Three-phase Matrix Converter Applied to Wind Energy Conversion System for Wind Speed Estimation

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Abstract: With continuous increasing concerns of the energy issues, renewable energy sources are getting much attention worldwide. This paper presents a full description of the grid-tie Wind Energy Conversion System (WECS) based on interfacing a Permanent Magnet Synchronous Generator (PMSG) to the utility grid by using the direct AC/AC matrix converter. Due to the random variation of wind velocities, wind speed estimation control technique is used to estimate the wind velocity and extracts the maximum power at all wind velocities. The matrix converter controls the maximum power point tracking MPPT by adjusting the PMSG terminal frequency, and hence, the shaft speed. In addition, the matrix converter controls the grid injected current to be in-phase with the grid voltage for the unity power factor. Space Vector Modulation is used to generate the PWM signals of the matrix converter switches. The MPPT algorithm is included in the speed control system of the PMSG. The system dynamic performance is investigated using Matlab/Simulink.

Keywords: Permanent Magnet Synchronous Generator (PMSG), Matrix Converter (MC)

1. Introduction

Due to the continuous increased demand of the electrical energy, and the lack in reserve stocks of non-renewable energy sources such as fossil fuels, huge efforts are being made to generate the electrical power from renewable energy sources. Renewable energy sources, such as wind and solar, provide clean and cheap energy sources, [1-3]. Wind power is now one of the most energy sources that expand rabidly in the industry due to its abundance. Wind Energy is also advantageous over traditional methods of generating energy, in the sense that it is getting cheaper and cheaper to produce energy. Different types of generators are being used with wind turbines such as induction machine, double fed induction machine and PMSG [4-7]. PMSG has become the most familiar type of synchronous generators because of its good features that it has High efficiency and low maintenance cost. In addition, it has Small size and simple construction. There is no need for a separate DC excitation source. On the other hand, PMSG has some drawbacks that it has high initial cost compared with other generators at the same rating. And Overloading, short circuit and high temperate reduce, and weaken the magnetization of the permanent magnets [8-10]. The work in this paper is based on PMSG.

Because of the random variation on the wind velocities, the electrical power generated from the PMSG will vary also and unable to connect to the grid. Therefore, MPPT has been emerged and becoming an essential part in the variable speed wind turbine. Many methods have been proposed to locate and track the maximum power point. tip speed ratio (TSR) technique was presented, which depends mainly on measuring the wind velocity, then using the optimal value for the tip speed ratio in order to estimate the optimal value for the shaft speed[11, 12]. Power signal feedback (PSF) control technique was presented, which depends upon lookup tables for the shaft speed and its maximum output power at each wind velocity [13-15]. Also the optimal control technique was presented in some researches [16, 17]. The main theory of this method is to adjust the generator torque in order to obtain wind turbine torque for each wind velocity. Perturbation and observation (P&O) method that is independent of the wind velocity detections has been presented in [15, 18, 19]. This method is based on perturbing

the shaft generator speed in small step-size and observing the resulting changes in the output power until the slope becomes zero. The P&O is a robust, simple and reliable technique [15]. Wind speed estimation control technique presents in [20]. This method uses the efficiency curve of the blade to estimate the wind velocity without using wind velocity sensor. The work in this paper based on this technique.

In order to connect the electrical power to the grid so it converted to DC power then it enter an inverter to convert it to AC power compatible with the grid, this converter called traditional back-to-back converter. but this converter have some drawbacks including: operation on two stages reduces the reliability of the system, the bulky short life-time capacitor on the rectification stage, high power losses, and high amount of harmonics [21]. To overcome the previous mentioned drawbacks of traditional converters the AC/AC matrix converters are applied. Matrix converter is a single-stage AC/AC bi-directional power flow converter that takes power from AC source and converts it to another AC system with different amplitude and frequency. The reduction in the number of switches provides more compact than the traditional converter. Since it has only one power stage, there is no need for the bulky and lifetime limited energy-storing electrolytic capacitor that is considered an essential part in the conventional converters based two stages. It also has the ability to control the output voltage magnitude and frequency in addition to operation at unity power factor for any load. Moreover, it provides sinusoidal input and output waveforms, with minimal higher order harmonics and no sub-harmonics[21, 22]. The first attempt for modulation strategy technique of matrix converters is the Venturini method that depends mainly on the product of the input voltage and the modulation index matrix to generate the output voltage. However, this method has a poor voltage transfer ratio of 50% [23] . A modification to the strategy proposed in [24] was presented to enhance the maximum transfer ratio to its maximum limit of 86.7%. The scalar modulation strategy is used to utilizes the input voltage to produce the active and non-active states of the converter switches[25-27].

This paper presents a full description of grid-tie wind energy conversion system based on PMSG interfaced to the grid with the direct AC/AC matrix converter. The matrix converter controls the PMSG speed in order to track the maximum power point at all wind speeds based on wind velocity estimation technique. In addition, the matrix converter controls the grid side power factor to be unity in order to inject only active power to the grid. Section I represents the introduction. Section II gives a description of wind turbine and its mathematical model. Section III describes the MPPT control technique based on wind velocity estimation method. Section IV gives a full description of the matrix converter and its PWM using indirect SVM technique. Section V presents a control technique of the WECS. The result of this work is presented in section VI. Finally, the conclusions are presented in section VII.

2. Wind Turbine Performance

The wind kinetic energy is converted into mechanical power on the PMSG shaft through the wind turbine. This PMSG converts the mechanical power into electrical power. The mechanical power can be formulated as follows:

$$P_{Mech} = 0.5\rho A C_p V_w^3 \tag{1}$$

where: P_{mech} is the output mechanical power from the turbine in Watts, ρ is the air density in Kg/m^3, A is the turbine rotor area in m^2 (A=πR_r^2) and R_r is the rotor blade radius, C_p is the power coefficient and V_w is the wind velocity in m/s. If the air density ρ and the area A are constant, the power coefficient C_p can be formulated as follows:

$$C_p = \frac{p_{turbine}}{p_{wind}} \tag{2}$$

$$C_p = 0.5176[\frac{116}{\lambda_i} - (0.4\theta - 5)]e^{\frac{-21}{\lambda_i} + (0.0086\lambda)} \tag{3}$$

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}} \tag{4}$$
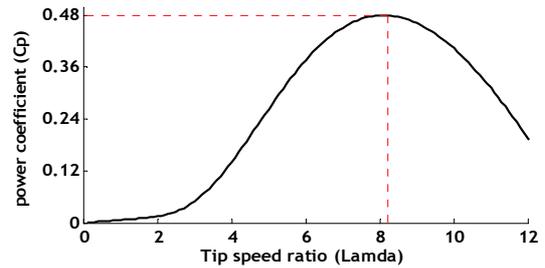

*Fig. 1. Wind turbine power coefficient versus tip speed ratio.*
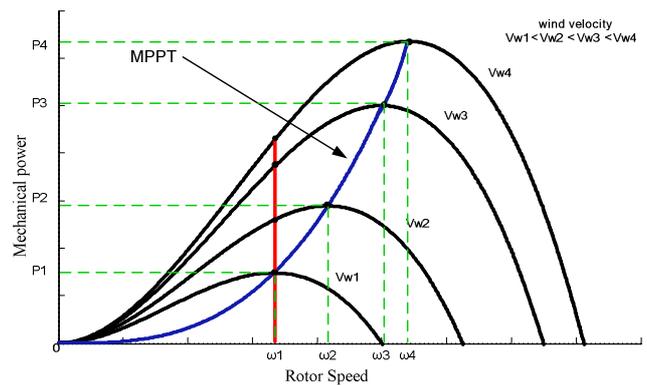
*Fig. 2. MPPT control scheme at different wind velocities.*where θ is the pitch angle, which is considered zero. Therefore, the tip speed ratio (λ) is formulated as follows:

$$\lambda = \frac{Tip_{speed}}{Wind_{speed}} = \frac{\omega_r R_r}{V_w} \tag{5}$$

The optimum value of C_p is about 0.48 for a tip speed ratio

of 8.1. In order to keep the system operates at the MPP, the tip speed ratio should be always at this value at operational conditions [28], as shown in Fig. (1).

3. Maximum Power Point Tracking Control (MPPT)

Fig. 2 shows the relationship between the output mechanical power and shaft speed at different values of wind velocity. According to Fig. 2, for each wind speed there is a unique rotational speed that record maximum mechanical power. Maximum Power Point Tracking (MPPT) is used to extract the maximum mechanical power from the wind turbine at each wind velocity.

It is clear that the maximum power extraction occurs at different rotational speeds. For example, at wind speed (V_{w1}), the maximum output power is P_1, which is obtained at a rotational speed ω_1. If the wind speed increases to V_{w2}, V_{w3}, or V_{w4}, applying a constant shaft speed controller to keep the rotational speed constant at ω_1 results in a mechanical power less than the maximum available power at the corresponding wind speed. Therefore, in order to extract the maximum power at each wind speed, the rotational speed should be controlled to follow the change in wind speed. If MPPT control is applied, the shaft speed will increase to ω_2 at wind speed of

V_{w2} to extract the maximum power available for this point P_2. The same concept applies for the other velocities, i.e. V_{w3} and V_{w4} [5].

To estimate the value of the wind velocities at each change the power coefficient (C_p) equations in (2, 3), this nonlinear equation depend on TSR (λ) that formulate in (5). It approximately rewritten in third order polynomial form to be formulated as in (6)[20]:

$$C_p(\lambda) = a_0 + a_1\lambda + a_2\lambda^2 + a_3\lambda^3 \qquad (6)$$

Where: a_0 through a_3, are constant which can be found numerically. The numerical solution generates values:

$a_0 = 0.00715814, a_1 = -0.04454063, a_2 = 0.02899277,$

$a_3 = -0.00202519.$

Referring to the mechanical power that formulated in (1), after equation (6) substitute the power coefficient it can be formulated as follow:

$$P_{Mech} = 0.5\rho A(a_0 + a_1\lambda + a_2\lambda^2 + a_3\lambda^3)V_w^3 \qquad (7)$$

Also equation (5) substitutes the TSR (λ) in (7):

$$P_{Mech} = 0.5\rho A(a_0 V_w^3 + a_1\omega_r R_r V_w^2 + a_2\omega_r^2 R_r^2 V_w + a_3\omega_r^3 R_r^3) \qquad (8)$$

$$V_w^3 + \frac{a_1}{a_0}\omega_r R_r V_w^2 + \frac{a_2}{a_0}\omega_r^2 R_r^2 V_w + \frac{a_3}{a_0}\omega_r^3 R_r^3 - \frac{P_{Mech}}{a_0 0.5\rho A} = 0 \qquad (9)$$

The numerical solution for equation 9 generates three values

for the wind velocity. The second answer value is the more accurate empirical solution[29, 30].

4. Matrix Converter Switching Scheme

Matrix converter is a one stage converter consists of nine bi-directional switches that establish a 3x3 matrix as shown in Fig. 3. In order to avoid short circuit that might be occurred between the input phases and open circuit on the output phases, one and only one switch per column must be ON and the other switches still OFF.

$$S_{m1} + S_{m2} + S_{m3} = 1 \quad m \in \{1, 2, 3\} \qquad (10)$$

The input three-phase voltage can be formulated as follows:

$$\begin{bmatrix} e_r \\ e_s \\ e_t \end{bmatrix} = E_m \begin{bmatrix} \cos(\omega t + \phi_i) \\ \cos(\omega t + \phi_i - 2\pi/3) \\ \cos(\omega t + \phi_i + 2\pi/3) \end{bmatrix} \qquad (11)$$

Where ϕ_i is the phase angle of the input voltages waveform.
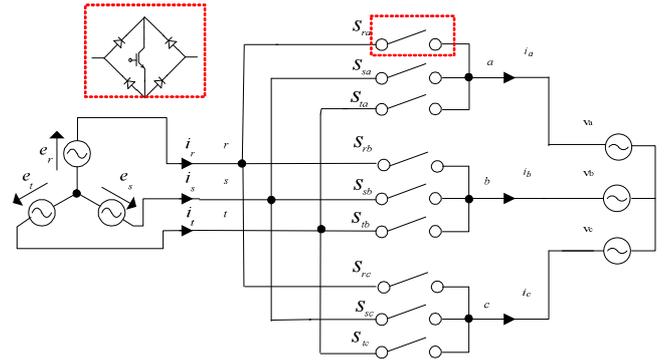
Fig. 3. *Matrix Converter.*

The output three-phase voltage can be formulated as follows as follow:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = V_m \begin{bmatrix} \cos(\omega t + \phi_o) \\ \cos(\omega t + \phi_o - 2\pi/3) \\ \cos(\omega t + \phi_o + 2\pi/3) \end{bmatrix} \qquad (12)$$

Where ϕ_o is the phase angle of the output voltages waveform.

The relation between the input and the output waveforms can be formulated as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} S_{ra} & S_{sa} & S_{ta} \\ S_{rb} & S_{sb} & S_{tb} \\ S_{rc} & S_{sc} & S_{tc} \end{bmatrix} \begin{bmatrix} e_r \\ e_s \\ e_t \end{bmatrix} \qquad (13)$$

The input current equation is obtained as follows:

$$\begin{bmatrix} i_r \\ i_s \\ i_t \end{bmatrix} = \begin{bmatrix} S_{ra} & S_{sa} & S_{ta} \\ S_{rb} & S_{sb} & S_{tb} \\ S_{rc} & S_{sc} & S_{tc} \end{bmatrix}^T \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (14)$$

Each element in the 3x3 modulation index matrix represents the duty cycle of the switches. These duty cycles of switches are determined by the space vector modulation control.

Space-vector modulation (SVM) is better than conventional PWM techniques because of its advantages as it generates controlled output voltage magnitude and frequency, it generates lower THD and it is suitable for digital controllers [31]. However, the implementation of space vector modulation control technique is complex, and need more switching states.

In order to simplify the states of direct matrix converter, indirect space vector modulation method is considered.
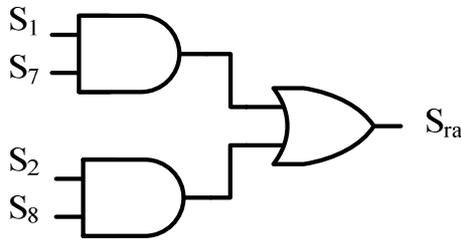
Fig. 4. *Implementation of the duty cycle of the switch Sra.*

The indirect space-vector modulation technique depends on two virtual stages, i.e., the rectification and the inversion stages[32, 33]. The modulation index for the matrix that formulated in (13) is subdivided into the product of two matrices, the rectifier matrix and the inverter matrix (15).

$$A = I_{inverter} \cdot R_{rectifier}$$

$$\begin{bmatrix} S_{ra} & S_{sa} & S_{ta} \\ S_{rb} & S_{sb} & S_{tb} \\ S_{rc} & S_{sc} & S_{tc} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \bullet \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \quad (15)$$

The combination of the rectifier and the inverter duty cycles is used to generate the duty cycles of the nine switches of the Matrix Converter, so that $S_{ra} = S_1 * S_7 + S_2 * S_8$. This equation is represented using the logic circuit as shown in Fig. 4 [32]. The rectification matrix (S_1-S_6) represents the duty cycles of the rectification stage switches, and the inversion matrix (S_7-S_{12}) represents the duty cycles of the inversion stage switches.

5. Control Scheme of Wind Energy Conversion System.

Fig. 5 shows the overall system of the grid-tie wind energy conversion system including PMSG, Matrix converter and its controller circuit, an input filter, and finally the grid side. The wind turbine developed torque T_m is applied to the generator

shaft; the wind velocity estimation block is used to estimate the value of the wind velocity which multiplying with the optimum value of the Tip Speed Ratio to generate the MPP speed that achieves the maximum power extracted at this wind velocity. The reference generator speed is compared with the actual generator speed and the error signal is applied to conventional PI controllers to generate the reference value for the q-axis component; in the other hand the reference value for the d-axis component (Id^*) is zero in order to keep the d-axis component flux equals zero. The actual three-phase generator currents are detected and converted to the d-q axis component (i_{ds}-i_{qs}) using Park/Clark Transformation. The actual load current in the d-q axis components are compared with their reference values and the error signal is applied to conventional PI controllers to generate the reference d-q axis voltage components V_d^* and V_q^*. The gains of the PI controllers have been manually tuned in order to achieve acceptable transient response. The d-q reference voltage components are converted to the three-phase axis using the invers Park/Clark Transformation in order to obtain the relevant three-phase voltage of matrix converter voltage. Fig.6 Illustrates the block diagram of control scheme of wind energy conversion system.

6. Results

The grid-tie wind turbine model based on PMSG and three-phase-to-three-phase matrix interface converter has been carried out in Matlab/Simulink environment. The parameters of the whole system are listed in Table I. Fig. 7 shows the wind velocity profile applied in the simulation. Fig. 8 illustrates the estimated and actual wind speed. Fig. 9 shows the effectiveness of the controller as the feedback speed tracks well the reference speed. Fig. 10 shows the value of C_p that remains constant at its optimal value regardless of the variation in the wind and generator speed. Fig. 11 shows the Tip Speed Ratio (λ) that remains constant at its optimal value at all values of the wind speed. The power generated from the machine varies according to the wind speed variation, as shown in Fig. 12. The generated three-phase currents of the PMSG change due to the wind speed variation as shown in Fig. 13. Fig. 14 shows the variation in the mechanical and electromagnetic torque of the PMSG shaft. It is clear that both torques are in good agreement. Fig. 15 shows the utility grid three-phase currents and voltages at all values of wind velocities. fig.16 shows the grid side phase voltage and its corresponding line current at all wind speeds. It is clear that the grid current and voltage are in-phase at all wind speeds. Therefore, the wind turbine injects active power only to the utility grid. Fig. 17 provides the FFT analysis of the three-phase currents of the PMSG, which shows a decrease in the THD of the output current waveform to 1.96% which can be neglected compared to the other control techniques. Fig. 18 analysis of the grid current waveform which shows that the THD of the grid current has a good level of 9.4%.

7. Conclusions

This paper presents a study of a grid connected wind energy conversion system for electrical power extraction from wind energy based on PMSG to compensate the shortage of non-renewable energy sources. In order to extract the maximum available power at each wind speed the excellent tracking of the Maximum Power Point based on wind velocity estimation method is applied. The electrical power generated by the PMG is tied to the grid through a matrix converter, which solve all the problems of the traditional converters. The Matrix Converter, controlled by SVM, enables excellent transient response while sinusoidal current waveforms is dominant with grid currents in-phase with the grid voltage for unity power factor. Simulation results prove that the wind turbine system based three-phase PMSG tracks the MPP and injects only active power to the grid at all wind speeds. Fig. 5 WECS modeling
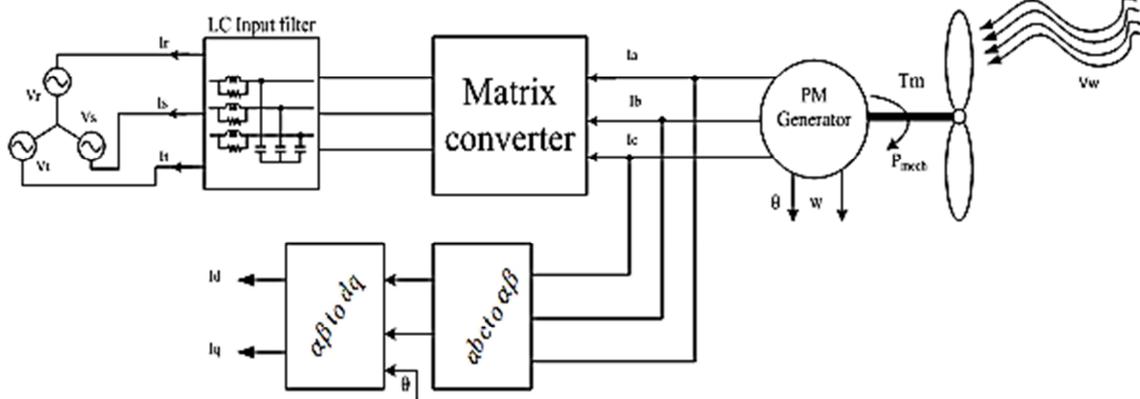
Fig. 5. *WECS modeling.*
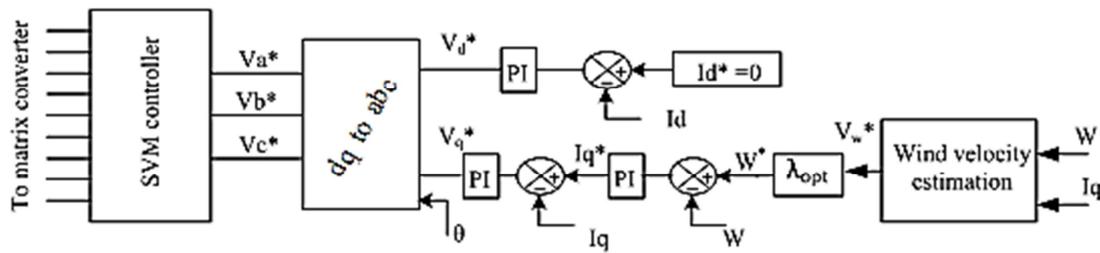
Fig. 6. *Block diagram of Matrix Converter Controller.*
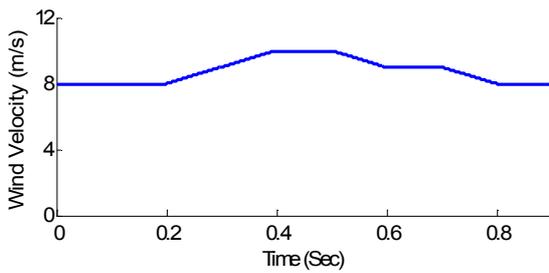
**Fig. 7.** *wind velocity profile.*
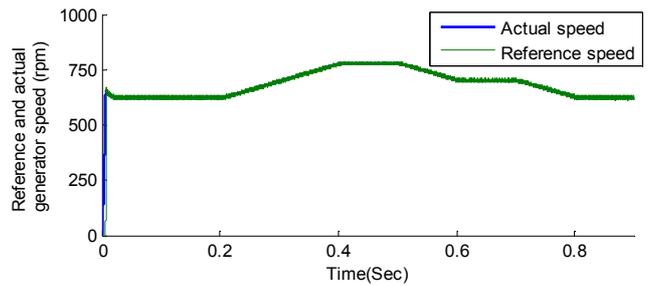
**Fig. 9.** *actual and reference generator speed.*
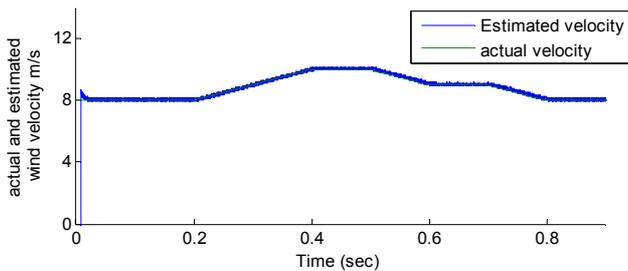
**Fig. 8.** *The actual and estimated wind velocity.*
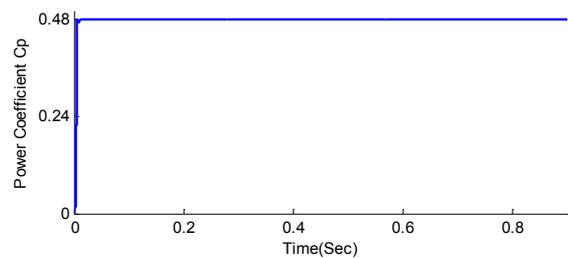
Fig. 10. *Power Coefficient Cp.*
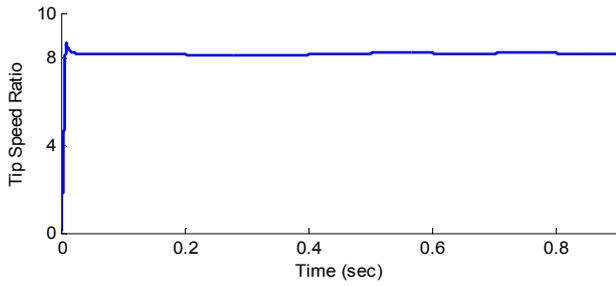
Fig. 11. *Tip speed ratio.*
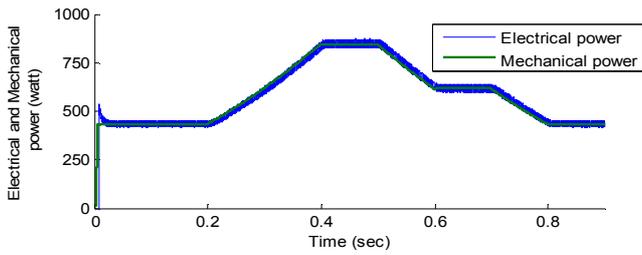
**Fig. 12.** *Electrical and Mechanical Power of PMSG.*

a) The generator currents

b) The generator current at Vw=8m/s

c) The generator current at V w=10 m/s

Fig. 13. *The generator currents variation.*

Fig. 14. *Mechanical and Electromagnetic torque.*
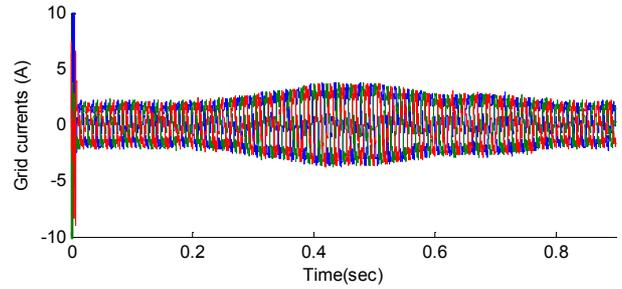
Fig. 15. *Three-phase Grid Currents.*
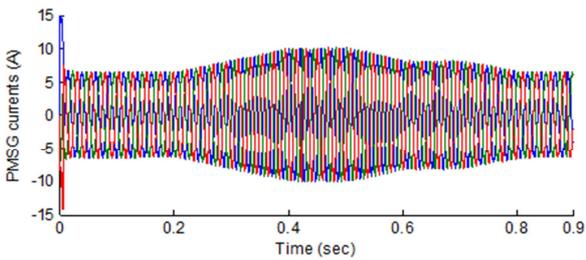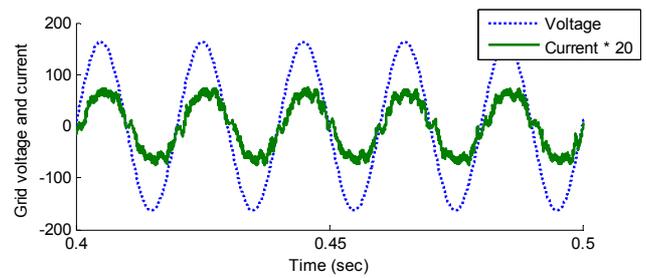
Fig. 16. *Grid voltage and current.*
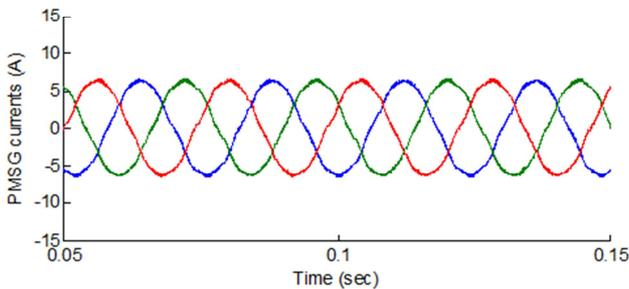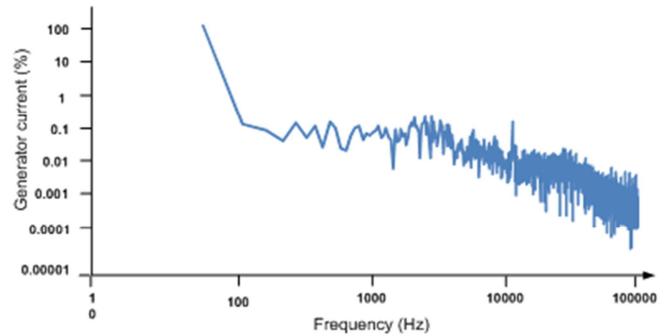

**Fig. 17.** *FFT analysis for the Output currents of PMSG.*
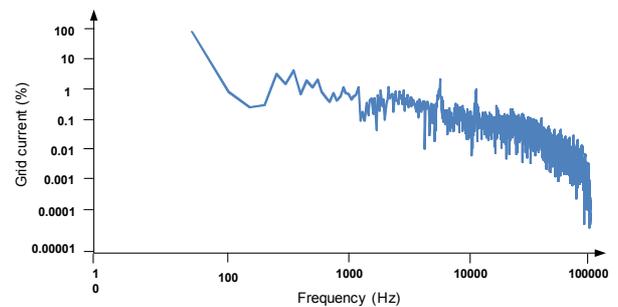
Fig. 18. *FFT analysis for the Grid currents.*

Appendix

Matlab Simulink parameters of the overall system shown in Fig.(8).

Table 1. System parameters.

Machine parameters	
No. pairs pole	P=4
Stator resistance	R_s=2.875Ω
Stator inductance	L_d=L_q=0.0085 H
Moment of inertia	J=0.00008 kg.m^2
Flux linkage	Ψ=0.175 wb
Grid parameters	
Phase voltage	V_a=220v
LC filter	
L= 15 mH C= 8 uF R_d= 47 Ω	

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