Speed, Torque and Voltage Performances of the Doubly Fed Induction Generator


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***Abstract*—Wind as a renewable energy source over the last decade have received global attention as conventional energy sources are limited and cause some effects to mankind and his environment. The model of Doubly Fed Induction Generator (DFIG) based Wind Energy Conversion Systems (WECS) control with back-to-back converter has some drawbacks such as high weight, current harmonics and cost owing to the DC link capacitor circuitry. This paper evaluates the dynamic model of the DFIG driven by an Indirect Matrix Converter (IMC) in MATLAB/Simulink environment. The asynchronous machine was modeled in synchronous reference frame under stator flux orientation for which d-axis is aligned. An Indirect Space Vector Modulation (ISVM) was applied to control the matrix converter. Maximum Power Point Tracking (MPPT) control based on Indirect Speed Control (ISC) was applied to the wind turbine so as to track maximum power from the wind. The simulation results show the effectiveness of proposed system under different wind speed. For instance, when the wind speed is 10m/s the rotor speed is 0.94pu at steady state operation, after 6 seconds the wind speed increases to 12m/s while the rotor speed attained a new steady state operation of 0.97pu. The DFIG-based wind turbine system operates under sub-synchronous mode for the wind speed variation applied to wind turbine.**

***Keywords*—** Indirect Matrix Converter, Indirect Speed Control, Maximum Power Point Tracking, Wind Turbine, Indirect Space Vector Modulation.

I. INTRODUCTION

The conventional energy sources are limited and cause pollution to the environment. More attention and interest have been paid to the utilization of renewable energy sources such as wind and solar in order to meet the energy demand of the global population. According to statistics by Global Wind Energy Council (GWEC) the total installed capacity of wind power plants worldwide has exceeded 318GW since 2013 and it was estimated to be about 712GW as reported in [1]. Wind energy is one of the renewable energy sources obtained with wind turbines which is the highest growth in modern power systems and has minimum negative effect on environment. There are two different types of wind turbines connected to the grid. These are fixed Speed Wind Turbine (FSWT) based on a Squirrel Cage Induction Generator (SCIG) and Variable Speed Wind Turbine (VSWT) consisting of a Doubly Fed Induction Generator (DFIG) or a Permanent Magnets Synchronous Generator (PMSG) [2], [3]. The conventional voltage source converter (VSC) is bidirectional converter consisting of the rotor side rectifier (RSR) and the Grid Side Converter (GSC) with DC-link in between. Rotor side converter enables the control of stator active and reactive power of DFIG by controlling the rotor current [4].

Matrix Converter (MC) is a group of AC–AC converter that connect directly a three-phase source to a three-phase load and are able to convert energy of the ac-source to variable output voltages with unrestricted frequency without using the bulky energy storage elements, which generally has limited lifetime. In the variable voltage and variable frequency AC drive applications, MC has received extensive research attention because of their distinctive advantages such as high quality sinusoidal input and output waveforms, adjustable input power factor, lack of bulky energy storage components and capability of regeneration [5]. Fig. 1 illustrates the WECS based DFIG based wind turbine driven by Matrix Converter. One of the most preferred modulations for matrix converters is the Space Vector Modulation (SVM) because of the better harmonic performance using different switching strategies. Two versions of SVM are direct SVM (DSVM) and indirect SVM (ISVM). The number of switching commutations and consequently the switching losses in each switching period depends on the number and position of zero configurations used in switching pattern. It also has some effect on the ripples of input and output voltages and currents [6].

In this paper the dynamic model of DFIG-based Wind turbine driven by matrix converter is simulated for different wind speed variation in MATLAB/Simulink under stator flux orientation. A Maximum Power Point Tracking (MPPT) control technique is applied to the wind turbine to extract maximum energy from the wind.

Section 2 presents the aerodynamic model of the wind turbine. Modeling of DFIG is presented in section 3. Modeling of Indirect Matrix Converter and vector control for DFIG driven by indirect matrix converter is discussed in section 4. Sections 5 and 6 present the simulation results and conclusion of the proposed DFIG control technique respectively.

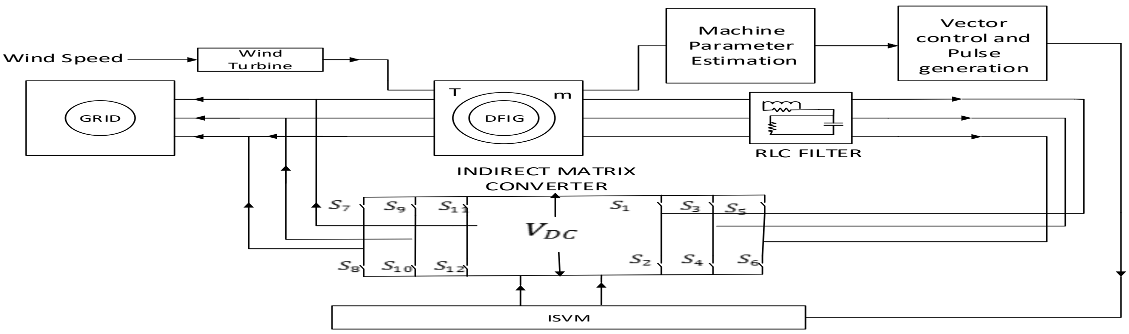


Fig. 1: DFIG-Based Wind Turbine

II. Wind Turbine Aerodynamic Model

The aerodynamic of wind turbine entails the mechanical energy extraction from the wind by the turbine blades. The mechanical power (P_m) capture or extracted from the wind by the wind turbine is given as follows [7].

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta)V_W^3 \quad (1)$$

Where; ρ is the air density in kg/m^3, A is the area of the wind turbine blade, C_p is the power coefficient, λ is the tip speed ratio, β is the pitch angle and V_w is the wind speed in (m/s).

The tip speed ratio λ is defined as the ratio of the angular rotor speed of the wind turbine to the linear wind speed at the tip of the blades and can be expressed as follows [2].

$$\lambda = \frac{\omega_r R}{V_w} \quad (2)$$

ω_r is the angular velocity of the rotor and R is the wind turbine blade radius in (m). The mechanical angular velocity of the rotor ω_r in (rad/sec),

$$\omega_r = \frac{2\pi n}{60} \quad (3)$$

The driving torque around the rotor shaft can be expressed as in [8].

$$T_m = \frac{1}{2}\rho A R C_T V_W^2 \quad (4)$$

Where C_T is the torque coefficient given as:

$$C_T = \frac{C_p}{\lambda} \quad (5)$$

For a variable speed wind turbine (VSWT), the coefficient C_p is calculated as follows [7].

$$\lambda_i = \frac{1}{\frac{1}{\lambda + 0.002\beta} - \frac{0.03}{\beta^3 + 1}} \quad (6)$$

The value of tip-speed ratio λ can be obtained as;

$$C_P(\lambda,\beta) = 0.73\left[\frac{151}{\lambda} - 0.58\lambda - 0.002\beta^{2.14} - 13.2\right] e^{\frac{184}{\lambda_i}} \quad (7)$$

An Indirect speed control (ISC) was adopted to extract maximum power from the wind by designing MPPT controller based on Fig. 2. The reference electromagnetic torque from the output of controller is expressed as follows [9].

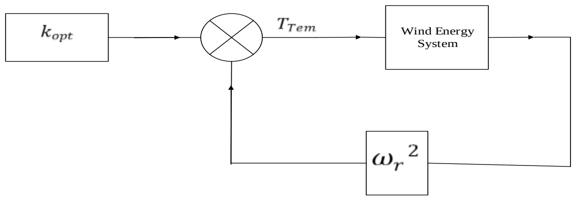


Fig. 2: MPPT controller

$$T_{Tem} = k_{opt} \quad (8)$$

$$k_{opt} = \frac{1}{2}\rho\pi R^5 \frac{(C_p)max}{(\lambda_{opt})^3}\omega_r{}^2 \quad (9)$$

Where, $(C_p)max$ is maximum value of power coefficient is the tip speed ratio at its optimal.

III. DFIG Modeling

The stator winding of DFIG is directly connected to the grid while the rotor side was indirectly feeds the grid by Indirect Matrix converter as illustrated in Fig. 1. The equivalent circuit of DFIG in synchronous reference frame is shown in Fig. 3 [10], [11].

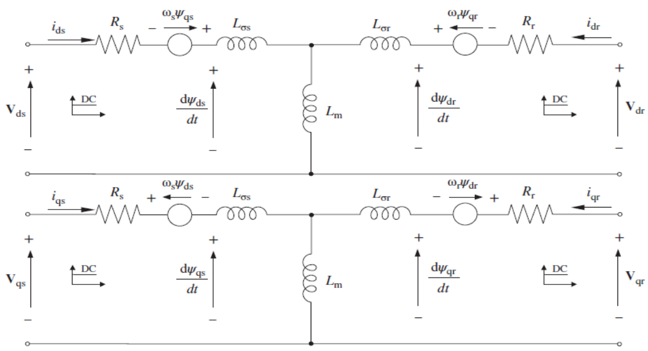


Fig. 3: d-q equivalent circuit of a DFIG synchronous reference frame.

Taking the fluxes as the state-space magnitudes, the state space representation of the DFIG is given by equation (10) as in [12], [10].

Taking the fluxes as the state-space magnitudes, the state space representation of the DFIG is given by the following equation. The stator and rotor $d-q$ fluxes equations are given by the following equations;

$$\frac{d}{dt}\begin{bmatrix}\psi_{ds}\\ \psi_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix} = \begin{bmatrix}\frac{-R_s}{\sigma L_s} & 0 & \frac{R_s L_m}{\sigma L_s L_r} & 0\\ 0 & \frac{-R_s}{\sigma L_s} & 0 & \frac{R_s L_m}{\sigma L_s L_r}\\ \frac{R_r L_m}{\sigma L_s L_r} & 0 & \frac{-R_r}{\sigma L_r} & -w_r\\ 0 & \frac{R_r L_m}{\sigma L_s L_r} & w_r & \frac{-R_r}{\sigma L_r}\end{bmatrix} . \begin{bmatrix}\psi_{ds}\\ \psi_{qs}\\ \psi_{dr}\\ \psi_{qr}\end{bmatrix} \tag{10}$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ (11)

The electromagnetic torque (T_{em}) can be expressed as follows [13].

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_s}\left(\psi_{qs} i_{dr} - \psi_{ds} i_{qr}\right) \tag{12}$$

Where; ψ, i are the flux and current quantities, *s* and *r* are the stator and rotor symbols, while *q* represent quadrature vector component of a given variable that can be either a flux, current or voltage.

IV. Indirect Matrix converter Modeling and Vector Control for DFIG driven by IMC

A- Modeling of Indirect Matrix Converter

The equivalent circuit of Matrix Converter is illustrated in Fig. 4. It can be observed that the Matrix Converter drives the load by modulating the switches at both rectifier and inverter stages of the converter.

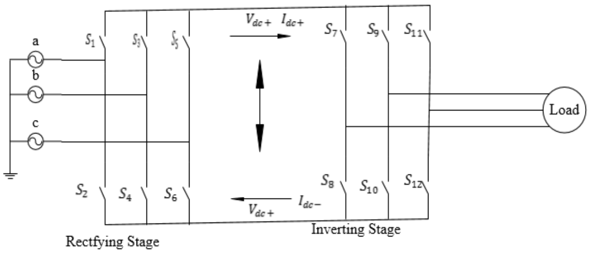


Fig. 4: Indirect matrix converter equivalent circuit with ideal switches

The switching function is expressed as follows [14], [5].

$$S_{ij} = f(x) = \begin{cases}1, & S_{ij}\ closed\\ 0, & S_{ij}\ open\end{cases} \quad i \in (a,b,c),\ j \in (A,B,C) \tag{13}$$

The switch combination is constrained as follows;

$$S_{aj} + S_{bj} + S_{cj} = 1, \quad j \in (A,B,C) \tag{14}$$

The output voltage and input current magnitude of the Matrix Converter is expressed as follows:

$$V_O = T.V_i \tag{15}$$

$$\begin{bmatrix}V_A\\ V_B\\ V_C\end{bmatrix} = \begin{bmatrix}S_{aA} & S_{bA} & S_{cA}\\ S_{aB} & S_{bB} & S_{cB}\\ S_{aC} & S_{bC} & S_{cB}\end{bmatrix} . \begin{bmatrix}V_a\\ V_b\\ V_c\end{bmatrix} \tag{16}$$

$$I_i = T^T . I_o \tag{17}$$

$$\begin{bmatrix}I_a\\ I_b\\ I_c\end{bmatrix} = \begin{bmatrix}S_{aA} & S_{aB} & S_{aC}\\ S_{bA} & S_{bB} & S_{bC}\\ S_{cA} & S_{cB} & S_{cC}\end{bmatrix} . \begin{bmatrix}I_a\\ I_b\\ I_c\end{bmatrix} \tag{18}$$

An ISVM was applied to the matrix converter so as to enable decouple control of input current and output voltage of the converter based current and voltage space vectors [15]. The following expressions present an indirect modulation of rectifier and inverter stages of matrix converter.

$$T = I.R \tag{19}$$

$$\begin{bmatrix}S_{aA} & S_{aB} & S_{aC}\\ S_{bA} & S_{bB} & S_{bC}\\ S_{cA} & S_{cB} & S_{cC}\end{bmatrix} = \begin{bmatrix}S_7 & S_8\\ S_9 & S_{10}\\ S_{11} & S_{12}\end{bmatrix} . \begin{bmatrix}S_1 & S_3 & S_5\\ S_2 & S_4 & S_6\end{bmatrix} \tag{20}$$

Where the matrix **I** is the inverter transfer function and **R** is the rectifier transfer function matrix. Substituting equation (20) into (16)

$$V_O = I.R.V_i \tag{21}$$

$$\begin{bmatrix}V_A\\ V_B\\ V_C\end{bmatrix} = \begin{bmatrix}S_7 & S_8\\ S_9 & S_{10}\\ S_{11} & S_{12}\end{bmatrix} . \begin{bmatrix}S_1 & S_3 & S_5\\ S_2 & S_4 & S_6\end{bmatrix} \begin{bmatrix}V_a\\ V_b\\ V_c\end{bmatrix} \tag{22}$$

$$\begin{bmatrix}V_A\\ V_B\\ V_C\end{bmatrix} = \begin{bmatrix}S_7.S_1 + S_8.S_2 & S_7.S_3 + S_8 S_4 & S_7.S_5 + S_8.S_6\\ S_9.S_1 + S_{10}.S_2 & S_9.S_3 + S_{10}.S_4 & S_9.S_5 + S_{10}.S_6\\ S_{11}.S_1 + S_{12}.S_2 & S_{11}.S_3 + S_{12} S_4 & S_{11}.S_5 + S_{12}.S_6\end{bmatrix} . \begin{bmatrix}V_a\\ V_b\\ V_c\end{bmatrix} \tag{23}$$

B-Vector Control Applied to DFIG driven by Indirect Matrix Converter

The DFIG control scheme entails the decouple control of stator active and reactive power which is the function of rotor currents. The *d*-component and *q*-component of rotor current respective control stator reactive and active power using PI controllers in each control loop [16], [17] and [10]. If the stator flux is aligned with d-axis the d-q rotor voltage equations that enhance DFIG control are expressed as:

$$V_{dr} = R_r i_{dr} + \sigma \frac{d}{dt} i_{dr} - \sigma \omega_r i_{qr} + \frac{L_m}{L_s}\frac{d}{dt}\left|\overrightarrow{\Psi_s}\right| \tag{24}$$

$$V_{qr} = R_r i_{qr} + \sigma L_r \frac{d}{dt} i_{qr} + \omega_r \sigma L_r i_{dr} + \frac{L_m}{L_s}\left|\overrightarrow{\Psi_s}\right| \tag{25}$$

The complete control block diagram schematic for DFIG driven by the matrix converter is shown in Fig. 5. The triggering pulses of the Indirect Matrix converter were obtained using vector control shown in Fig. 5 Two PI

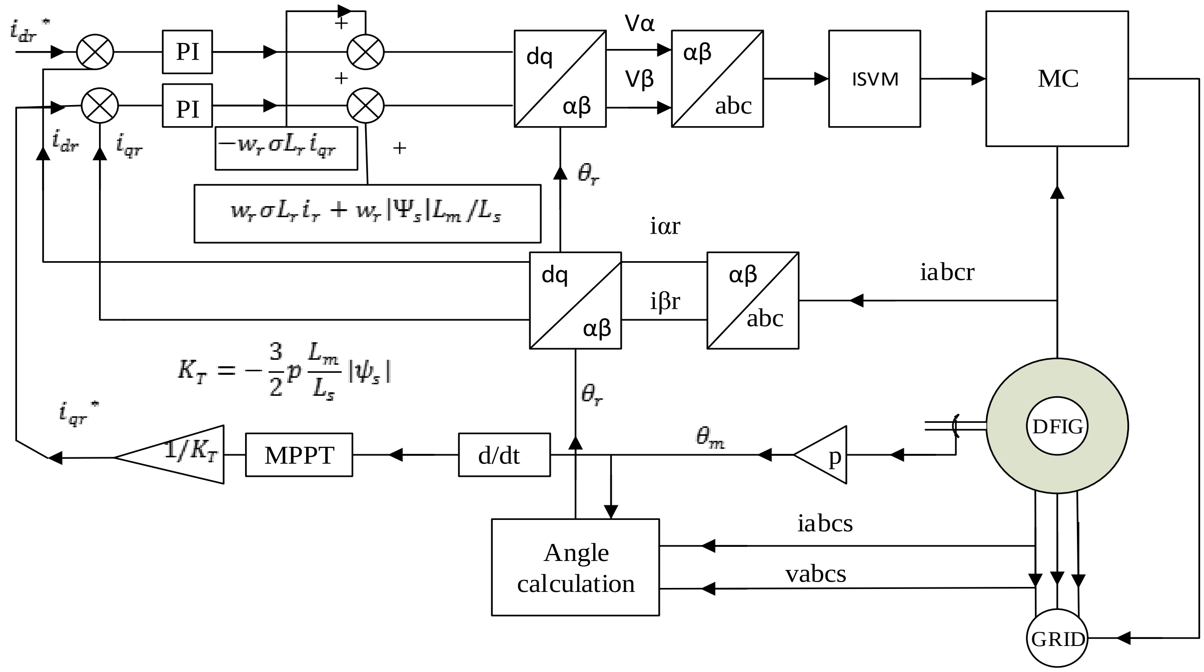


Fig. 5: Schematic Diagram of Vector Control for DFIG Drive by Matrix Converter

and a Maximum Power Point Tracking (MPPT) controller was incorporated so as to achieve maximum power extraction for the variable wind speed and generate *q*-rotor current reference for the PI controller in the control loop.

V. Simulation

The effectiveness of the proposed control scheme was verified in MALTAB/Simulink via simulation based on system parameter presented in Appendix I. The simulation is carried out based on two different wind speeds as follows:

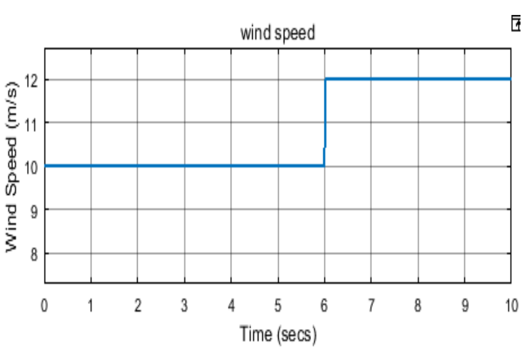


Fig. 6: Wind Speed Profile

The wind speed profile of Fig. 6. was applied to the wind turbine for which the wind speed of 10m/s was maintained before the step change to 12m/s at 6 secs and the aerodynamic torque output of the wind turbine is depicted in Fig. 7. The mechanical torque developed by the wind turbine increases with increased in wind speed which will also increase the mechanical output power of the wind turbine

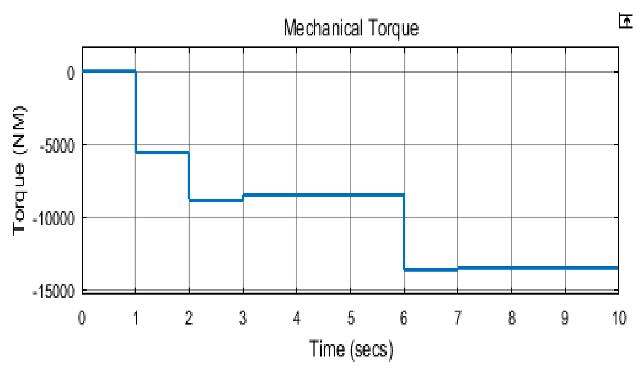


Fig. 7: Mechanical Torque

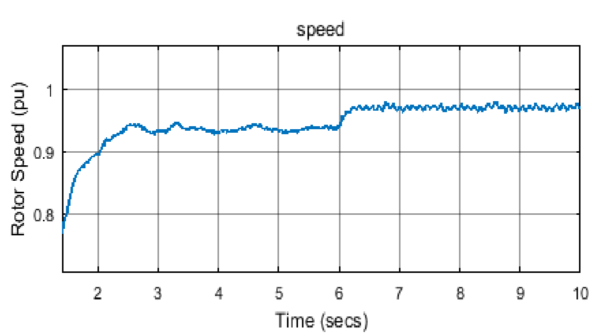


Fig. 8: Rotor Mechanical Speed

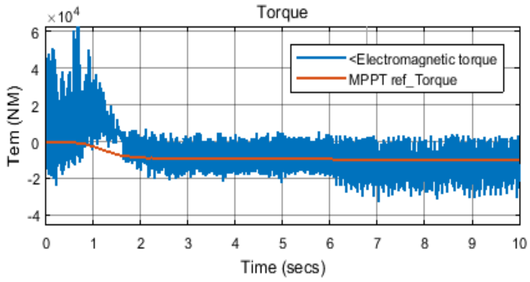


Fig. 9: Electromagnetic Torque

The rotor mechanical speed response of the system for the wind speed variation is shown in Fig. 8. The system attained steady state operating point corresponding to the wind speed Fig. 6. The rotor speed is 0.94pu at steady state for 10m/s wind speed and as the wind speed increased to 12m/s at 6 secs, the rotor speed attained a new steady state operation of 0.97pu. The DFIG-based wind turbine system operates under sub synchronous mode for the wind speed variation applied to wind turbine. The electromagnetic torque response is illustrated in Fig. 9. The machine operates as a generator as the electromagnetic response is negative. The reference MPPT torque was used to generate the reference i_{qr}^* for the PI controller in *q*-rotor current component and ensured the maximum power tracking from the wind.

The stator three phase voltages and current of the DFIG, the three phase rotor current and the three phase output voltage of the indirect matrix converter responses are depicted in Fig. 10-13 under wind speed variation.

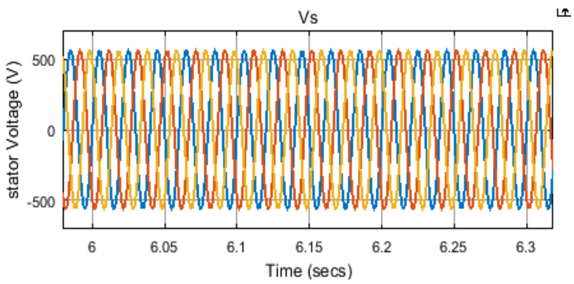


Fig. 10: Three Phase Stator Voltage

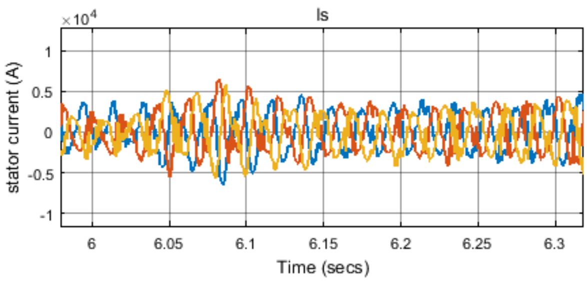


Fig. 11: Three Phase Stator Current

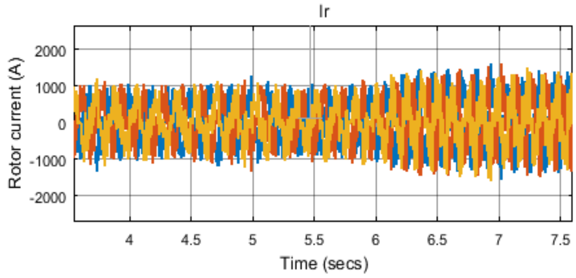


Fig. 12: Three Phase Rotor current

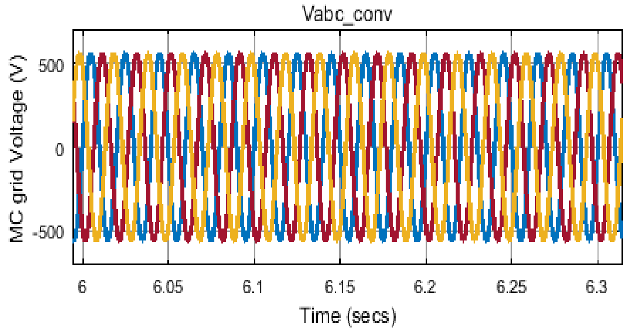
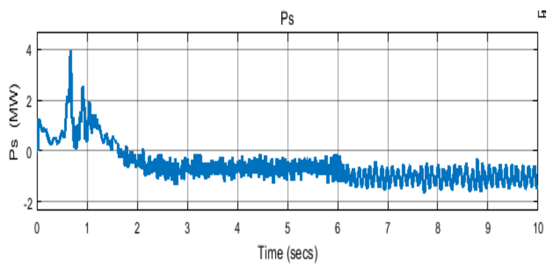


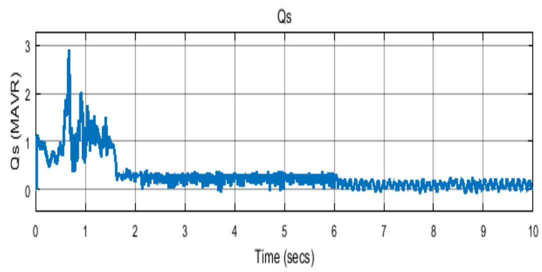
Fig. 13: Three Phase MC Grid Voltage

It can be observed that irrespective of the change in wind speed from 10m/s at 6 sec to 12m/s the grid terminal voltages remain constant around 690V so as to ensure continuous synchronism with grid. Fig. 11 and Fig. 12 depict the three phase stator and rotor current responses of the system subjected to the wind speed variation. The magnitude of the currents responses increases with increase in wind speed which will result in corresponding increase in the active power generated by the system. Also the grid active and reactive power response from both stator and rotor is presented in Fig. 14. The power response is a function of wind speed.

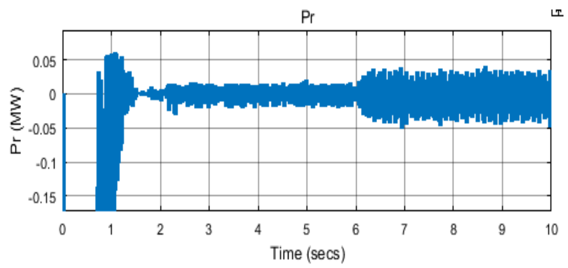
As wind speed changes from 10m/s and 12m/s at 6 secs, the stator active power response also increases as more power was extracted and the reactive power at the stator is around zero as the reactive power is a function of d-current rotor component. The rotor active and reactive power responses are depicted in Fig. 14(c)-(d). The rotor side of the DFIG system consumed power from the grid as the system operates at sub synchronous under the wind speed variations.



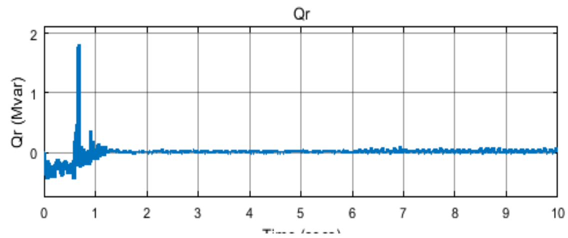
(a) Stator Active Power



(b) Stator Reactive Power



(c) Rotor Active Power



(d) Rotor Reactive Power

Fig. 14: Stator and Rotor Active and Reactive Power

VI. Conclusion

This paper has tried to measure the performance of DFIG-based wind turbine driven by an indirect matrix converter via simulation in MATLAB/ Simu-link. The aerodynamic model of the three blade wind turbine driving. rotor shaft of DFIG was evaluated The DFIG was modelled in synchronous reference frame under stator flux orientation for which *d*-axis was aligned. The indirect matrix converter driving the rotor circuit of the DFIG was modelled based on Indirect Space Vector Modulation (ISVM). The complete system model was simulated under wind speed variation and[15] the results obtained have demonstrated the effectiveness of the proposed system to extract more power from the wind as MPPT controller ensured maximum power from the wind. As wind speed changes from 10m/s to 12m/s at 6 seconds interval, the stator active power response also increase as more power was extracted while the reactive power at the stator is maintained at a value of zero.

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Appendix I:

DFIG Parameters

PARAMETER	RATING	PARAMETER	RATING
Rated Power	**2MW**	**Rotor Resistance**	**2.9 mΩ**
Rated Stator Voltage	**690V**	**Stator Leakage Inductance**	**0.087mH**
Rated Stator Current	**1.76kA**	**Rotor Leakage Inductance**	**0.087mH**
Stator/Rotor Turn Ratio	**1/3**	**Mutual Inductance**	**2.5mH**
Rated Rotor Voltage	**2070V**	**Rated Rotational Speed**	**1800rpm**
Rated Frequency	**50Hz**	**Angular Momentum**	**60kg-m^2**
Number of Pole	**2**	**Mechanical Damping Ratio**	**0.001**
Stator Resistance	**2.6mΩ**	**Rated Torque**	**12732N-m**
		Maximum Slip	**1/3**

Appendix II:

Wind Turbine Parameters

Parameter	Rating	Parameter	Rating
Radius	42m	Pitch Angle	0
Rated wind speed	12m/s	Power Co-efficient	
Gear Box Ratio	1:100	Tip speed ratio	7.2
Air Density	1.225kg/m^3		