

# Power Regulation of PMSG fed Grid Connected Matrix Converter

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**Abstract:** This paper presents the Modelling and simulation of variable speed wind turbine driven permanent magnet synchronous generator (PMSG) connected to grid through matrix converter (MC). MC is used to convert three phase ac variable frequency variable rotor voltages into constant frequency ac voltage. Modelling of PMSG is done using its dynamic equations and then MC is integrated for the direct conversion to constant frequency, variable voltage output. A normal voltage oriented vector control approach with proportional and integral (PI) is employed to track the maximum power from wind and regulate the active and reactive power injected into the power grid. Simulation results obtained using MATLAB /Simulink prove the performance of the proposed system for different generator output powers.

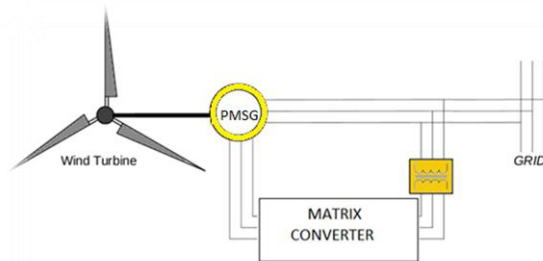
**IndexTerms**—wind turbine; permanent magnet synchronous generator; Matrix Converter; Mathematical model.

## I. INTRODUCTION

With the development of wind power generation the green energy trend is being projected and flourished globally. Increased amount of electricity produced from variable speed wind electrical systems (VSWES) is one of the ways to reach the goal of lowering emissions of greenhouse gases from energy production. To capture large energy from the wind, variable speed wind power generation enables operation of the turbine at its maximum power coefficient over a wide range of wind speeds [1]. These variable speed wind electrical systems (VSWES) are usually based on doubly fed induction generators (DFIGs) or permanent magnet synchronous generators (PMSGs) [2, 3]. PMSGs are favored in VSWES because of small size, simplicity of construction, low cost of maintenance, availability of high efficiency and no requirement of any extra dc source for excitation of magnetic field for synchronizing purpose to obtain unity power factor. It has better voltage and power capabilities. Also, it does not require brushes and slip rings which increase the maintenance work and cost too [6]. Electricity generated by PMSG has variable amplitude and frequency, unable to connect to the grid. In [4], the control strategy for the generator side converter to extract maximum power is discussed.

A matrix converter (MC) is used for direct ac-ac power conversion without the need for an intermediate dc link. It is also known as forced commutated ac converter [5]. MC uses an array of controlled bi-directional semiconductor switches as the main power circuit and converts ac input voltage into variable ac voltage with unrestricted output frequency. The output can be supplied to any load that requires variable voltage with variable frequencies such as to drive an induction motor and the permanent magnet synchronous motor. This topology can be used in the fields of industrial AC motor drives, in a marine application, in a military application especially for military vehicles, in an aerospace application. The control pulses for the converter are developed in Matlab. The proposed modulation technique for matrix converter is Venturini Modulation.

The paper is organized as follows: section II deals with the modelling and simulation of VSWES with MC. Section III presents Power regulation with gain scheduled PI controllers. Section IV presents simulation results and discussions. Section V outlines the conclusions.



**Fig-1: Block diagram of wind energy conversion system**

## II. I. MODELLING OF WIND TURBINE

The steady-state model of the wind turbine developed in [7, 8] is adopted in this work and is given as follows

$$P_m = c_p(\lambda, \beta_p) \frac{\rho A}{2} v_w^3 \quad (1)$$

Where  $P_m$  mechanical power of the turbine (W) is,  $C_p$  is the performance coefficient of the turbine,  $\rho$  is the air density (kg/m<sup>3</sup>),  $A$  is the turbine swept area (m<sup>2</sup>),  $\lambda$  is the tip speed ratio,  $\beta_p$  is the pitch angle and  $v_w$  is the wind speed (m/s).

$$c_p(\lambda, \beta_p) = c_1 \left( \frac{c_2}{\lambda_i} - c_3 \beta_p - c_4 \right) e^{(-c_5/\lambda_i)} + c_6 \lambda; \quad (2)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta_p} - \frac{0.035}{\beta_p^3 + 1}$$

The mechanical torque  $T_m$ , the developed torque  $T_e$  and the rotational speed  $\omega_m$  are given in the following equations

$$T_m = \frac{P_m}{\omega_m}; \quad T_e = \frac{P_e}{\omega_e} \quad (3)$$

$$\omega_m = \int \frac{\omega_e - T_e}{J} dt \quad (4)$$

Where  $J$  is the moment of inertia (kg m<sup>2</sup>),  $P_e$  is the electrical power,  $P_m$  is the mechanical power and  $\omega_e$  is the electrical speed of the rotor.

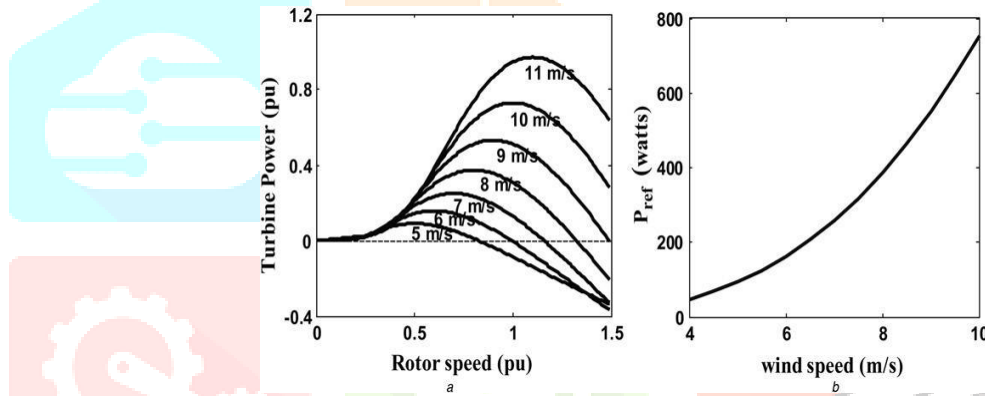


Fig-2.1: Power coefficient curves versus tip speed ratio

## II. II. MODELLING OF PMSG

The mathematical d-q model for PMSG is obtained by using its dynamic equations [3] as follows:

$$i_d R_s - v_d = -L_d \frac{di_d}{dt} + \omega_r L_q i_q \quad (5)$$

$$i_q R_s - v_q = -L_q \frac{di_q}{dt} + \omega_r (L_d i_q + \psi_{pm1}) \quad (6)$$

Where  $v_d$  and  $v_q$  are d-q axis voltages,  $i_d$  and  $i_q$  are d-q axis currents,  $R_s$  is the stator resistance,  $L_d$  and  $L_q$  are the d-q axis inductances,  $\omega_r$  is the generator rotational speed,  $\psi_{pm1}$  is the permanent magnetic flux.

The electromagnetic torque of PMSG is given as follows

$$T_e = \frac{3}{2} P_{iq} [(L_d - L_q) i_d] \quad (7)$$

Where  $P$  is number of pole pairs.

The above equations are transformed into d-q frame and 'd' and 'q'-axis voltages are given as follows

$$v_d = L_d \frac{di_d}{dt} - \omega_r L_q i_q + i_d R_s \quad (8)$$

$$v_q = L_q \frac{di_q}{dt} - \omega_r (L_d i_q + \psi_{pm1}) + i_q R_s \quad (9)$$

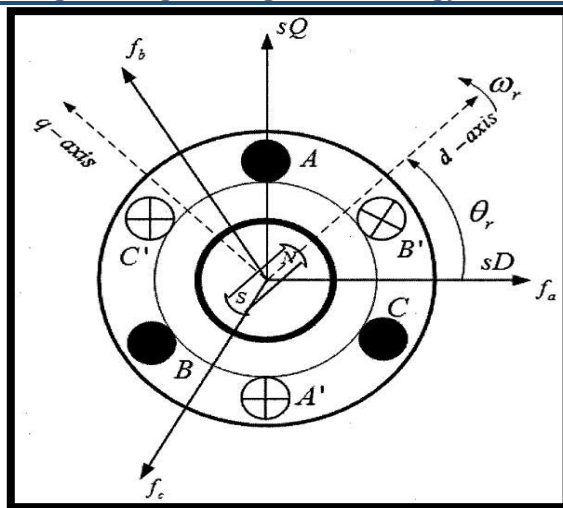


Fig-2.2: Cross-section view of PMSG

## II. III. MODELLING OF MC USING VENTURINI ALGORITHM

The MC is a single stage converter, which has an array of  $m \times n$  bi-directional power switches to connect directly an m-phase voltage source to an n-phase load. The bi-directional switches connect any of the input phases A, B, C to any of the output phases a, b, c, as shown in Fig.2.3. The switches are controlled in such a way that the output voltage is a sinusoid of desired frequency with desired amplitude.

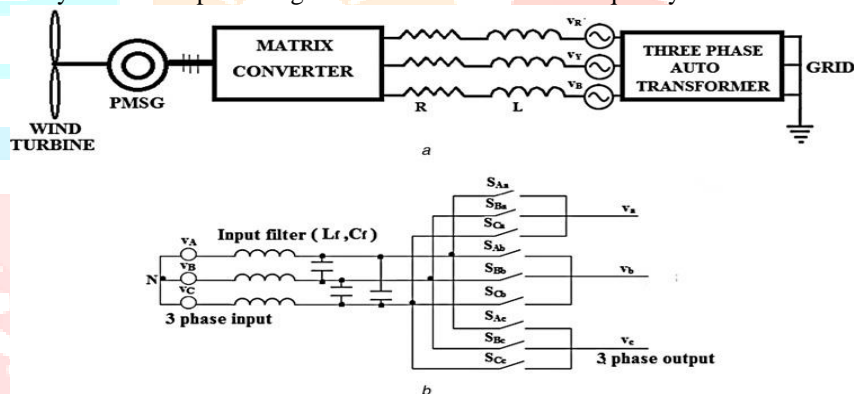


Fig-2.3: VSWES with MC

The three-phase input voltages  $v_i(t)$  of the converter are given as follows

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} V_{im} \cos \omega_i t \\ V_{im} \cos \left( \omega_i t - \frac{2\pi}{3} \right) \\ V_{im} \cos \left( \omega_i t - \frac{4\pi}{3} \right) \end{bmatrix} \quad (10)$$

The desired output voltages  $v_o(t)$  of the converter are given as follows

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} V_{om} \cos \omega_o t \\ V_{om} \cos \left( \omega_o t - \frac{2\pi}{3} \right) \\ V_{om} \cos \left( \omega_o t - \frac{4\pi}{3} \right) \end{bmatrix} \quad (11)$$

Where  $\omega_i$ ,  $V_{im}$  and  $\omega_o$ ,  $V_{om}$  are the frequency and peak value of input and output voltages of the MC, respectively. The relationship between the output and the input voltage vectors is given as follows

$$v_o(t) = M(t)v_i(t) \quad (12)$$

Where  $M(t)$  is the transfer matrix and is given as follows

$$M(t) = \begin{bmatrix} M_{Aa} & M_{Ba} & M_{Ca} \\ M_{Ab} & M_{Bb} & M_{Cb} \\ M_{Ac} & M_{Bc} & M_{Cc} \end{bmatrix} \quad (13)$$

Here  $M_{ij} = (t_{ij}/T_s)$ ;  $\{i = A, B, C \text{ and } j = a, b, c\}$  is the duty cycle and  $t_{ij}$  is the 'on' time of the switch  $S_{ij}$ .  $T_s$  is the sampling period. The relationship between input current vector  $i_i(t)$  and output current vector  $i_o(t)$  is given as follows

$$i_i(t) = M^T i_o(t) \quad (14)$$

Duty cycles must satisfy the conditions given in (15), in order to avoid short circuit on the input side

$$M_{Aa} + M_{Ba} + M_{Ca} = 1; M_{Ab} + M_{Bb} + M_{Cb} = 1;$$

$$M_{Ac} + M_{Bc} + M_{Cc} = 1 \quad (15)$$

Since the switches are to be controlled using PWM technique, the duty ratios of the switches are generated by modulating the desired MC output voltages of variable amplitude with grid frequency with their respective switching functions[9]. The generated duty ratios are given as follows

$$M_{Aa} = \frac{1}{3} [1 + 2q_v \cos(\omega_m t + \theta)];$$

$$M_{Ba} = \frac{1}{3} \left[ 1 + 2q_v \cos \left( \omega_m t + \theta - \frac{2\pi}{3} \right) \right]$$

$$M_{Ca} = \frac{1}{3} \left[ 1 + 2q_v \cos \left( \omega_m t + \theta - \frac{4\pi}{3} \right) \right];$$

$$M_{Ab} = \frac{1}{3} \left[ 1 + 2q_v \cos \left( \omega_m t + \theta - \frac{4\pi}{3} \right) \right]$$

$$M_{Bb} = \frac{1}{3} [1 + 2q_v \cos(\omega_m t + \theta)];$$

$$M_{Cb} = \frac{1}{3} \left[ 1 + 2q_v \cos \left( \omega_m t + \theta - \frac{2\pi}{3} \right) \right]$$

$$M_{Ac} = \frac{1}{3} [1 + 2q_v \cos(\omega_m t + \theta)];$$

$$M_{Bc} = \frac{1}{3} \left[ 1 + 2q_v \cos \left( \omega_m t + \theta - \frac{4\pi}{3} \right) \right]$$

$$M_{Cc} = \frac{1}{3} [1 + 2q_v \cos(\omega_m t + \theta)] \quad (16)$$

where  $q_v$  is the voltage gain  $= (V_{om}/V_{im})$ ,  $V_{om}$  is the peak value of output voltage,  $V_{im}$  is the peak value of input voltage,  $\omega_m = \omega_o - \omega_r$

In this study the pitch angle  $\beta_p$  for wind turbine is set as zero to obtain maximum  $C_p$ , the PMSG efficiency is set as 0.9. The MC is connected to grid through three-phase auto-transformer with the secondary voltages are set at 20 V peak in each phase and the same acts as ac sink load ( $V_{RYB}$ ). The resistance and inductance of the transformer circuit are  $R = 0.4 \Omega$ ,  $L = 0.5 \text{ mH}$ . The parameters of PMSG used in this work are given in Appendix 1. For wind speeds from 4 to 10 m/s the wind generator has been simulated and power curves obtained are shown at Fig. 2.1a. From the power curves, the maximum power output of the generator for different ' $v_w$ ' has been computed. This data is used to relate the  $P_{max}$  to ' $v_w$ ' using polynomial curve fit [10] given as follows

$$P_{max} = -3 + 1.08v_w - 0.125v_w^2 + 0.842v_w^3 \quad (17)$$

The maximum power that can be supplied by PMSG to grid is set as  $P_{ref}$  which is related with  $P_{max}$  as follows

$$P_{ref} = \eta_g P_{max} \quad (18)$$

Where  $\eta_g$  is the efficiency of the generator. The reference power for each wind speed is obtained from (17), (18) and plotted in Fig. 2.1b.

**III. POWER REGULATION****III.I. VOC SCHEME TO REGULATE ACTIVE AND REACTIVE POWER**

The control objective is to track and extract maximum power from the VSWG and to transfer the same to ac sink load. The control scheme to regulate power flow is shown in Fig. 3. The output voltages from MC,  $v_a$ ,  $v_b$ ,  $v_c$  are controlled by VOC for their magnitudes and phase shift from the supply to meet the required flow of active and reactive powers. The ac sink voltages  $v_R$ ,  $v_Y$ ,  $v_B$  are transformed into  $d^e - q^e$  by the synchronously rotating reference frame transformation and given as follows

$$v_{ds}^e = \frac{2}{3} \left[ v_R \cos \theta_e + v_Y \cos \left( \theta_e - \frac{2\pi}{3} \right) + v_B \cos \left( \theta_e + \frac{2\pi}{3} \right) \right] \quad (19)$$

$$v_{qs}^e = \frac{2}{3} \left[ v_R \sin \theta_e + v_Y \sin \left( \theta_e - \frac{2\pi}{3} \right) + v_B \sin \left( \theta_e + \frac{2\pi}{3} \right) \right] \quad (20)$$

Similarly  $i_{ds}^e$ ,  $i_{qs}^e$  are also calculated. As the  $d^e$ -axis of the synchronously rotating reference frame is aligned along the ac sink voltage vector, the angular position of the  $d^e$ -axis is computed as follows

$$\theta_e = \arctan \frac{v_{qs}^e}{v_{ds}^e} \quad (21)$$

Where  $v_{ds}^s$ ,  $v_{qs}^s$  are obtained by transforming  $v_R, v_Y, v_B$  into stationary reference frame.

The voltage equations for feeder inductors are given as follows

$$v_{ds}^e = R i_d^e + L \frac{di_d^e}{dt} - \omega L i_q^e + v_{dl}^e \quad (22)$$

$$v_{qs}^e = R i_q^e + L \frac{di_q^e}{dt} - \omega L i_d^e + v_{ql}^e \quad (23)$$

where  $v_{dl}^e$  and  $v_{ql}^e$  are MC output voltages along the  $d^e$ - and  $q^e$ -axis, respectively,  $R$ ,  $L$  are resistance and inductance of the auto-transformer. The actual active power ( $P_s$ ) and reactive volt ampere ( $Q_s$ ) flowing through the grid are computed using the following equations

$$P_s = v_{ds}^e i_{ds}^e + v_{qs}^e i_{qs}^e \quad (24)$$

$$Q_s = v_{qs}^e i_{qs}^e - v_{ds}^e i_{ds}^e \quad (25)$$

These powers are compared with the reference values  $P_s^*$  and  $Q_s^*$  to generate the reference values of the MC phase voltages  $v_{dl}^{e*}$ ,  $v_{ql}^{e*}$  and in accordance with equations (22), and (23). The  $v_{dl}^{e*}$  and  $v_{ql}^{e*}$  are again transformed to  $v_{abc}$ , which will become the modulating reference voltage for MC to fix the voltage gain  $q_v$  [12]. The power flows through the ac voltage sink load can be written as follows

$$P_s = -3 \frac{v_{abc} v_{RYB}}{X_L} \sin \delta \quad (26)$$

Where  $\delta$  is the angle between MC terminal voltages  $v_{abc}$  and ac voltage sink  $v_{RYB}$ . When  $\delta = 90^\circ$  the maximum power is drawn by ac voltage sink from MC with unity power factor. Hence the MC output currents  $i_a, i_b, i_c$  (flowing through ac sink load) are in phase with  $v_R, v_Y, v_B$ , respectively [11].

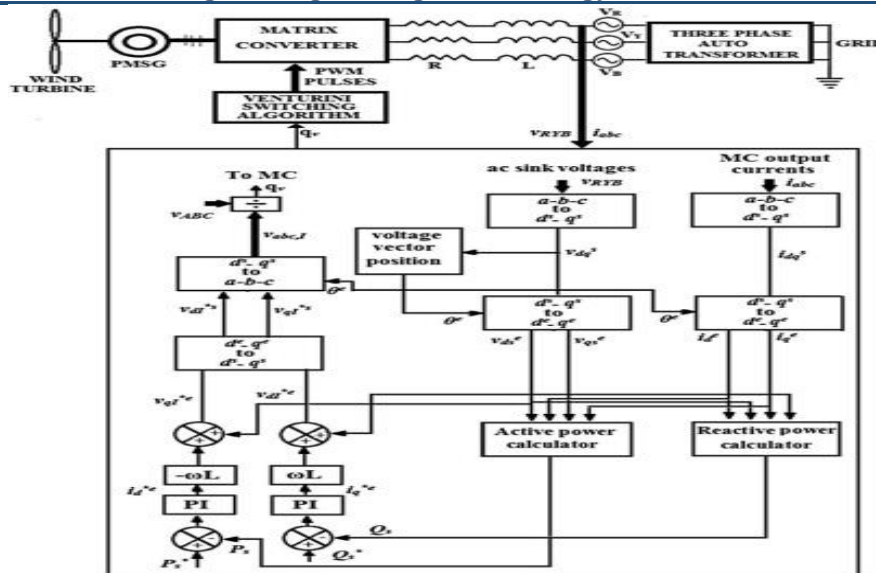


Fig-3. Control scheme to regulate power flow

### III. II SYSTEM WITH GAIN SCHEDULED PI CONTROLLERS

During closed-loop power flow regulation with VOC, using (17), and (18) the maximum reference power according to the variation of the wind speed is calculated, and the reactive volt ampere is set as zero. The actual real and reactive powers calculated from (24), and (25) are compared with reference active and reactive powers. PI controllers are used to process the active and reactive power error  $e_p$ ,  $e_q$  as given in (27)–(29). These controllers generate d-, q-axes current references  $i_d^e$ ,  $i_q^e$

$$e_p = P_s^* - P_s; \quad e_q = Q_s^* - Q_s \quad (27)$$

$$i_d^e = k_p e_p(t) + k_i \int e_p(t) dt \quad (28)$$

$$i_q^e = k_p e_q(t) + k_i \int e_q(t) dt \quad (29)$$

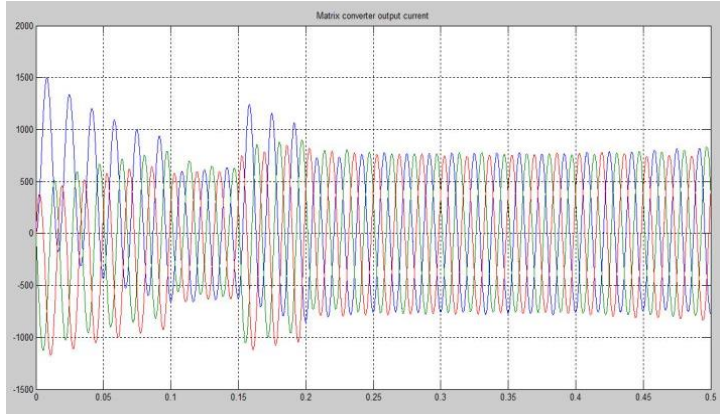
Where  $P_s^* - P_{ref}$ ,  $Q_s^* - Q_{ref}$ ,  $P_s$  is the actual active power,  $Q_s$  is the actual reactive power,  $k_p$  is the proportional gain and  $k_i$  is the integral gain.

The reference currents are then processed through proportional controllers to generate 'd'- and 'q'-axes reference voltages  $v_{d1}^e$ ,  $v_{q1}^e$  which are transformed into 'abc' coordinates as  $v_{abc,1}$ , the new voltage gain ( $q_v$ ) MC terminal voltage which in turn set the new voltage gain ( $q_v$ ) to MC. Thus the MC gives the corresponding output voltage with appropriate phase shift according to new  $q_v$ .

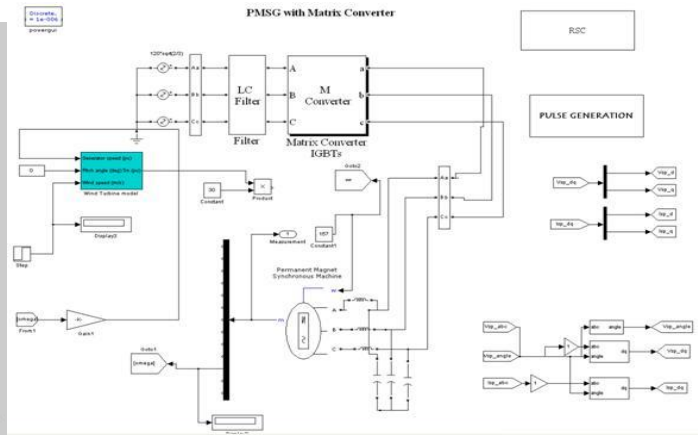
From (17) and Figs. 2.1a and b, it is understood that the relationship between maximum power from wind and wind speed ' $v_w$ ' is non-linear. Hence a single PI controller does not serve the purpose for all wind speeds. It is required to design separate PI controller parameters for each  $P_{ref}$ . In order to extract maximum power for the entire operating range of wind speeds, gain scheduling of the controller parameters is required which has been implemented here as shown in Fig.4a. According to  $P_{ref}$  range, the gain scheduler adjusts corresponding PI controller parameters  $K_p$ ,  $K_i$  to the controller. The reactive power reference  $Q_{ref}$  is set as zero. Since the  $Q_{ref}$  is constant, single PI controller is insufficient for reactive power control. The closed-loop response of VSWES with PMSG, MC incorporated in power regulation scheme is studied and simulated using Matlab-simulink for each wind speed with gain scheduled PI controllers.



#### IV. SIMULATION RESULTS

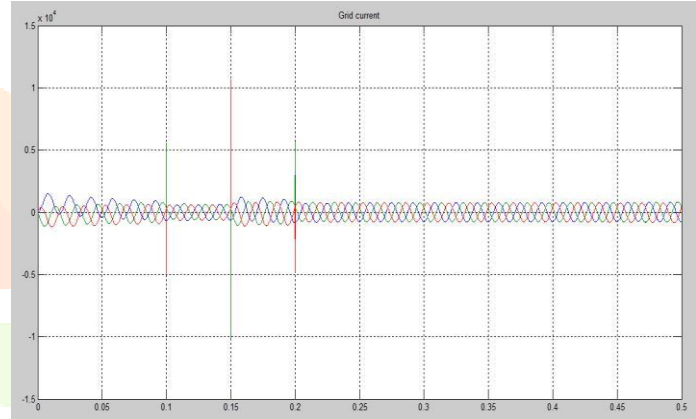
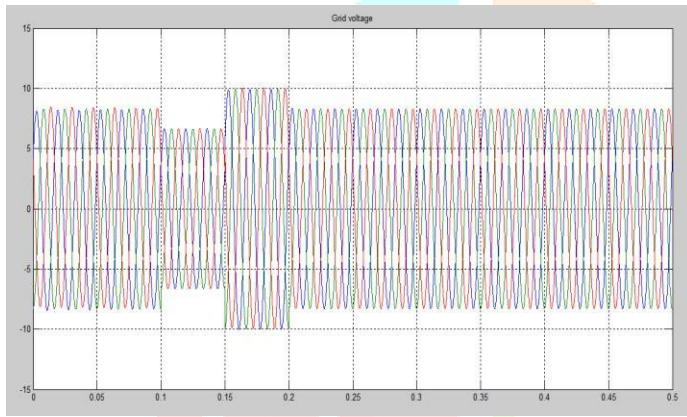


**Fig-4.1: SIMULINK modeling of matrix converter with PMSG**



**Fig-4.2: Output Voltage waveform of Matrix Converter**

The Simulation is done for various wind speeds ranging from cut-in speed of 5m/sec to 8m/sec. For different speeds, variable frequency, variable voltage is obtained and the PMSG interfaced with the MC is connected with the grid with  $R=10\Omega$ ,  $L=1\text{mH}$ ,  $E=10\text{V}$ .



**Fig-4.3: Voltage waveform of Grid connected to wind energy system**  
**Fig-4.4: Current waveform of Grid connected to wind energy system**

The final output waveform is getting in the figure 4.3&4.4 respectively as well as the performance of wind turbine is shown in figure 4.5&4.6 respectively.

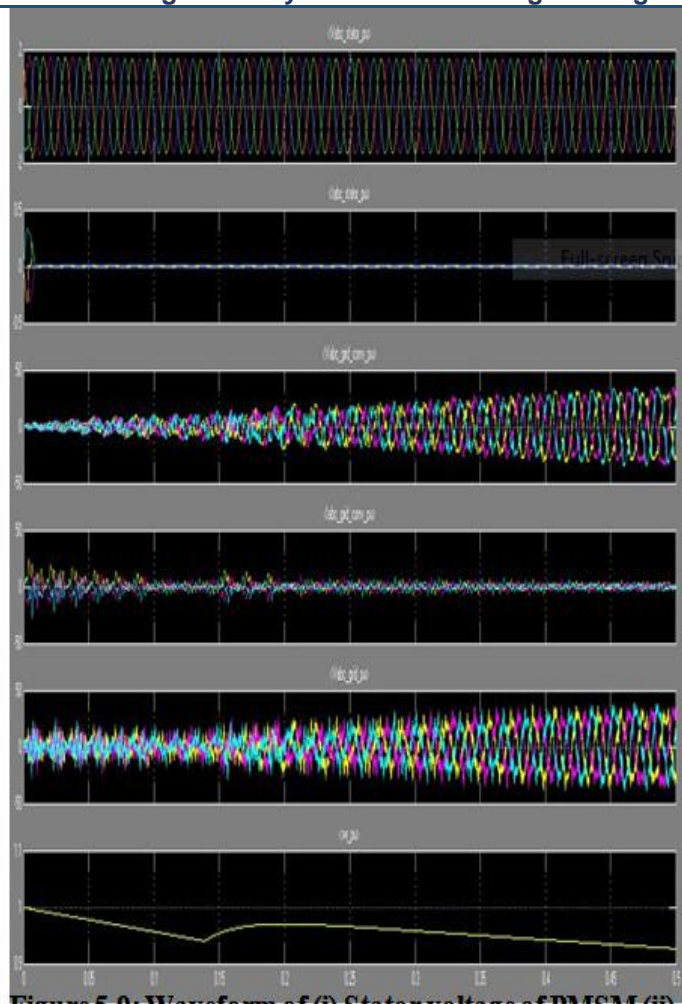


Figure 4.5: Waveform of (i) Stator voltage of PMSM (ii) Stator current of PMSM (iii) Voltage of grid connected wind energy (iv) Current waveform of grid (v) Voltage waveform of grid (vi) Rotor Speed.

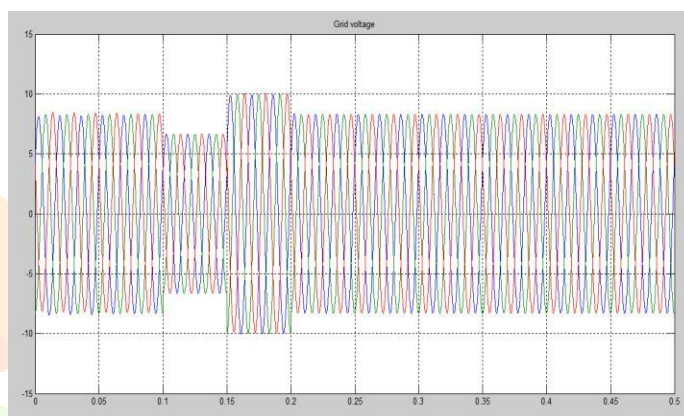


Fig-4.5: Waveform of (i) Stator voltage of PMSM (ii) Stator current of PMSM (iii) Voltage of grid connected wind energy (iv) Current waveform of grid (v) Voltage waveform of grid (vi) Rotor Speed.

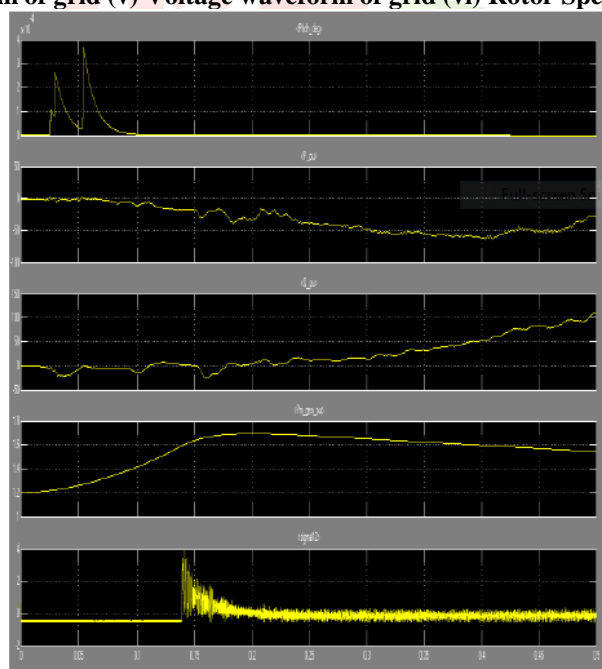


Fig-4.6: Waveform of (i) Pitch angle (ii) Active power of wind turbine (iii) Reactive power of wind turbine (iv) Mechanical power of generator (v) Field Voltage of PMSM.



## V. CONCLUSION

Thus the modeling of PMSG is done in Simulink and for variable wind speed it produces variable frequency variable voltage output. This paper presents mathematical model of matrix converter and interfacing with PMSG is done using MATLAB/Simulink. For variable frequency input source voltage generated by PMSG, the matrix converter is able to produce constant frequency output that can be integrated with the grid.

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