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Enhancement in performance of wind energy conversion system including matrix converter

Prabhat Ranjan Sarkar, Abhishek Kashyap, Vineeta Agarwal

Abstract- **This paper contributes a role in enhancement of performance of wind energy conversion system. A variable speed wind turbine faded with matrix converter with new topology is proposed. A direct AC-AC matrix converter is implemented alternative to the conventional AC-DC-AC converter faded wind turbine and two quadrant mode operation of doubly fed induction generator. Matlab/Simulink is used to build the dynamic model and simulate the result. Characteristics of the power produced and power exchange not only depends on induction generator but also depends on matrix converter. This paper demonstrates the two quadrant operation of doubly fed induction generator and also dynamic model is presented on the basis of simulation result to demonstrate the performance of proposed system.**

Index Terms- **Wind energy conversion system, Doubly fed induction generator, AC-AC matrix converter, Variable speed wind turbine, Power control.**

I. Introduction

In present scenario peoples are more and more concerned with the fossil fuel exhaustion and the environmental problems caused by the conventional power generation, renewable energy sources such as solar energy, wind power, hydro, and other renewable energy sources are wildly used for energy generation. This trend will continue during the next years because the energy produced by renewable sources is expected to satisfy 25% and more than 50% of the total needs of power in 2020 and 2050, respectively[1]. The recent significant advances in power electronics play a vital role to focus the research in renewable energy sources. Wind energy conversion system become more important in power generation due to its easy availability and eco-friendly nature and its demand has grown consistently by 17% to 24% per annum. In last few decades wind turbine manufacturers are moving to the concept of variable speed drive due to certain advantages such as optimum energy extraction, reduction in mechanical stress, Easy pitch control and higher efficiency [2] in which conventional Synchronous generators (SG), Permanent magnet synchronous generators (PMSG) and doubly fed induction generators (DFIG) are commercially used as wind generators. In recent wind power applications doubly fed induction generator (DFIG) have drawn interest of research scholars due to its various advantages over other variable-speed WTGs. A doubly fed induction generator (DFIG) is a wound rotor induction machine in which stator winding is directly connected to the grid and its rotor windings is connected to the grid through Matrix converter.

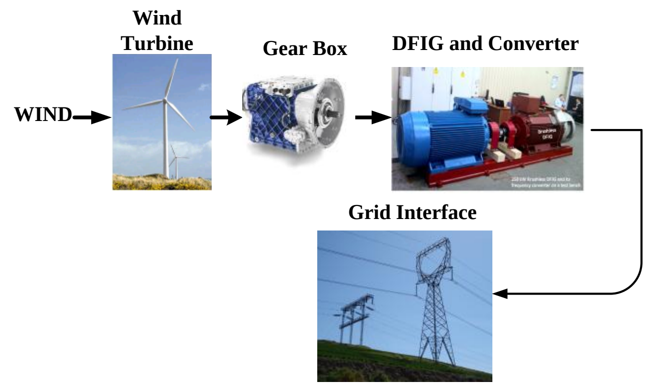

Fig.1 Block Diagram showing globle wind energy conversion system.

In DFIG the power generated is delivered through two paths, one directly from stator to grid and another from rotor to grid through matrix converter. DFIG is a single adjustable speed drive which consume fractional of total power may be (22% to28%) and have less mechanical stress. Doubly Fed Induction generator has an ability to output more power than its rated value without becoming overheated. One more advantage of DFIG is that it is able to operate in both sub and super synchronous mode for transferring the maximum power over a wide speed range [2, 3]. In this induction generator power rating of converter is reduced because it is connected to the rotor side and maximum power flows through the stator. In conventional implementation of doubly fed induction generator, back to back (AC-DC-AC) converters are connected in which rotor side converter controls the torque and magnetizing currents of rotor side while DC bus voltage is controlled by grid side connected converter [3].

In this paper the conventional back to back (AC-DC-AC) converter is replaced by a matrix (AC-AC) converter. Matrix converter is able to convert variable AC to fixed AC in a single stage and also eliminates the use of DC link elements due to which system become more compact and reliable, reduces size. Matrix converter allows bidirectional flow of power and operates at unity power factor for any load due to man advantage of matrix converter it attracts researchers to focus on developing new control and modulation technique to optimise the performance in wind energy conversion system. Fig. 2 shows a doubly fed induction generator with matrix converter. Matrix converter has certain limitations which must be overcome for commercial applications [4]:

1- Limited Voltage transfer ratio only 86.6%.

Authors are with the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Allahabad-211004, India
(email: sarkarprabhat@rediffmail.com, qwertyabhi@gmail.com, vineeta@mnnit.ac.in).

2- Absence of natural bidirectional switches and freewheeling paths.

3- Very sensible to input disturbances and complex modulation and commutation techniques.

II. Modelling of the Integrated System:

A. *Modelling of the wind turbine and gearbox:*

The mechanical power output of wind turbine is given by [5]:

$$P_t = \frac{1}{2} Cp*(\lambda, \beta)\rho \Pi R^2 v^3 \quad (1)$$

Where P_t is the mechanical power output, ρ is the air density, R is the blade length, C_p is the power coefficient and V is the velocity of wind.

The turbine torque is the ratio of the output power to the shaft speed. It is expressed by ω_t .

$$T_{aer} = \frac{P_t}{\omega_t} \quad (2)$$

Wind turbine and generator shaft is normally coupled through gear box having gear ratio **G** for maintaining the shaft speed Within suitable range. The shaft speed and torque of the wind turbine is expressed as:

$$T_g = \frac{T_{aer}}{G} \text{ and } \omega_t = \frac{\Omega_{mec}}{G}. \quad (3)$$

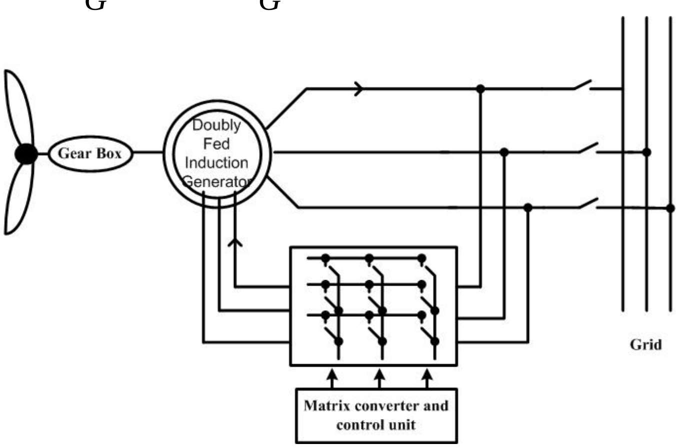

Fig 2 Schematic diagram of a wind turbine with DFIG –WECS

Tip speed ratio is the ratio of blade tip speed and wind speed and expressed by:

$$\lambda = \frac{\Omega_t R}{v}. \quad (4)$$

The power coefficient (C_p) is depending on pitch angle (θ) of the rotor blades and the tip speed ratio (λ) and expressed as [6]:

$$C_p = 0.73(\frac{151}{\lambda_i} - 0.58\theta - 0.002\theta^{2.14} - 13.2)e^{-18.4/\lambda_i} \quad (5)$$

And
$$\lambda_i = \frac{1}{\frac{1}{(\lambda_i - 0.02\theta)} - \frac{0.003}{\theta^3 + 1}} \quad (6)$$

For maximizing the power coefficient, pitch angle Of the turbine should be zero. Putting $\theta = 0$ we get C_{pmax}= 0.502 and λ_{opt}= 9.92.
Figure 3 shows a typical relationship between coefficient of performance and tip ratio at different pitch angles.

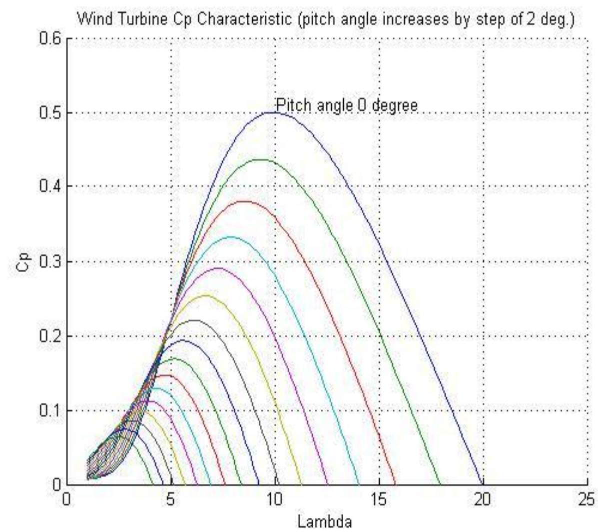

Fig. 3 Wind turbine Power- Coefficient characteristics

The simplified representation of wind turbine and its control is shown in fig 4 with the help of block diagram [7].

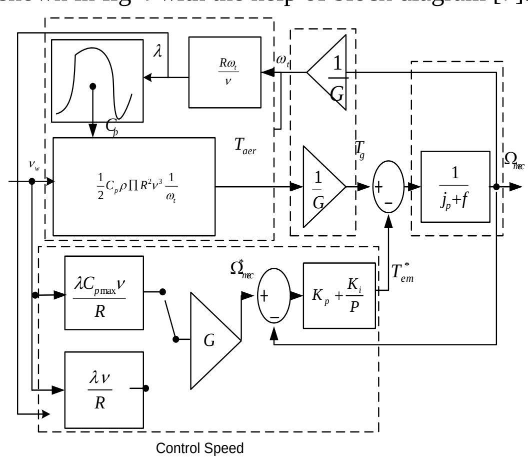

Fig. 4 Wind turbine Control Scheme.

B. *Modelling of the Doubly Fed Induction Generator:*

Wind turbine having doubly fed induction generator will have various advantages :

1- Flexible speed operation (±33% of synchronous speed)
2- Four quadrant active and reactive power transfer capability.
3- Less converter cost (20% of total system power)
4- Minimum power loss.

DFIG is robust and requires little maintenance. The control scheme of DFIG is usually termed in stator voltage or stator flux in synchronous dq frame, the generator dynamic model written in synchronously rotating frame dq in matrix form is given by:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \phi_{ds} \\ \phi_{qs} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_s \\ \omega_s & 0 \end{bmatrix}\begin{bmatrix} \phi_{ds} \\ \phi_{qs} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \phi_{dr} \\ \phi_{qr} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_r \\ \omega_r & 0 \end{bmatrix}\begin{bmatrix} \phi_{dr} \\ \phi_{qr} \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} \phi_{ds} \\ \phi_{qs} \\ \phi_{dr} \\ \phi_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (9)$$

Where R_s and R_r are respectively stator and rotor resistances. L_s, L_m and L_r are respectively stator, mutual and rotor inductances. i_{ds} and i_{dr} are direct axis stator and rotor current respectively. i_{qs} and i_{qr} are quadrature axis stator and rotor current respectively [8].
The mechanical equation is given by:

$$T_{em} - T_g = J\frac{dQ_{mec}}{dt} + f.Q \quad (10)$$

Where T_{em} is electromagnetic torque of the DFIG and expressed by:

$$T_{em} = P.(\varphi_{ds}.i_{qs} - \varphi_{qs}.i_{ds}) \quad (11)$$

J is the inertia constant of shaft and f is the viscous friction coefficient. The active and reactive powers at stator and rotor are defined in terms of matrix is given as:

$$\begin{bmatrix} P_s \\ Q_s \end{bmatrix} = \begin{bmatrix} v_{ds} & v_{qs} \\ v_{qs} & -v_{ds} \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (12)$$

And
$$\begin{bmatrix} P_r \\ Q_r \end{bmatrix} = \begin{bmatrix} v_{dr} & v_{qr} \\ v_{qr} & -v_{dr} \end{bmatrix}\begin{bmatrix} i_{dr} \\ i_{qr} \end{bmatrix} \quad (13)$$

$P_g = P_s + P_r$ similarly $Q_g = Q_s + Q_r$ (14)

III. Modelling of the Matrix converter:

The matrix converter performs direct conversion of variable AC to fixed AC with high degree of controllability which controls output voltage, frequency and phase angle independently. In the proposed system matrix convertor controls the voltage and frequency of induction generator in such a manner that the wind turbine system is operated on maximum power point. In matrix converter, the three-phase ac voltages on input side is connected to the three-phase voltages on output side by a 3×3 matrix (or array) of bi-directional switches. It means, matrix converter needs 9 bi-directional switches, one switch between each input phase and each output phase. The switching function of matrix converter shown in figure 5 is given by [9]:

$$S_{ij} = \begin{cases} 1 \; Sij \text{ is closed} \\ 0 \; Sij \text{ is open} \end{cases} \quad i \in \{a,b,c\},\; j \in \{A,B,C\} \quad (15)$$

The following constraint applies to the switching functions:

$$S_{ia} + S_{ib} + S_{ic} = 1, \quad I = A, \; B, C. \quad (16)$$

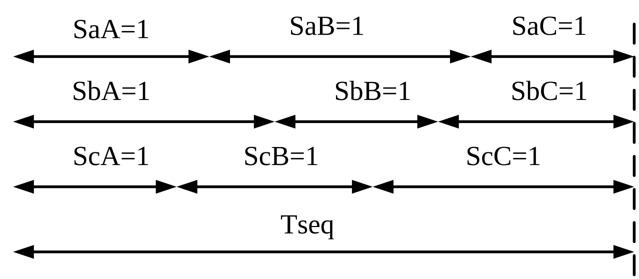

Fig. 5 switching pattern of matrix converter

A. *VENTURINI Algorithm:*

In this algorithm the switch S_{ij} is controlled in such a manner that the low frequency part of the synthesized output voltage (v_a,v_b, v_c) and input rotor current (i_{Ar}, i_{Br} and i_{Cr}) are purely sinusoidal in nature with the reset values of input and output frequency, the displacement factor and input amplitude[10]. The average values of output voltages during N^{th} cycle in terms of matrix is given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{T_s} \begin{bmatrix} t_{aA}^N & t_{aB}^N & t_{aC}^N \\ t_{bA}^N & t_{bB}^N & t_{bC}^N \\ t_{cA}^N & t_{cB}^N & i_{cC}^N \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (17)$$

If the time remains constant and time of conduction modulated in shape of sine wave [11]with frequency w_m then these times are defined as fallowing :

A- For 1st phase:

$$t_{aA} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta))$$
$$t_{aB} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta-\frac{2\Pi}{3})) \quad (18)$$
$$t_{aC} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta-\frac{4\Pi}{3}))$$

B- For 2nd phase:

$$t_{bA} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta-\frac{4\Pi}{3}))$$
$$t_{bB} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta)) \quad (19)$$
$$t_{bC} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta-\frac{2\Pi}{3}))$$

C- For 3rd phase:

$$t_{cA} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta-\frac{2\Pi}{3}))$$
$$t_{cB} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta-\frac{4\Pi}{3})) \quad (20)$$
$$t_{cC} = \frac{T_s}{3}(1+2m\cos(\omega_m t+\theta))$$

Where θ is the initial phase angle.

The output voltage is given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} 1+2m\cos\alpha & 1+2m\cos(\alpha-\frac{2\Pi}{3}) & 1+2m\cos(\alpha-\frac{4\Pi}{3}) \\ 1+2m\cos(\alpha-\frac{4\Pi}{3}) & 1+2m\cos\alpha & 1+2m\cos(\alpha-\frac{2\Pi}{3}) \\ 1+2m\cos(\alpha-\frac{2\Pi}{3}) & 1+2m\cos(\alpha-\frac{4\Pi}{3}) & 1+2m\cos\alpha \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

Where $\begin{cases} \propto = \omega_m t+\theta \\ \omega_m = \omega_o - \omega_i \end{cases}$ 0<m<0.866. (22)

IV. System Modeling:

A. Grid Modeling:

Figure 6 shows how the electrical network is connected with wind generator through transmission line and modeled as Z_{line} impedance and equivalent thevenin's impedance (Z_{th}) is given by:

$$Z_{th} = \frac{U^2}{S_{cc}} \quad (23)$$

Where U is the rated output voltage and S_{cc} is the short circuit capacity [12].

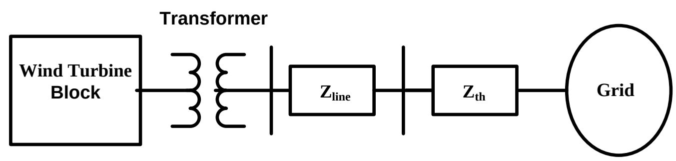

Fig. 6 Simplified Grid Modelling.

B. DFIG Control:

Figure 7 shows the block diagram of power control which controls the active and reactive power exchange between grid and doubly fed induction generator. For connecting the DFIG with utility grid we have to consider that the stator voltage must be synchronized with grid voltage as a reference[12]. On considering the zero quadrature component of the stator i.e.:

$$\phi_{ds} = \phi_s \text{ and } \phi_{qs} = 0 \quad (24)$$

Putting these values we simplified torque and it is given by

$$T_{em} = -P\frac{L_m}{L_s} I_{qr}\phi_{ds} \quad (25)$$

With slip $s = \frac{\omega_s - \omega}{\omega_s}$ the equation 12 can be written as:

$$P_D = (S-1).V_s \frac{L_m}{L_s}.i_{qr} \quad (26)$$

$$Q_D = \frac{v_s^2}{\omega_s . L_s} + (S-1).V_s \frac{L_m}{L_s}.i_{dr} \quad (27)$$

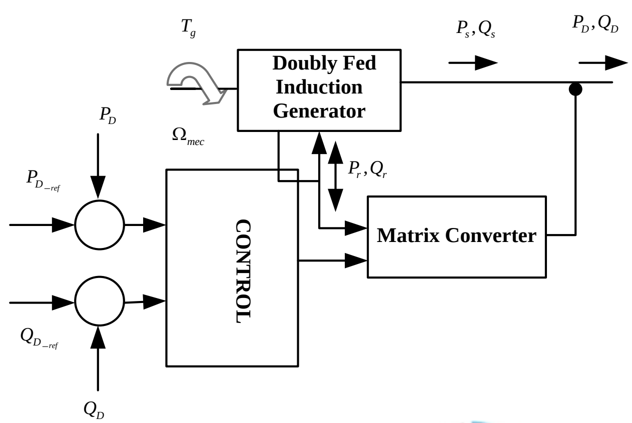

Fig. 7 Schematic Diagram of Power control of DFIG.

VI. SIMULATION STUDY:

The simulation result of DFIG, controlled by its rotor connected matrix converter and stator is directly connected to the grid are done in matlabR2010a. Figure 8 shows the active and reactive power supplies to the grid. From this figure we conclude that DFIG supplies only active power The voltage and current wave form of grid is shown in figure 9 and zoom out of grid voltage and current are shown in figure 10. Stator voltage and current waveforms are shown in figure 11. Fig 12 shows zoom out of current and voltage waveform.. Figure 13 shows the o/ p of the matrix converter and figure 14 zoom out of current and voltage wave forms.

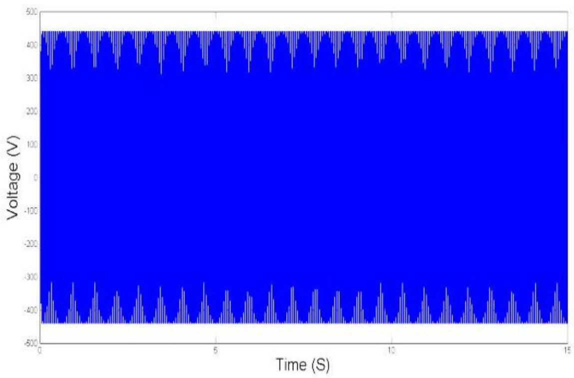

Fig. 9 Grid Voltage and Current waveforms

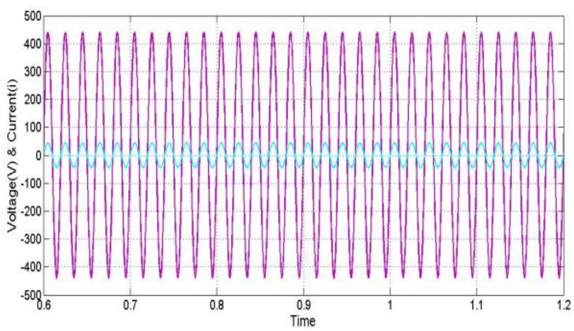

Fig. 10 Zoom out of Grid Voltage and Current waveforms

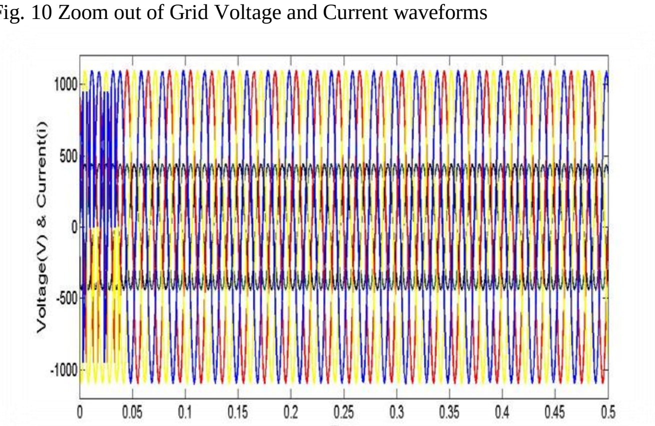

Fig. 13 Matrix converter o/p voltage and current.

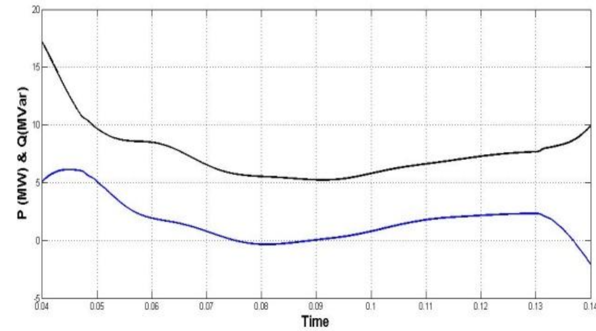

Fig .8 Active and reactive power of grid.

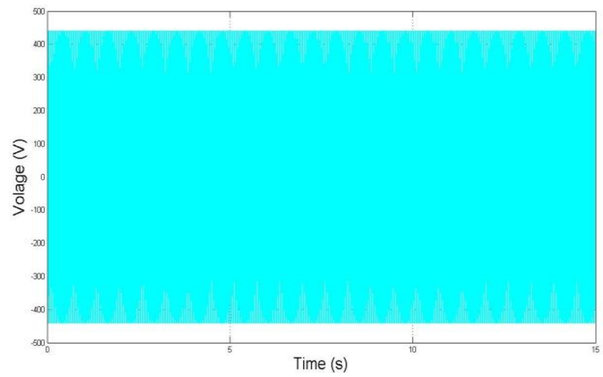

Fig. 11 Stator Voltage and Current waveforms

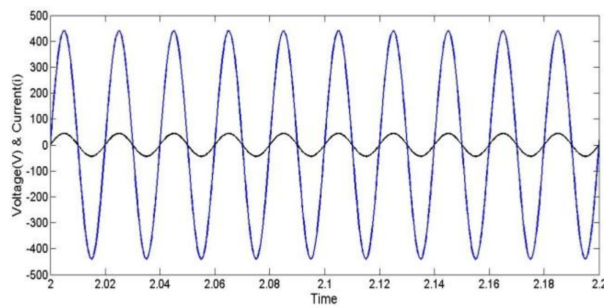

Fig. 12 Zoom out of Stator Voltage and Current waveform

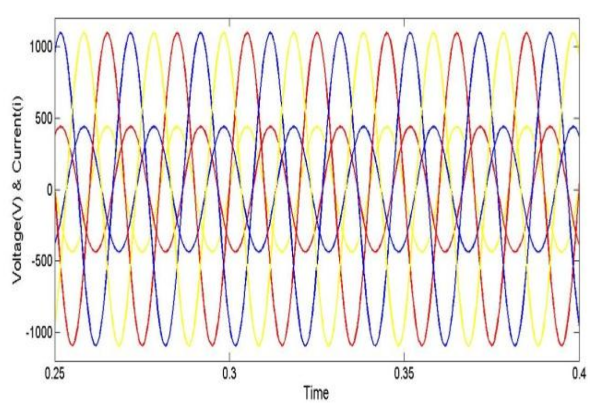

Fig. 14 Zoom out of matrix converter o/p voltage and current.

VI. Conclusion:

In this paper a doubly fed induction generator based wind turbine is proposed including matrix converter. This paper plays a contribution in improvement of wind energy conversion system. Stator and rotor flux control technique is used for stable operation of overall system. A proposed technology is validated by control of active and reactive power of DFIG through simulation results.

Analyzing and observing modeling and simulation results we conclude that Matrix converter are the best alternative of conventional AC-DC-AC converter. Doubly fed induction generator is operated in two modes. For s>0 It runs in sub synchronous mode and for s<0 it runs in super synchronous mode. DFIG only supplies active power to the grid in all operating mode in all operating modes.

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Biographies

Prabhat Ranjan Sarkar was born in Deoria, India on May 05, 1990. He graduated from the Uttar Pradesh Technical University, Lucknow, India with B.Tech. degree in Electricals and Electronics Engineering in 2011. He is currently pursuing his M.Tech in Power Electronics and ASIC Design at MNNIT Allahabad. My topic of intrest is renewable energy, wind energy, cycloconverters and resonance converters.

Abhishek Kashyap was born in Bareilly, Uttar-Pradesh, India on 23-03-1988. He has passed his Bachelor of Technology degree in Electronics and Communication from GLAITM Mathura in 2010. Presently he is a student of M.Tech in Power Electronics and ASIC design in MNNIT Allahabad. His topic of interest is Z Source converter, Cycloinverter, Resonant Converters.

Vineeta Agrawal (SM'09) received the M.S. degree from Allahabad University, Allahabad, India, in 1984, and the Ph.D. degree in power electronics from Motilal Nehru Regional Engineering College, Allahabad, India.

She joined the Electrical Engineering Department, Motilal Nehru Regional Engineering College, Allahabad, India, as a Lecturer in 1982. She is currently is a Professor with the Department of Electrical Engineering, Motilal Nehru National Institute of Technology, Allahabad. She has taught numerous courses in electrical engineering and electronics. Her research interests are in single phase to three-phase conversion and ac drives. She has authored and co-authored a number of publications in journals and conferences in her field. She has attended and presented papers at both national and international conferences.