A MATLAB Based Analysis of Direct Torque Control of a Matrix Converter Fed Grid Connected Doubly Fed Induction Generator

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Abstract— **Doubly Fed Induction Generator (DFIG) is the most popular variable speed generator for wind energy application due to its superior performance, lower cost and control flexibility. The DFIG has been widely used and researched in wind generator application. Instead of back-to-back converters, matrix converter (MC) can be a good alternative for connecting the DFIG rotor to the grid. This paper presents a matrix converter based control for a variable speed constant frequency (VSCF) DFIG. Design of DFIG based wind power generation system with the help of matrix converter is analyzed by means of MATLAB/SIMULINK block set.**

***Index terms*— Doubly Fed Induction Generator, Matrix Converter,wind energy, Wing Energy Conversion System, Space vector modulation.**

NOMENCLATURE

ws ,w, wr	Synchronous, shaft and slip speed of the DFIG
φ_s, φ_r	Stator and rotor flux vector magnitudes
δ	Angle between the stator and the rotor flux
σ	Leakage factor
Ls , Lr ,Lm	Stator self inductance, rotor self inductance, and magnetizing inductance referred to the stator.
Rs , Rr	Stator and rotor resistance referred to the stator.
Qs	Stator reactive power
Te	Electromagnetic torque

I. INTRODUCTION

The renewable energy sources are one of the biggest concerns of our times. High prices of oil and global warming make the fossil fuels less and less attractive solutions. Wind power is a very important renewable energy source. DFIG is most commonly used generator because it has more advantages than PMSG and SCIG [8]. In DFIG, both stator and rotor having field windings. So significant power transfer between shaft and electrical system. And varying speed of machine shaft is limited to around synchronous speed. In DFIG power converters are connected in rotor to grid or load, only slip power is transmitted through rotor to grid, so it required only small ratings of converters [3].

For variable speed wind power generation the doubly fed induction generator (DFIG) with fractional rated back-to-back converters has already proved its superiority over other configurations [1]. Instead of using conventional back-to-back converters with DC-link capacitor, direct matrix converter, with reduced passive element (the dc-link capacitor, line filter components etc.) requirement [2] can be a good alternative for this kind of generation system. It was shown in [2] that MC topologies enable a 2.5 times higher maximum power density and a five times higher maximum power to mass ratio at a higher efficiency compared to the back-to-back voltage source converter system for the same input voltage, output power and switching frequency range[1].

II. PROBLEM DEFINITION

The DFIG has been widely used in wind energy conversion systems. The primary benefits of this system over other configurations is that power electronic converters in the system need only to convert power to and from the rotor windings of wound rotor induction machine that is DFIG. This translates to convert a power rating of approximately 25% of the total generator power rating. However, these power converters in DFIG system usually rely on a back-to-back DC link configuration to produce AC-AC conversion. The disadvantage of applying back-to-back converters for DFIG is that these electronic devices are relatively expensive and that they introduce additional losses in the system due to the conduction and switching losses of the semiconductor valves.This paper is an investigation into a feasibility of using MC to conduct a AC-AC conversion in rotor circuit by using a MATLAB simulation tool.

III. LITERATURE REVIEW

The purpose of this literature review is to outline in some detail literature relevant to control of DFIG using a back-to-back converter and MC.

R.Rana, J.C.Clare, G.M.Asher have experimently preformed a back-to-back converter technology on a 7.5 kW WECS and concluded that this technology provide a smooth operation on a synchronous speed as well as low distortion currents fed to the supply.

S.L.Kaila and H.B.Jani have studied a direct torque control of a induction machine using a space vector modulation. The switching frequency of different space vectors are determined for each sampling period in order to minimize the torque ripple.

T. Friedli, J. W. Kolar, J. Rodriguez, and P. W. Wheeler have studied a matrix converter(MC) technologies and showed that MC topologies enable a 2.5 times higher maximum power density and a five times.

Djohra Saheb-Koussa ,b Mourad Haddadi ,a Maiouf Belhamel,aMustapha koussa &aSaid noureddine proposed a methodology for modeling and simulating a windgenerator with fixed speed wind turbine by Matlab/Simulink, using Simulink library browser concept.

J. Amini, R. Kazemzahed, H. Madadi Kojabadi have studied a performance Enhancement of Indirect Matrix Converter Based Variable Speed Doubly-Fed Induction Generator.

Stephen Meier has compared a losses in back-to-back converter and matrix converter (MC) technologies.

From the above literature outcomes, it has been observed that DFIG characteristics are affected by its injected rotor voltage. By varying the amplitude and phase angle of the rotor injected voltage.

IV. DFIG CONTROLUSING MATRIX CONVERTER TOPOLOGY

Aero turbines convert energy in moving air to rotary mechanical energy. In general they require pitch control and yaw control for proper operation. A mechanical interface consisting of a step up gear and a suitable coupling transmits the rotary mechanical energy to an electrical generator. The output of this generator is connected to a load or grid.

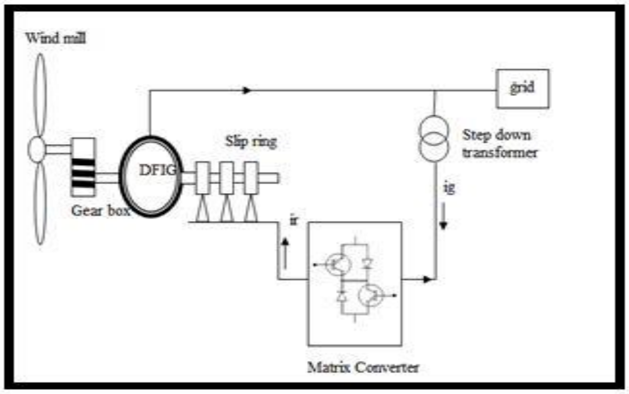

Fig.1. Schematic diagram of DFIG using MC

A.Stator reactive power and speed control

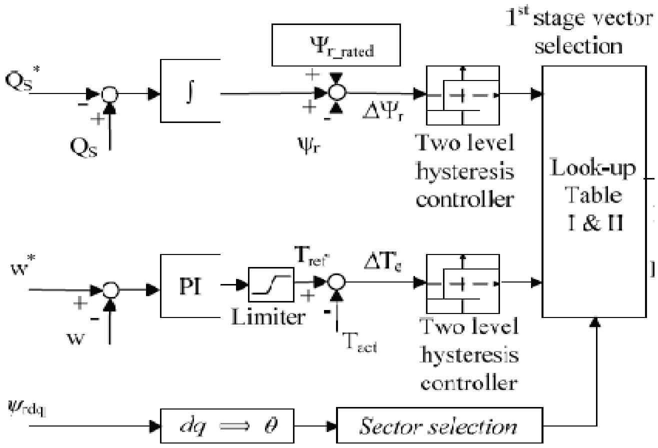

Fig.2.Reactive power and speed control [1].

Stator reactive power is given by,

$$Qs = -\frac{3}{2}\frac{w_s}{\sigma L_s}\varphi_s\left[\frac{L_m}{Lr}\varphi_s - \varphi_r\cos\delta\right] \qquad (1)$$

Under healthy grid condition □□ can be assumed to be

Constant [5]. Then, in terms of small perturbations,

$$\Delta Q_s = -\frac{3}{2}\frac{w_s}{\sigma L_s}\varphi_s\Delta\varphi_r\, cos\,\delta + \frac{3}{2}\frac{w_s}{\sigma L_s}\varphi_s\varphi_r\sin\delta\,\Delta\delta \quad (2)$$

As σ is normally small $\cos\sigma \approx 1$ and $\sin\sigma \approx 0$ then (2) can be approximated as,

$$\Delta Q_s = -\frac{3}{2}\frac{w_s}{\sigma L_s}\varphi_s\Delta\varphi_r \qquad (3)$$

Therefore, a single integral controller (Fig. 2) has been used for the rotor flux reference generation from the stator reactive power error. As the rotor flux varies only around the rated value, the integrator output is added to a feed-forward term representing the rated rotor flux to reduce transient during starting of the reactive power controller. The torque reference has been generated from the speed error using another PI controller as shown in Fig. 2. The torque reference is limited to a maximum value of 0, to avoid active power drawn from the source during acceleration.

B. Rotor flux and torque control

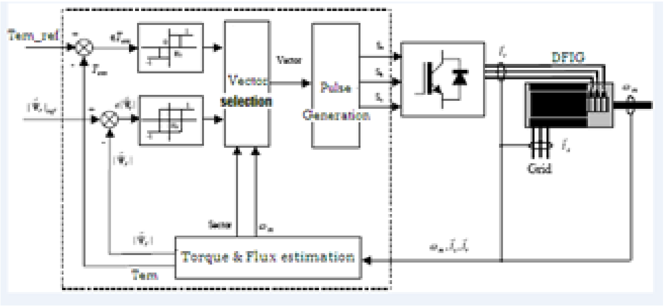

Fig.3. Rotor flux and torque control

Equations for flux and torque are given by,

$$\frac{d\varphi_r}{dt} = \left(\frac{R_r L_m}{\sigma L_s L_r}\right)\varphi_s \cos\delta - \left(\frac{R_r}{\sigma L_r}\right)\varphi_r + \frac{2}{3}V_{DC}\cos\left(w_{rt} - \frac{\pi}{3}(n-1)\right) \tag{4}$$

$$\frac{dT_e}{dt} = T_e\left(\frac{w_r}{\tan\delta} - \frac{R_s}{\sigma L_s} - \frac{R_r}{\sigma L_r}\right) + P\frac{L_m}{\sigma L_s L_r}V_{DC}\sin\left(w_{rt} + \delta - \frac{\pi}{3}(n-1)\right) \tag{5}$$

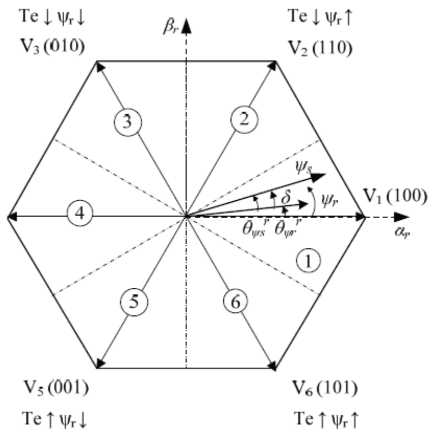

Fig.4. Inverter voltage vector selection in MC[1]

In the conventional DTC strategy, with the rotor flux in sector 1 (Fig. 4), voltage vectors V2 and V3 are applied for decreasing torque while V5 and V6 are used for increasing torque [1].

V. MATRIX CONVERTER OPERATION AND CONTROL

For the grid connected DFIG, supplied by back-to-back VSI

The machine torque and the stator reactive power are controlled by the rotor side converter. DTC and DPC for DFIG using VSI are described in detail in [5]-[6].

Matrix converter can be used to direct conversion of generator variable AC frequency into the grid constant AC frequency. So it is also called AC-AC converter. The control of input and output voltage waveforms of proposed converter can be achieved through PWM technique.

A. Space vector modulation for MC

Space vector modulation is a form of pulse width modulation that is based on a two phase representation of a three phase quantities. SVPWM has a wide linear modulation range and switching frequency is much greater than the input fundamental frequency and thus it is possible to remove high frequency components using a low pass filters [7].

SVPWM consists of a Voltage source rectifier and voltage source inverter which are joint by a fictitious DC link.

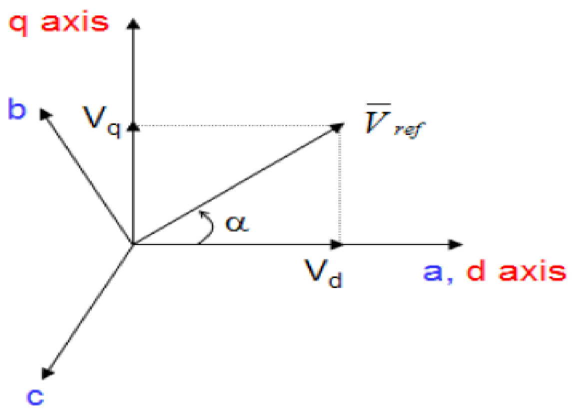

Fig.5.Voltage Space Vector and its components in (d, q).

B. Principles of space vector modulation

i) Treats the sinusoidal voltage as a constant amplitude vector rotating at constant frequency.

ii) This PWM technique approximates the reference voltage V_{ref} by a combination of the eight switching patterns (V_0 to V_7)

iii) Coordinate Transformation (abc reference frame to the stationary d-q frame: A three-phase voltage vector is transformed into a vector in the stationary d-q coordinate frame which represents the spatial vector sum of the three-phase voltage.

iv) The vectors (V1 to V6) divide the plane into six sectors (each sector: 60 degrees)

v) Vref is generated by two adjacent non-zero vectors and two zero vectors.

C. Matrix Converter voltagee vectors

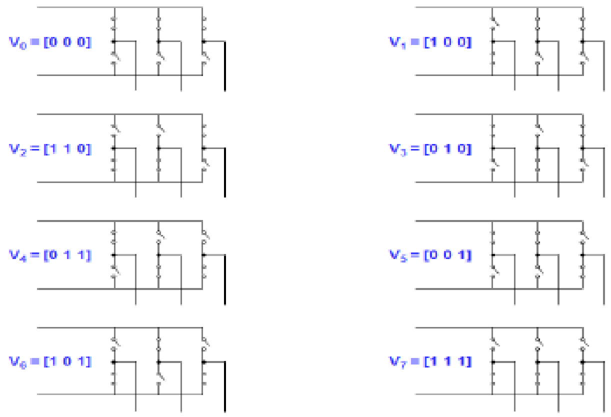

Fig.6.Converter switching states in MC

Phase voltages and output line-to-line voltages in SVPWM

Voltage Vectors	Switching Vectors			Line to neutral voltage			Line to line voltage		
	a	b	c	Van	Vbn	Vcn	Vab	Vbc	Vca
Vo	0	0	0	0	0	0	0	0	0
V1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V2	1	1	0	1/3	1/3	-2/3	0	1	-1
V3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V4	0	1	1	-2/3	1/3	1/3	-1	0	1
V5	0	0	1	-1/3	-1/3	2/3	0	-1	1
V6	1	0	1	1/3	-2/3	1/3	1	-1	0
V7	1	1	1	0	0	0	0	0	0

D. *Matrix converter control*

In the proposed topology of WECS the MC is controlled using the SVM scheme. In the convention method used for the analysis, two rotating axes are required. Towards the input side, a synchronous frame rotating at the grid electrical frequency is used. This frame is orientated along the input voltage vector. For the output side, a conventional vector control system, for DFIGs, is used. In this case, the reference rotating frame is orientated along the stator flux. It is assumed that the MC is controlled to operate with close-to-unity power factor at the input. Current and voltage at the output side are controlled by controlling the duty cycle of the switches.

The relations between voltage and current are justified by following equations.

$$VABC = S.\ Vabc \qquad (6)$$

$$Iabc = ST.\ IABC \qquad (7)$$

Where, VABC= Output Voltage

Vabc = Input Voltage

IABC = Output Current

Iabc = Input Current

$$S=\begin{bmatrix} S11 & S12 & S13 \\ S21 & S22 & S23 \\ S31 & S32 & S33 \end{bmatrix}$$

S11 – S33 is duty cycle of corresponding switches of matrix converter.

Instead of using conventional back-to-back converters with DC-link capacitor, direct matrix converter (DMC, Fig.2, with reduced passive element (the dc-link capacitor, line filter components etc.) requirement can be a good alternative for this kind of generation system. It was proved in [2] that MC topologies enable a 2.5 times higher maximum power density and a five times higher maximum power to mass ratio at a higher efficiency compared to the back-to-back voltage source converter system for the same input voltage, output power and switching frequency range.

VI. SIMULATION STUDY

Simulation software is used to simulate the dynamic behaviour of the system that is represented by a mathematical model. While the model is being simulated, the state of the simulation using either time-based or event-based solvers. Simulation software also typically includes visualization tools, such as data displays, to help monitor the simulation as it runs. There are different software available viz LTSPICE from Linear Technology, Qucs from source forge, Electric from Static Fee Software, MATLAB and Simulink software. In this paper MATLAB R2013a software is used for simulation study because of the following advantages:

i) It is often cheaper and easier to create and simulate a model than to create and test a hardware prototype.
ii) Early in the development process, if hardware is not yet available for testing, one can use simulation software to explore the design space and test different scenarios as early as possible.
iii) Once hardware becomes available, one can connect it to the simulation software pieces of the system interface with one another.

A. *Simulation Diagram*

i) Simulation diagram of DFIG without any control strategy:

A) Simulation model of DFIG without using any control strategy:

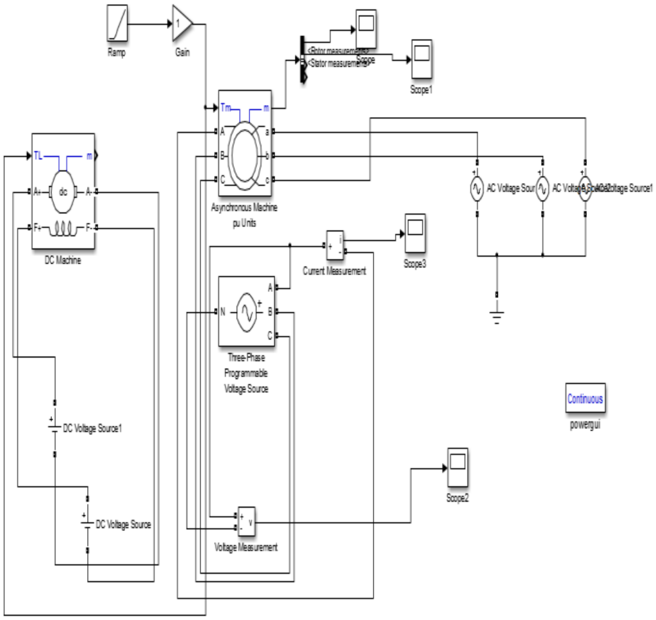

Fig.7. Simulation model of DFIG without any control strategy.

B) Results

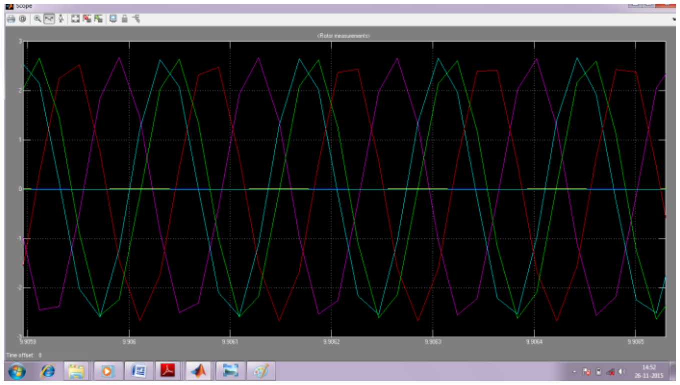

Fig.8. simulation result of rotor measurements

Without using any control strategy for DFIG an output is a distorted waveforms. Rotor currents of three phases are distorted as in fig.8

ii) Simulation diagram of controlling DFIG using a matrix converter

A) Simulation model of controlling DFIG using MC

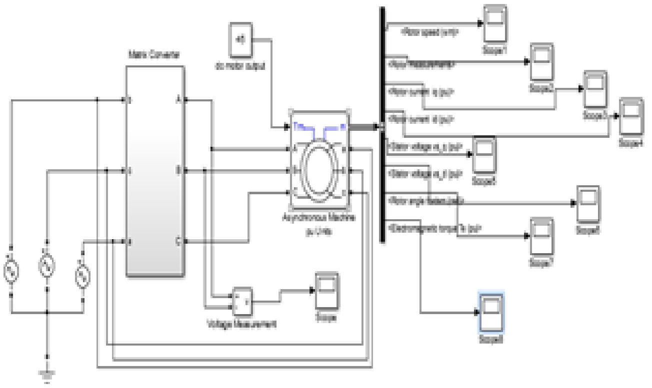

Fig.9. Simulation model of controlling DFIG using MC

B) Simulation model of matrix converter

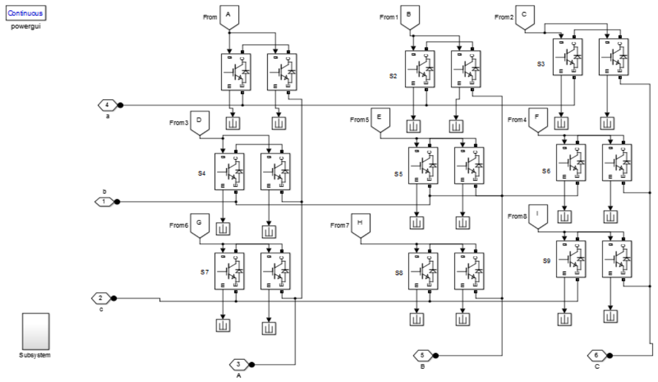

Fig.10. simulation model of matrix converter

C) Simulation model of space vector modulation of MC

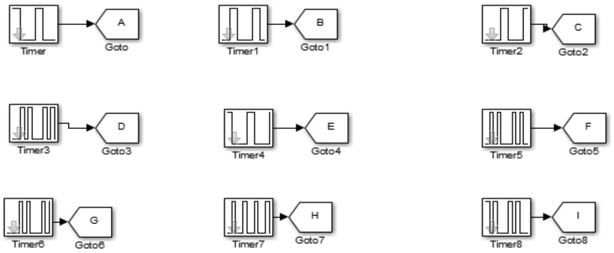

Fig.11.simulation model of SVPWM

VII. RESULT AND DISCUSSION

This study deals with the analysis of a matrix converter technologies for controlling a DFIG used in WECS using MATLAB software. Simulation was carried out using MATLAB Simulink.

i) The graph below shows a rotor current q axis component in per unit value. By using a matrix converter technologies waveforms are less distorted

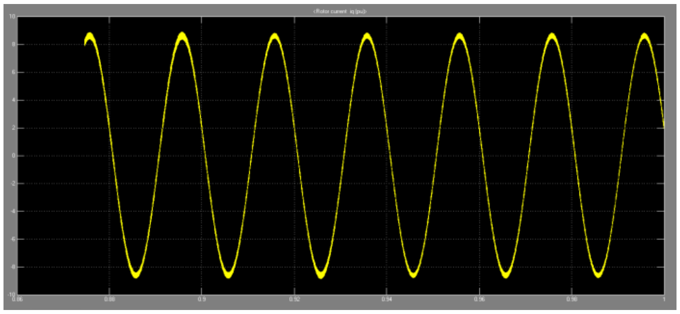

Fig.12. Rotor current q axis(pu)

ii) The graph below shows a rotor current d axis component in per unit value

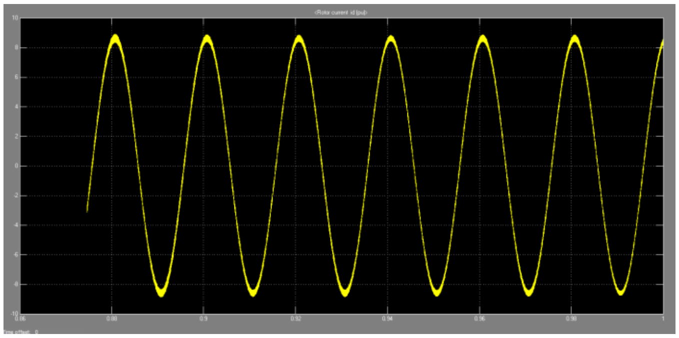

Fig.13. Rotor current d axis (pu)

iii) The graph below shows a stator voltage q axis in per unit value

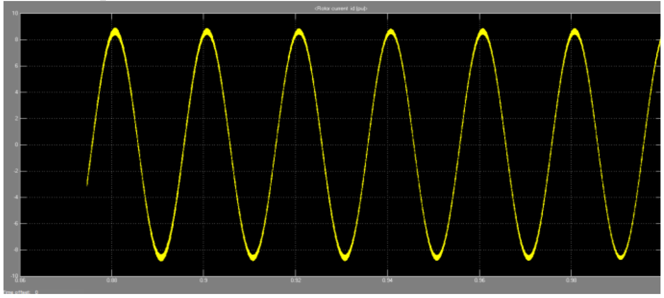

Fig.14. Stator voltage q axis(pu)

iv) The graph below shows a stator voltage d axis in per unit value

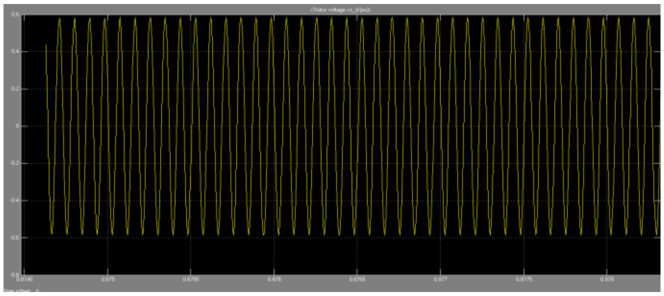

Fig.15. Stator voltage d axis (pu)

v) The graph below shows a electromagnetic torque developed

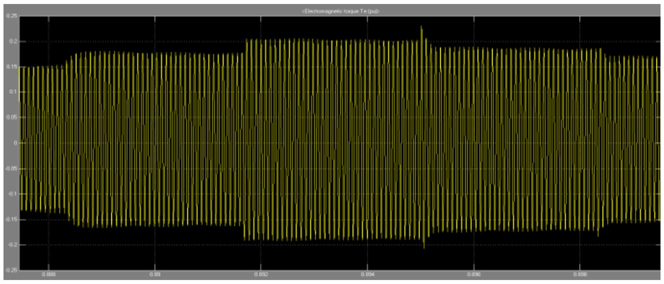

Fig.16. Electromagnetic torque

vi) The graph below shows rotor speed of DFIG

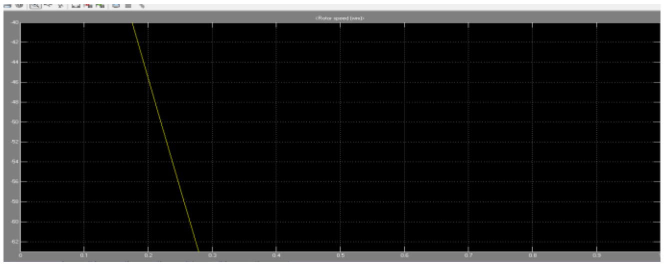

Fig.17. Rotor speed of DFIG

From the above results it is seen that matrix converter controls DFIG based wind turbine consists of rotor side converter and grid side converter with a fictitious DC link in between. The rotor side converter applies the voltage to the rotor windings of DFIG. The purpose of rotor side converter is to control the rotor currents such that the rotor flux position is optimally oriented with respect to the stator flux in order that the desired torque is developed at the shaft of the machine.

Matrix converter topologies enables a system to take less time to stabilize. Torque quality and voltage stability is better in matrix converter as seen from results the waveforms are less distorted [9].

VIII. CONCLUSION

A modified DTC controller, suitable for an MC fed DFIG based VSCF wind power generation system, has been analyzed in detail in this paper. In the proposed control strategy the machine speed and the stator reactive power are controlled in closed loop to generate the machine torque and the rotor flux references for the DTC. From the performance results obtained from the matrix converter technology (MC), it is observed that, the matrix converter (MC) performances are similar to voltage back-to-back converter technology except total harmonic distortion (THD).

MC has a minimal higher order harmonics and has minimal energy storage requirements, which allows to get rid of bulky and lifetime-limited energy storing capacitors. For reduction of total harmonic distortion a novel look-up table based controller for a variable speed constant frequency (VSCF) DFIG supplied from a direct matrix converter is used. This up-gradation of the input current control switching table reduces the distortion in the grid supplied current waveform.

From the simulation results obtained from MATLAB Simulink it is observed that, using a MC technologies there is less total harmonic distortion in supplied stator currents and voltages.

REFERNCES

[1]. Suman Mondal and Debaprasad Kastha,member IEEE," Improved Direct Torque and Reactive Power Control of a Matrix Converter Fed Grid Connected Doubly Fed Induction Generator".2015.

[2]. T. Friedli, J. W. Kolar, J. Rodriguez, and P. W. Wheeler, "Comparative evaluation of three-phase AC–AC matrix converter and voltage DC-link back-to-back converter systems," *IEEE Trans. Ind. Electron.*, vol. 59, no. 12, pp. 4487 - 4510, Dec. 2012.

[3]. P R Aswathy, R. Rajesekaran, SNS College of Technology, Coimbatore, Tamilnadu," Analysis of Power Transformation in DFIG Based Wind Farm Using Matrix Converter".2014.

[4]. Lars Helle and Stig Munk-Nielsen, Aalborg University,Institute of Energy Technology,"Comparison of Converter Efficiency in Large Variable Speed Wind Turbines".2001.

[5]. Benjamin.J.Harris,"matrix converter technology in DFIG for wind generator", Faculty of informatics, University of Wollongong.2009.

[6]. Zhixin Miao, Lingling Fan,"The art of modeling and simulation of induction generator in windgeneration applications using high-order model", Midwest Independent Transmission System Operator, St. Paul, MN 55108, United States, Department of Electrical & Computer Engineering, North Dakota State University, Fargo, ND 58105, United States.2008.

[7]. Amit Kumar Sinha, C.Hemalatha, Mridul Pandey, Dipayan Adhikary,"Performance Evaluation of Wind Energy Conversion System using Matrix Converter".2014.

[8]. Stephan Meier, Department of Electrical Engineering ETS," Losses in Power Electronic Converters".

[9]. F.Boumaraf, L.Khettache,R.Abdessemed, M.L.Mendaas, Research Laboratory, Department of Electrical Engineering, University of Batna,"Power and torque ripple minimization of DFIG in WECS using Space vector modulation".2014.

[10]. C. Ponmani, M. Rajaram,"Compensation strategy of matrix converter fed induction motor drive under input voltage and load disturbances using internal model control".2012

[11]. Martin Jones, I. Nyoman Wahyu Satiawan," A simple multi-level space vector modulation algorithm for five-phase open-end winding drives"2012.

[12]. Péter Stumpf, Rafael K. Járdán, István Nagy," Analysis of the impact of space vector modulation techniques on the operation of ultrahigh speed induction machines".2012.

[13]. Mohammed T. Lazim, Muthanna J. M. Al-khishali, Ahmed Isa. Al-Shawi," Space Vector Modulation Direct Torque Speed Control Of Induction Motor".2011.

[14]. Farid Khoucha, Soumia Mouna Lagoun, Khoudir Marouani, Abdelaziz Kheloui, Mohamed Benbouzid," Hybrid Cascaded H-Bridge Multilevel-Inverter Induction-Motor-Drive Direct Torque Control for Automotive Applications".2010.

APPENDIX

Parameters of DFIG simulated

i) Rated power : 3 kW
ii) Stator voltage: 460 V
iii) Frequency : 60Hz
iv) Stator resistance (Rs): 0.01909
v) Stator inductance(Ls): 0.0397
vi) Rotor resistance(Rr): 0.01909
vii) Rotor inductance(Ls): 0.0397
viii) Mutual inductance (Lm): 1.354
ix) No.of poles: 4
x) Synchronous speed: 1800 rpm