output voltage to input voltage is given by

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} = \frac{I_o}{I_{in}} \qquad \text{……….. (11)}$$

Where, V_o and V_{in} are the output and input voltages, respectively. The term I_o and I_{in} are the output and input current, respectively. The term D is the duty ratio and defined as the ratio of the on time of the switch to the total switching period.

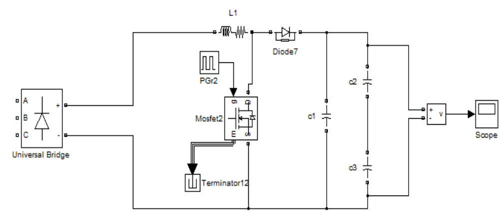

Fig 9. Simulink model for DC-DC boost converter

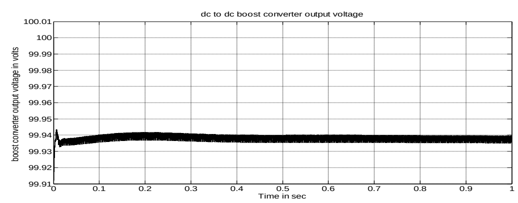

Fig 10. DC-DC boost converter output voltage

The Simulink model of DC- DC boost converter shown in Figure 9.The generated rectified output voltage is obtained 50V DC, then voltage is boosted up to a 100V DC is shown in figure 10. DC – DC boost converter parameter of V_{in}- 50 V, V_{out} – 100V, Duty ratio D= 50%, Switching frequency f_s- 100 KHz

V. OPERATIONS OF ACTIVE DIODE CLAMPED MULTILEVEL INVERTER

A three- level active diode clamped multilevel inverter is shown in Figure 11 and the output voltage is depicted in Figure 12.An m-level inverter leg requires 2(m-1) switching devices and (m-1) (m-2) clamping switches. For a three-level inverter, (m=3), it needs four switching devices and two clamping switches per leg as shown in Figure 11 [6 - 8].

1. For an output voltage of $V_o = V_{dc}$, all the upper-half switches of a phase leg are turned on, i.e., T_1, T_2 and T_6 are on.
2. For output voltage of $V_o = V_{dc/2}$, all the lower-half switches of a phase leg are turned on, i.e., T_3, T_4 and T_5 are on.

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Vol. 1, Issue 8, November 2013

3. For output voltage of $V_o = 0$, only T_1, T_3 and T_6 are on.

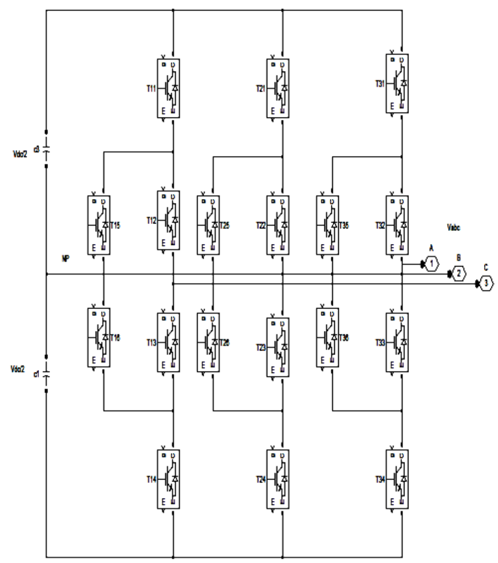

Fig .11: Three Level active diode clamped inverter

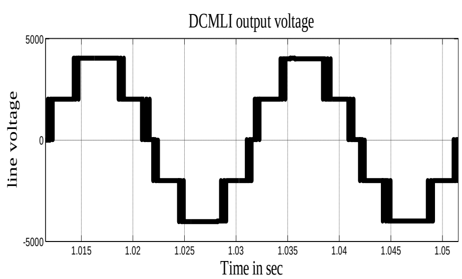

Fig .12: Output voltage waveform of ADCMLI

Table 3 shows the switching sequence of the proposed ADCMLI. State "1" means the switch is on and state "0" means the switch is off. It should be noticed that there are two complementary switch pairs. These switch pairs for single leg of the inverter are (T_1, T2, T6) & (T_3, T4, T_5).Thus, if one of the complementary switch pairs is turned on state, the other of the same pairs must be off state. Two switches are always turned on at the same time.

Table 3: Conduction table for ADCMLI

Voltage level	T_1	T_2	T_3	T_4	T_5	T_6
Vdc	1	1	0	0	0	1
V dc/2	0	0	1	1	1	0
zero	1	0	1	0	0	1

VI. ANALYSIS OF MODULATION STRATEGIES FOR ADCMLI

The performance of an inverter is mainly decided by the control strategies as it is related to the harmonic contents of the output voltage. Many control methods exists in the literature [9-17], but this paper insists on a novel double carrier PWM technique which is compared with that of the conventional multicarrier technique. The performance of the inverter is investigated and the parameters are calculated for the proposed PWM technique and compared with multicarrier to show the effectiveness of the proposed technique.

A. MODULATION STRATEGY FOR DOUBLE CARRIER PHASE DISPOSITION PWM

The proposed double carrier modulation makes it possible to change the modulation index for each level of the inverter to control the balance of each DC voltage and also can reduce the higher harmonics as same as sinusoidal modulation. To decrease the switching loss, the modulation signal should be kept at zero or more than one as long as possible. The least number of the switching actions is achieved by this method. The reference and carrier waveform is shown in Figure 13. The signal waveforms can satisfy the minimum switching condition. However, it is possible to change the charge/discharge current of each level without changing the total modulation index. The gating patterns of switches are shown in Figure 14. The offset of the two modulation signals for the lower and the higher voltage level are controlled. The control of the offset results in the control of the charging/discharging current. It is also noticed that the switching of lower level during the higher voltage level switching occurs, and this fact causes the increase of total switching loss. The positive signal will be compared to the upper triangular signal, while the negative signal will be compared with the lower triangular signal. By adding some offset signals to the new signals the DC-bus can be controlled. The reduction of the switching loss compared with the double sinusoidal modulation signal may be half of the conventional one [18- 20].

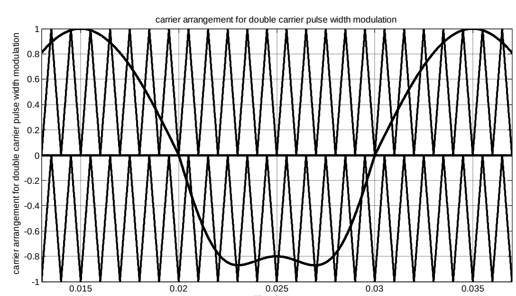

Fig.13 Carrier arrangements for double carrier PWM strategy

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Vol. 1, Issue 8, November 2013

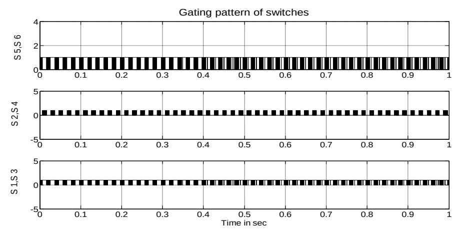

Fig .14 Gating patterns of switches

VII. SIMULINK MODEL FOR ADCMLI FOR PMSG

The Simulink model of the proposed ADCMLI for PMSG system is shown in Figure 15.The effectiveness of the proposed method is demonstrated through simulation results. The generated rectified voltage obtained is 50V DC and the multilevel inverter output obtained is 100V AC which is shown in Figures 16. The output from the wind turbine is a variable one. In order to obtain constant voltage and frequency, a three-level ADCMLI is used and it reduces the harmonic contents in the voltage compared to that of the conventional diode clamped inverter.

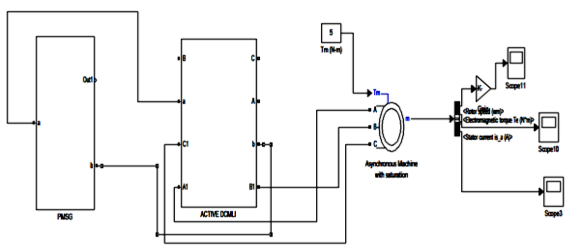

Fig .15 Simulink model of the Proposed ADCMLI for PMSG System

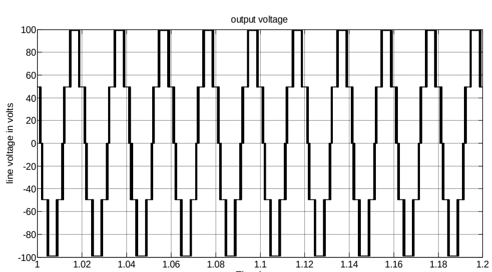

Fig.16.Output line to line voltage for PMSG

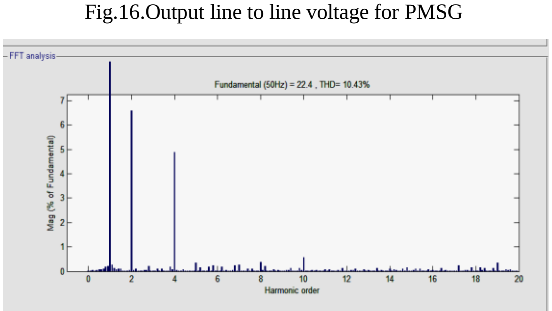

Fig .17: line to line voltage THD of variable frequency PWM technique for Active DCMLI

It shows in fig 17 the Active DCMLI multilevel inverter output line to line voltage total harmonic distortion is obtained the value of 10.43 %

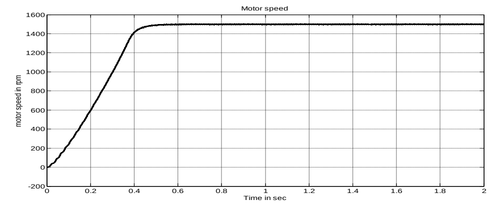

Fig .18: Rotor speed for Induction motor

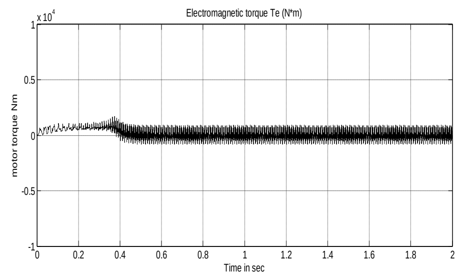

Fig .19: Motor torque for Induction motor

The output of the inverter is used to feed Induction Motor of rating 4HP, 400V, 50Hz. The performance (rotor speed & electromagnetic torque) of induction motor is shown in Figures 18 & 19 respectively.

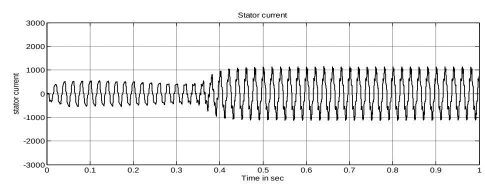

Fig .20: Stator current for Induction motor

Figure 20 shows the proposed ADCMLI for variable frequency double carrier PWM technique has been reduced in the stator current T.H.D compare to the conventional PWM technique

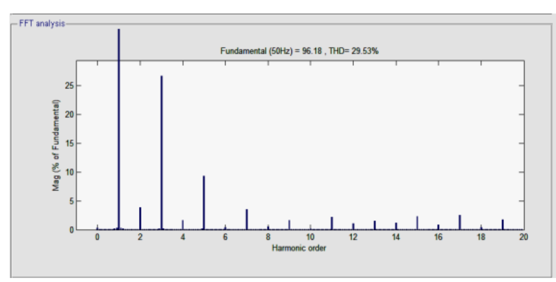

Fig .21: Stator current THD of variable frequency PWM technique for Active DCMLI

It shows in fig 21 the Active DCMLI multilevel inverter stator current total harmonic distortion is obtained the value of 29.53 %

VIII. POWER DEVELOPED FROM PMSG

The power developed in the wind turbine depends on wind velocity. Thus the power captured by the wind turbine is the cubic function of wind speed. The maximum power

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Vol. 1, Issue 8, November 2013

extracted from wind turbine generator is 1 KW at a wind speed of 8 m/s and the real, reactive power is shown in Figures 22 and 23. Thus the output power of PMSG is uniquely determined by its operating speed. Wind speed changes do not affect the value of reactive power produced by generator.

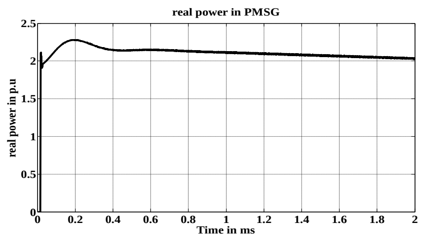

Fig .22 Real power for PMSG

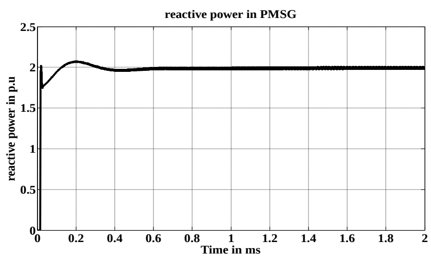

Fig .23 Rective power for PMSG

IX. CONCLUSION

Simulation studies and modeling for PMSG based wind energy conversion system for stand-alone application has been presented. A power electronic interface comprising an Active Diode clamped multilevel inverter is used to maintain the DC bus voltage constant for different wind velocities and to extract maximum power from the wind and the unwanted higher order harmonics are reduced and generated reactive power is also controlled in the proposed PMSG based wind energy conversion system. Therefore, the effective use of PMSG based wind energy conversion system results in better performance which is well suited for wind energy systems.

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