Analysis of Doubly Fed Induction Generator Connected Matrix Converter in Wind Farm

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***Abstract*— In recent years, wind energy has become one of the most important and promising sources of renewable energy, which demands maintaining better means of system stability. Here the dynamic performance of a grid-connected wind energy conversion system (WECS), based on a doubly fed induction generator (DFIG) fed by a matrix converter (MC), is presented. The stator winding of the DFIG is connected directly to the grid and the rotor of the DFIG is connected to the grid through a matrix converter. For instance, due to the absence of electrolytic capacitors, the MC can potentially be robust and reliable. In a conventional implementation the rotor side converter controls the magnetizing current and rotor torque. The grid side converter regulates the voltage in the dc bus of the back-to-back converters. In this paper, a back-to-back (B2B) converter is replaced by a Matrix converter (MC). A space vector modulation technique is used to control the MC, regulating the rotor torque and magnetizing currents. Dynamic analysis of the DFIG is done by using both repeating table parameters and constant value parameters. In repeating table parameter, the time values are fixed as [0 0.01 0.3 0.31]. Here the values of time should be monolithically increasing. From the output waveform it was concluded that, irrespective of the wind gust the generator speed is maintained to a rated value of 1500rpm and the voltage and frequency changes due to fluctuations in wind speed is also maintained constant and the stability achieved**.

***Keywords*— Wind turbine, DFIG, Back to Back converter (B2B), Matrix converter (MC), Space vector modulation technique.**

I. INTRODUCTION

Matrix converters (MCs) have many advantages, which are well documented in the literature. The MC provides bidirectional power flow, sinusoidal input/output currents, and controllable input power factor. When compared to back-to-back (B2B) converters, the MC has some significant advantages. For instance, due to the absence of electrolytic capacitors, the MC can potentially be robust and reliable. In this project, a new topology is proposed. The back-to-back converters are replaced by an MC. A space vector modulation (SVM) is used to control the MC, regulating the rotor torque and magnetizing currents. In the MC input side, a second-order LC power filter is used to improve the current waveform and reduce the input voltage distortion. It is analysed in this paper that the dynamic performance improves, when the DFIG stator voltage is used by the space vector modulation technique to generate the MC switching pattern. The dynamic performance of two control arrangements is assessed and the stability of the proposed control system is analysed.

MOTIVATION

In conventional back to back converter, the presence of dc link produces some fluctuations and it also needs a separate converter called grid side converter to regulate the dc bus voltage. But in matrix converter, dc link is absent which results in exclusion of separate converter. Hence drive circuits used may also be reduced. Due to the absence of this electrolytic capacitor the matrix converter can potentially be robust and reliable.

OBJECTIVE

In recent years, wind energy has become one of the most important and promising sources of renewable energy, which demands maintaining better means of system stability. The performance of a grid connected DFIG fed by a Matrix converter is presented in this project. The stator winding of the DFIG is connected directly to the grid and the rotor of the DFIG is connected to the grid through a Matrix converter. Around 65-75% of the total power is transmitted through the stator windings and the remaining 25% of the total power is transmitted using rotor windings (i.e.) through the converter. Since the output frequency and voltage of the DFIG driven by the variable speed wind turbine are changed due to unexpected fluctuations in the wind, matrix converter is used to obtain constant frequency and constant voltage which is supplied to the loads or the utility grid.

II. SYSTEM DESCRIPTION EXISTING SYSTEM

The back-to-back (B2B) converter consists simply of a force-commutated rectifier and a force-commutated inverter connected with a common dc-link. The properties of this combination are well known; the line-side converter may be operated to give sinusoidal line currents, for sinusoidal currents, the dc-link voltage must be higher than the peak main voltage, the dc-link voltage is regulated by controlling the power flow to the ac grid and, finally, the inverter operates on the boosted dc-link, making it possible to increase the output power of a connected machine over its rated power.

The use of a current-fed DC-link converter has a number of disadvantages: the DC-link choke is expensive, and an extra commutation circuit is required for operation at synchronous speed (which lies within the Operational speed range), and this has resulted in poor performance at low slip speeds. In addition, such a converter draws rectangular current waveforms from the supply. The problem at synchronous speed may be overcome by use of cycloconverter.

PROPOSED SYSTEM

Most of all industrial applications are depended on ac to ac power conversion and the ac to ac converters takes power from one ac system and delivers it to another ac system with the waveform of different amplitude, frequency, or phase. These ac to ac converters are commonly classified into two categories, one is indirect converters and another one is direct converters. Indirect converters are those converters which utilize a dc link between the two ac systems and on the other hand direct converters are those which provide direct conversion. In General, direct converter can be identified as three distinct topological approaches, the first topology can be used to change the amplitude of an ac waveform. It is known as an ac-ac controller.

The second can be utilized if the output frequency is much lower than the input source frequency. This topology is called a cycloconveter. The last is matrix converter and it is most versatile without any limits on the output frequency and amplitude. It replaces the multiple conversion stages and the intermediate energy storage element by a single power conversion stage, and uses a matrix of semiconductor bidirectional switches, with a switch connected between each input terminal to each output terminal.

PROPOSED CONTROL SCHEME

Matrix converter was described to an equivalent circuit combining current source rectifier and voltage source inverter connected through virtual dc link as shown in Fig.1.1. Inverter stage has a standard 3 phase voltage source inverter topology consisting of six switches, S7 to S12 and rectifier stage has the same power topology with another six switches, S1 to S6. Both power stages are directly connected through virtual dc-link and inherently provide bidirectional power flow capability because of its symmetrical topology. PWM strategies specified in a certain application since then, still ambiguous for a beginner to grasp its operating principle.

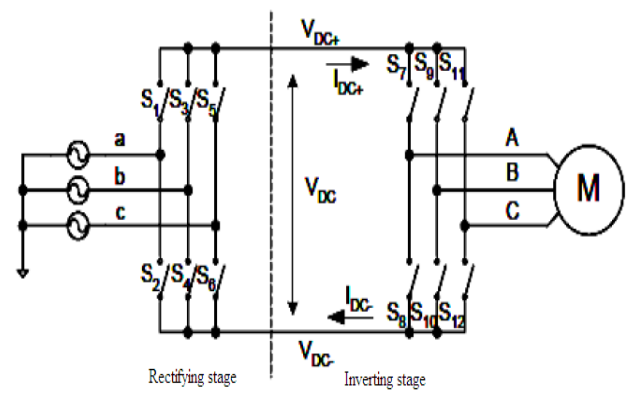

Figure 1.1 Equivalent circuit for induction modulation

The basic idea of the indirect modulation technique is to decouple the control of the input current and the control of the output voltage. This is done by splitting the transfer function T for the matrix converter in into the product of a rectifier and an inverter transfer function

$$T = I.R \qquad \ldots (1.1)$$

$$\begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \ldots (1.2)$$

Where the matrix I is the inverter transfer function and the matrix R is the rectifier transfer function. This way to model the matrix converter provides the basis to regard the matrix converter as a back-to back PWM converter without any dc-link energy storage.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \qquad \ldots (1.3)$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7S_1 + S_8S_2 & S_7S_3 + S_8S_4 & S_7S_5 + S_8S_6 \\ S_9S_1 + S_{10}S_2 & S_9S_3 + S_{10}S_4 & S_9S_5 + S_{10}S_6 \\ S_{11}S_1 + S_{12}S_2 & S_{11}S_3 + S_{12}S_4 & S_{11}S_5 + S_{12}S_6 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \ldots (1.4)$$

This means the well know space vector PWM strategies for voltage source inverter (VSI) or PWM rectifier can be applied to the matrix converter. The above transfer matrix exhibits that the output phases are compounded by the product and sum of the input phases through inverter switches S7 to S12 and rectifier switches S1 to S6. Therefore the indirect modulation technique enables well-known space vector PWM to be applied for a rectifier as well as an inverter stage. Among the possible combinations of switching sequence, a criterion which restricts the switching transition to be only once during each vector change is usually used to minimize total switching losses. Further, the zero vectors are also selected from a criterion where the number of "Branch Switch Overs" (BSO) in the matrix converter is minimized.

SVM FOR THE INVERTER STAGE

This section introduces a graphical interpretation of space vector PWM in the inverter stage. Consider the inverter part of the equivalent circuit as a standalone VSI supplied by a dc voltage source $V_{DC} = V_{DC+} - V_{DC-}$. The power conversion is performed by way of virtual dc- link V_{DC} . The output voltages can be represented as the virtual dc-link voltage V_{DC} multiplied by the switch state of the inverter stage which is inverter transfer function (I). At the same time, the dc-link current I_{DC} can be derived by using the transposed IT such as

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} V_{DC+} \\ V_{DC-} \end{bmatrix} \quad \ldots (1.5)$$

$$\begin{bmatrix} V_{DC+} \\ V_{DC-} \end{bmatrix} = \begin{bmatrix} S_7 & S_9 & S_{11} \\ S_8 & S_{10} & S_{12} \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad \ldots (1.6)$$

Then the output voltage space vector V_{OUT} and output current space vector I_{OUT} are expressed as space vectors using the transformation such as

$$V_{OUT} = \frac{2}{3}\left[V_A + V_B e^{j\frac{2\pi}{3}} + V_C e^{j\frac{4\pi}{3}}\right] \quad \ldots (1.7)$$

$$I_{OUT} = \frac{2}{3}\left[I_A + I_B e^{j\frac{2\pi}{3}} + I_C e^{j\frac{4\pi}{3}}\right] \quad \ldots (1.8)$$

The inverter switches, S_7 to S_{12} can have only eight allowed combinations to avoid a short circuit through three half bridges.

The voltage space vector *V*1 [100] indicates that output phase *VA* is connected to positive rail V_{DC+} and the other phase *VB*, *VC* are connected to negative rail V_{DC-} and its vector magnitude is calculated from

$$V_1 = \frac{2}{3}\left[V_A + V_B e^{j\frac{2\pi}{3}} + V_C e^{j\frac{4\pi}{3}}\right]$$

$$= \frac{2}{3}\left[\frac{2}{3}V_{DC} - \frac{1}{3}V_{DC}\, e^{j\frac{2\pi}{3}} - \frac{1}{3}V_{DC}\, e^{j\frac{4\pi}{3}}\right]$$

$$= \frac{2}{3}V_{DC}\, e^{j\frac{\pi}{6}} \quad \ldots (1.9)$$

The indirect space vector modulation is usually employed for the matrix converter operation and it decouples the control of the input current and the control of the output voltage. The indirect modulation is calculated by splitting the nine bidirectional switched power topology into the equivalent back-to-back PWM converter without dc-link energy storage elements.

SVM FOR RECTIFIER STAGE

To facilitate explanation, the rectification stage of the indirect matrix converter is firstly considered as a stand-alone current source rectifier. Due to the inductive nature of typical load and the high switching frequency operation, the output current, *ip*, is assumed constant for each switching period. As a result, the load of the rectifier can be assumed to be a DC current generator with a current of $i_p = I_{DC}$. At any instant, the switches of the rectifier are controlled so that the input lines must never be short-circuited. In order to generate input waveforms identical to the direct matrix converter, the rectifier not only generates the DC-link voltage V_{pn} but also has to maintain a set of sinusoidal and balanced input currents

Switching combination						Output phase voltage		
S_7	S_9	S_{11}	S_8	S_{10}	S_{12}	V_{AS}	V_{BS}	V_{CS}
1	0	0	0	1	1	$(2/3)V_{pn}$	$-(1/3)V_{pn}$	$-(1/3)V_{pn}$
1	1	0	0	0	1	$(1/3)V_{pn}$	$(1/3)V_{pn}$	$-(2/3)V_{pn}$
0	1	0	1	0	1	$-(1/3)V_{pn}$	$(2/3)V_{pn}$	$-(1/3)V_{pn}$
0	1	1	1	0	0	$-(2/3)V_{pn}$	$(1/3)V_{pn}$	$(1/3)V_{pn}$
0	0	1	1	1	0	$-(1/3)V_{pn}$	$-(1/3)V_{pn}$	$(2/3)V_{pn}$
1	0	1	0	1	0	$(1/3)V_{pn}$	$-(2/3)V_{pn}$	$(1/3)V_{pn}$
1	1	1	0	0	0	0	0	0
0	0	0	1	1	1	0	0	0

with controllable displacement angle with respect to the input voltages. As mentioned earlier, SVM is applied to control the rectifier. By using the space vector transformation, the input currents generated by the first six switching combinations are transformed into six distinctive input current space vectors with fixed directions. Each current vector refers to the connections of the input phase voltages to the DC-link. For example, the current vector I_1 (AC) represents the connection of the input phase voltage V_A to the *p*-terminal and V_C to the *n*-terminal of the DC link. The magnitudes of the current vectors depend on the instantaneous value of the current i_p.

The input currents can be represented as the virtual dc-link current IDC multiplied by the switch state of the rectifier stage which is rectifier transfer function, R. At the same time, the dc-link voltage can be derived by using the transposed RT such as

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S_5 & S_6 \end{bmatrix} \begin{bmatrix} I_{DC+} \\ I_{DC-} \end{bmatrix} \quad \ldots (1.10)$$

$$\begin{bmatrix} V_{DC+} \\ V_{DC-} \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad \ldots. (1.11)$$

then the input current space vector I_{IN} and input voltage space vector V_{IN} are expressed as space vectors using the transformation such as

Table 1.1 Valid Switching Combination For Voltage Source Inverter and the Generated output phase voltage

(Source: Bin Wu and Yongqiang Lang.,2011)

$$I_{IN} = \frac{3}{2}\left[I_a + I_b e^{j\frac{2\pi}{3}} + I_c e^{j\frac{4\pi}{3}}\right] \quad \ldots (1.12)$$

$$V_{IN} = \frac{3}{2}\left[V_a + V_b e^{j\frac{2\pi}{3}} + V_c e^{j\frac{4\pi}{3}}\right] \quad \ldots (1.13)$$

The rectifier switches, S1 to S6 can have only nine allowed combinations to avoid open circuit at the dc link rails. The nine combinations can be divided into six non-zero input currents which are active vector I_1 to I_6 and three zero input currents which are zero vector I_0. In addition, the amplitude and angle of the input current space vectors are evaluated for 6 active vectors and 3 zero vectors. I_1 [a b] indicates that input phase a is connected to the positive rail of the virtual dc-link V_{DC+} and input phase b is to the negative rail V_{DC-}. Its vector magnitude is calculated from

$$I_1 = \frac{3}{2}\left[I_a + I_b e^{j\frac{2\pi}{3}} + I_c e^{j\frac{4\pi}{3}}\right]$$

$$= \frac{3}{2}\left[I_{DC} - I_{DC} e^{j\frac{2\pi}{3}} + 0 e^{j\frac{4\pi}{3}}\right]$$

$$= \frac{2}{\sqrt{3}} I_{DC} e^{-j\frac{\pi}{6}} \quad \ldots (1.14)$$

Table 1.2 Valid switching combination for the Current Source Rectifier and its respective generated Voltage, Input Currents

Switching state						Output voltage			Input currents		
S_1	S_3	S_5	S_2	S_4	S_6	V_{pz}	V_{nz}	V_{pn}	i_a	i_b	i_c
1	0	0	0	0	1	V_A	V_C	V_{AC}	i_p	0	$-i_p$
0	1	0	0	0	1	V_B	V_C	V_{BC}	0	i_p	$-i_p$
0	1	0	1	0	0	V_B	V_A	V_{BA}	$-i_p$	i_p	0
0	0	1	1	0	0	V_C	V_A	V_{CA}	$-i_p$	0	i_p
0	0	1	0	1	0	V_C	V_B	V_{CB}	0	$-i_p$	i_p
1	0	0	0	1	0	V_A	V_B	V_{AB}	i_p	$-i_p$	0
1	0	0	1	0	0	V_A	V_A	0	0	0	0
0	1	0	0	1	0	V_B	V_B	0	0	0	0
0	0	1	0	0	1	V_C	V_C	0	0	0	0

(Source: Bin Wu and Yongqiang Lang.,2011)

III. RESULTS AND ANALYSIS

Simulations are done by means of the SimPower System block in the MATLAB/SIMULINK software package prior to its implementation.

The figure 1.2 shows the simulation model of a Doubly fed induction generator fed by a matrix converter. The vector control of DFIG and the space vector modulation technique implemented in matrix converter are designed in a separate subsystem as shown below.

VECTOR CONTROL OF GRID CONNECTED DFIG

Applying vector control techniques yields current control with high dynamic response. In grid-connected applications, the DFIG may be installed in remote, rural areas where weak grids with unbalanced voltages are not uncommon. As reported in induction machines are particularly sensitive to unbalanced operation since localized heating can occur in the stator and the lifetime of the machine can be severely affected. Furthermore, negative-sequence currents in the machine produce pulsations in the electrical torque, increasing the acoustic noise and reducing the life span of the gearbox, blade assembly and other components of a typical WECS .The FOP defines condition for decoupling the field control from the torque control.

A field oriented induction motor emulates a separately exited dc motor in two aspects:

• Both the magnetic field and torque developed in the motor can be controlled independently.

• Optimal condition for the torque production, resulting in the maximum torque per unit ampere, occurs in the motor both in steady state and in transient condition of operation.

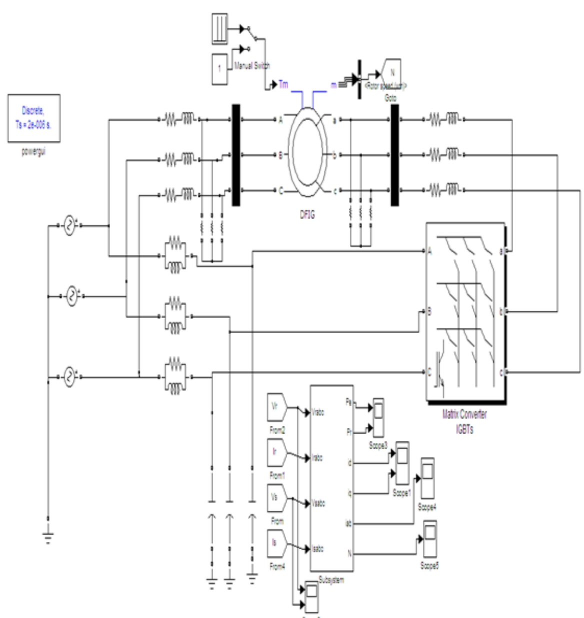

Figure 1.2 Simulation diagram of a DFIG fed by matrix converter

MATRIX CONVERTER WITH SVM SYMMETRIC SWITCHING

A matrix converter (MC) is an array of controlled semiconductor switches that directly connect each input phase to each output phase, without any intermediate dc link. The main advantage of MCs is the absence of bulky reactive elements that are subject to ageing, and reduce the system reliability. Furthermore, MCs provide bidirectional power flow, nearly sinusoidal input and output waveforms and controllable input power factor.

The SVM was successively developed in order to achieve the full control of the input power factor, to fully utilize the input voltages and to improve the modulation performance.

To turn on the switch S_{aA}, four switches must be activated and among these four switches two switches (i.e.) S_7 and S_8 will be in inverter stage, S_1 S_2 will be in rectifier stage. Similar concept is applied for all the other switches.

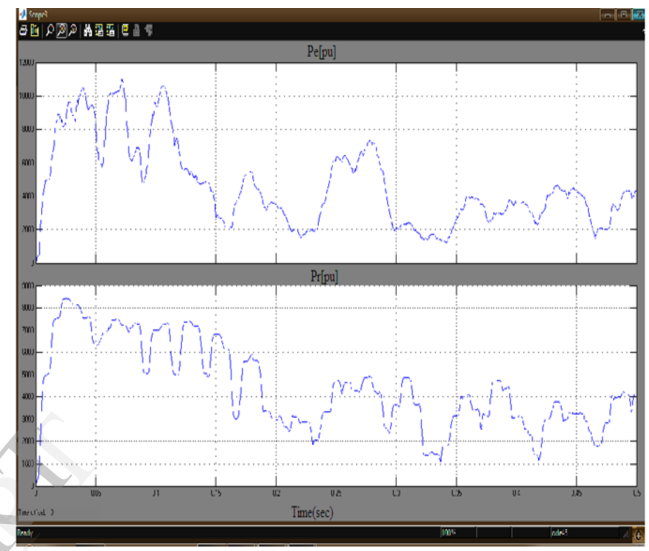

Figure1.3 Output Electrical Power (pe) and Rotor Power(pr) Waveform of a DFIG

The electrical power (pe) generated by the DFIG initially reaches the peak value of 10000 pu at a time period of 0.1sec after crossing 0.15 sec the fluctuating power will be regulated to 4000 pu. The rotor power (pr) of the DFIG reaches maximum value of 8000 pu at a time period of 0.05 sec, after crossing o.2 sec the unbalanced power will be regulated to 4000 pu as shown in Fig 1.3.

In Fig 1.4 the rotor current (id) reaches the maximum unbalanced peak value of 60A at the time period of 0.07ms, later beyond 0.2ms the rotor current is regulated to the current rating of 20A. Similarly the rotor current iq reaches the maximum peak value of 80A at the time period of 0.08ms finally after reaching the time period of 0.4ms the current iq attains the steady state value of 22A.

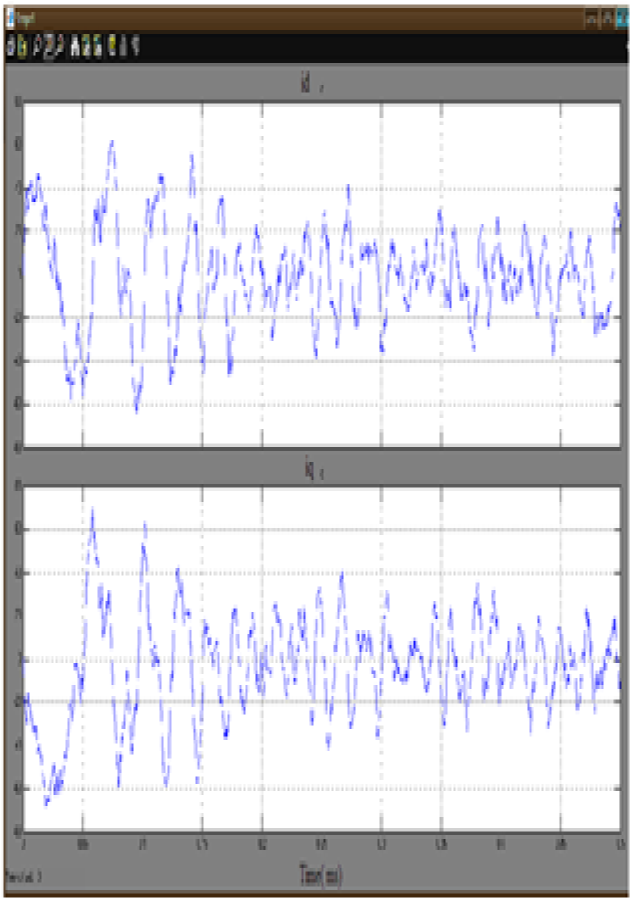

Figure 1.4 Output Rotor d-q Current waveform of a DFIG

Initially when the wind speed is low, the speed of the generator will be very lower (i.e.) at the time period of 0.1sec the generator speed will reach 600 rpm whereas above the time period of 0.35sec the DFIG will be regulated to 1500 rpm as shown in above figure 1.5.

The output speed waveform of DFIG feed by a matrix converter is shown in the figure 1.5 below and the waveform representation of a input current fed to a matrix converter is also shown in the figure 1.6 below.

Dynamic analysis of the DFIG is done by using both repeating table parameters and constant value parameters. In repeating table parameter the time values are fixed as [0 0.01 0.3 0.31]. Here the values of time should be monolithically increasing. From the waveforms it was analyzed that irrespective of the change in wind gust the generator speed is maintained to a rated value.

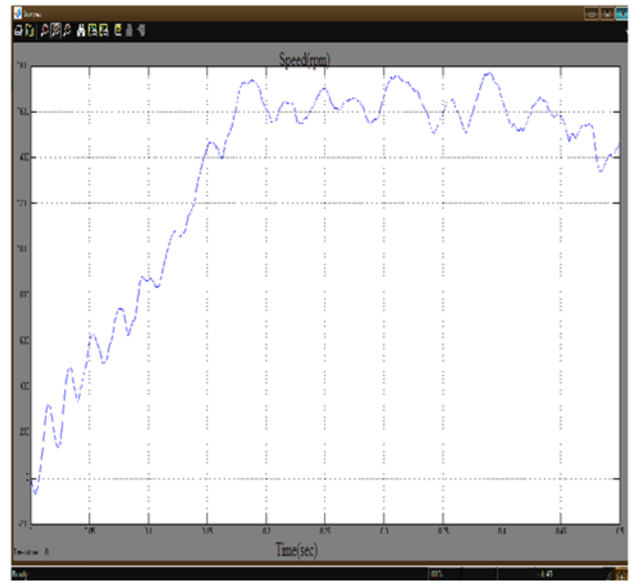

Figure 1.5 Output Speed Waveform of a DFIG fed by a Matrix Converter

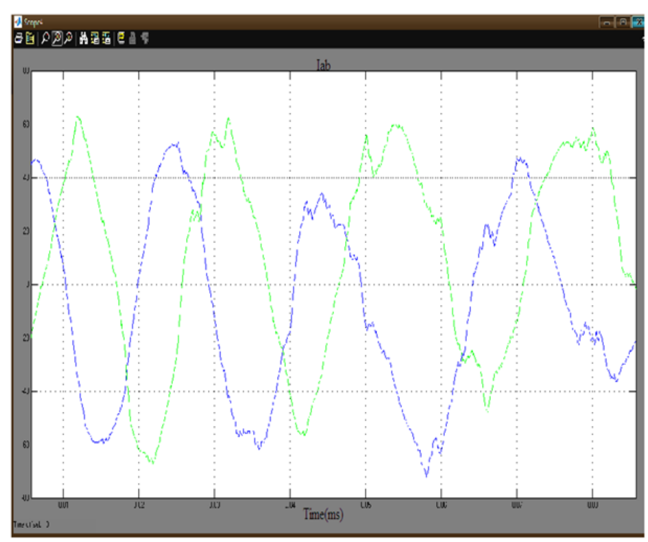

Figure 1.6 Waveform of Matrix Converter input current iab

The above figure 1.6 shows the waveform of input current (iab) used for operation in matrix converter. The distortion present in the current waveform is negligible because the input distortion is only due to the normal switching frequency harmonics and is acceptably low.

IV. CONCLUSION

This paper analyzes the stability of the system using a fixed and variable speed components and Matrix converter. It is analyzed in this project that the dynamic performance improves, when the DFIG stator voltage is used by the Space vector modulation technique to generate the MC switching pattern. Finally doubly fed induction generator speed (N), electrical power (Pe), DFIG rotor power (Pr), real and reactive current (id, iq), line current (iab) waveforms are observed. From the output waveform it was concluded that, irrespective of the wind gust the generator speed is maintained to a rated value and the voltage and frequency changes is also maintained constant by using matrix converter. Considering this performance and the advantages of MCs in terms of reliability and size, it has been concluded that MCs are good alternatives to the back-to-back converters conventionally used in DFIG-based WECSs.

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