Designing the Efficient System with Matrix Converter to Replace Back to Back Converter in DFIG System with ISVM

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Abstract: ***This paper proposes the Doubly Fed Induction Generator (DFIG) System with Matrix Converter and DFIG system with Back to Back Converter. Matrix Converter is very efficient one in DFIG system than Back to Back Converter in Design constraints, Power quality, losses, and controlling. Both converters are controlled by Indirect Space Vector Modulation (ISVM) technique. LCL filters are designed for both converters. All results are simulated on MATLAB/SIMULINK software. Performance of the system is analysed by FFT window.***

Keywords: Doubly Fed Induction Generator (DFIG), Matrix Converter (MC), Back to Back (BTB), Indirect Space-Vector Modulation (ISVM), LCL filters, Voltage source Inverter (VSI), Space Vector Modulation (SVM), Grid Side Converter (GSC), Rotor Side Converter (RSC).

1. Introduction

A Doubly fed induction generator (DFIG) is also called as wound rotor induction generator. “Doubly-Fed” means both the stator and rotor of an induction machine with a wound rotor is connected to electrical sources. This is popular for generation applications now-a-days with limited variable speed range. DFIG can produce or consume power from both stator and rotor of the machine depending upon the speed of the shaft.

Depending upon the value of a slip s, the operation of a DFIG can be classified in three different modes [1].

- $w_r < w_s$ … s > 0 .. Sub-synchronous mode.
- $w_r > w_s$ … s < 0 .. Super-synchronous mode.
- $w_r = w_s$ … s = 0 .. Synchronous mode.

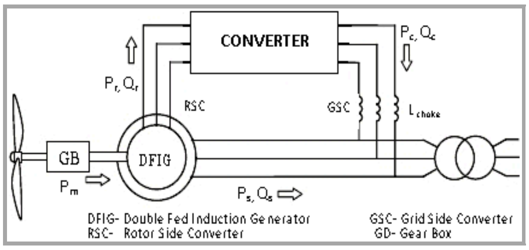


Figure 1: Block Diagram of DFIG System

Matrix converter is efficient converter topology in DFIG to connect the rotor output with the power grid and converting the low frequency ($s*f_s$) AC power to the 50Hz (f_s) commercial power. Back to back converter topology is replaced by Matrix converter topology because losses of the back to back converter are high, complexity in structure because it has 3-step power conversion such as AC-DC-AC and high rating DC link capacitor [2-3].

LCL filters are designed for both converters both sides (i.e. rotor side and grid side) because both converters works in both directions. When the wind speed is low then the rotor receives power from grid and when the wind speed is high then the rotor will supply power to the grid. LCL filters can reduce the harmonics which are produced by converter [4-5]. Filters are connected in delta shape in both sides parameters of the delta connected filters are shown in bellow table.

Table 1: Delta-Connected Filter Parameters

Parameters	L_1	L_2	R	C
Rotor Side	5e-	0.73e	0.57Ω	300e-
Grid Side	5e-	5e-4H	0.57Ω	0.5F

The basic LCL filter circuit is shown in below Figure 2.

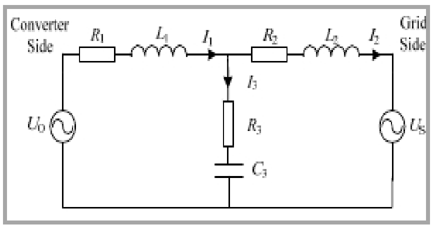


Figure 2: LCL filter equivalent circuit diagram

2. Converter Topologies

2.1 Back to Back Converter

Back to back converter is a two stage of converter, which converts AC-DC-AC. The AC-DC conversion is rectifier stage this converter is called as grid side converter (GSC) and the DC-AC conversion is inverter stage this converter is rotor side converter (RSC).Both converters are connected “back to back” with a DC link capacitor between them. Dc link capacitor puts voltage at constant for efficient inversion. RSC controls the torque or speed of the DFIG and also controls the power factor of the stator terminals but the GSC only puts DC link voltage at constant.

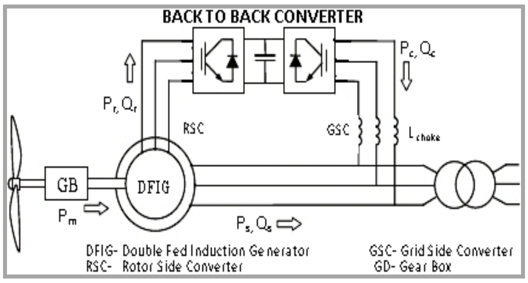


Figure 3: DFIG System with BTB

GSC works at grid frequency but RSC works at different frequencies according slip speed variations. Back to back converter converts variable voltage, variable frequency into constant voltage, constant frequency or constant voltage, constant frequency into variable voltage, variable frequency in "back to back" directions [6].

2.2 Matrix Converter

Matrix converter consists of nine bidirectional solid-state switches. Bi-directional solid-state switch is shown in bellow Fig.

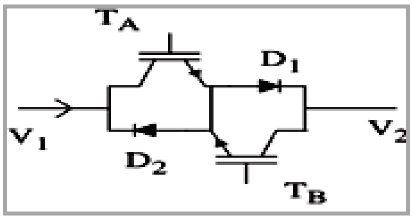


Figure 4: Bi-directional switch

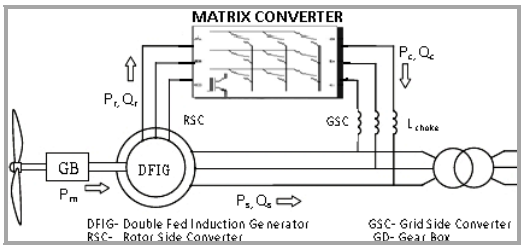


Figure.5: DFIG System with MC

Matrix converter is an AC-AC converter. Which converts variable voltage, variable frequency into constant voltage, constant frequency or constant voltage, constant frequency into variable voltage, variable frequency. MC can control the direction of the current independently; conduction losses are lesser than back to back converter and also controls the power factor effectively [7-8].

Matrix converter doesn't consist of DC link capacitor so that the cost of converter also reduced. Matrix converter technology is a newly lodged technology in wind energy generation it can convert AC-AC or AC-DC also.MC has three important topologies [9]. They are;

1. It can vary the input AC waveform so it simply called as AC controller topology.
2. It can be used if the out frequency is much lesser than the input source frequency this is cyclo-converter topology.
3. Finally it is matrix converter topology it is most robust without any limits on the out frequency and amplitude.

3. ISVM Control Technique

Both converters are controlled by indirect space-vector modulation (ISVM) scheme. It is similar to pulse width modulation but it is based on two-phase representation of three-phase quantities through transformation as follows.

$$X = \frac{2}{3}(x_a + \alpha x_b + \alpha^2 x_c) \quad (1)$$

$$\alpha = e^{j2\pi/3} = \cos\left(\frac{2\pi}{3}\right) + j\sin\left(\frac{2\pi}{3}\right) \quad (2)$$

Switching states are produced by adopting conventional VSI topology and SVM concept. If we draw the matrix converter equivalent circuit, it consists of current source rectifier and voltage source inverter connected through virtual DC-link. ISVM separates the control of the input current and output voltage. Nine switching pulses are produced by multiplying the two switching functions i.e. product or rectifier and inverter switching functions. Rectifier switching function and inverter switching functions are produced by SVM technique then two results will be combined [10].

$$\begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \times \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \times \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (4)$$

3.1 Rectifier Switching Functions

Mathematical representation of rectifier switching pattern in matrix form is [11]:

$$S_R = \begin{bmatrix} S_{R11} & S_{R12} & S_{R13} \\ S_{R21} & S_{R22} & S_{R23} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} S_{R11} & S_{R21} \\ S_{R12} & S_{R22} \\ S_{R13} & S_{R23} \end{bmatrix} \times \begin{bmatrix} I_{DC} \\ -I_{DC} \end{bmatrix} \quad (6)$$

Table 2: Rectifier Switching Function

Vectors	S_{R11}	S_{R12}	S_{R13}	S_{R21}	S_{R22}	S_{R23}	i_a	I_b	I_c	$\lvert I_{\alpha\beta}(t)\rvert$	δ_t	V_{DC}
I_1	1	0	0	0	0	1	I_{DC}	0	$-I_{DC}$	$\surd 2I_{DC}$	30	$-v_{ca}$
I_2	0	1	0	0	0	1	0	I_{DC}	$-I_{DC}$	$\surd 2I_{DC}$	90	V_{bc}
I_3	0	1	0	1	0	0	$-I_{DC}$	I_{DC}	0	$\surd 2I_{DC}$	150	$-v_{ab}$
I_4	0	0	1	1	0	0	$-I_{DC}$	0	I_{DC}	$\surd 2I_{DC}$	-150	v_{ca}
I_5	0	0	1	0	1	0	0	$-I_{DC}$	I_{DC}	$\surd 2I_{DC}$	-90	$-v_{bc}$
I_6	1	0	0	0	1	0	I_{DC}	$-I_{DC}$	0	$\surd 2I_{DC}$	-30	V_{ab}
I_7	1	0	0	1	0	0	0	0	0	0	-	0
I_8	0	1	0	0	1	0	0	0	0	0	-	0
I_9	0	0	1	0	0	1	0	0	0	0	-	0

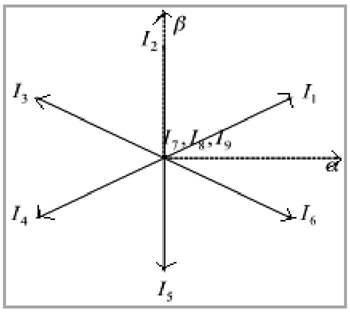


Figure 6: Rectifier Current vectors

3.2 Inverter Switching Functions

Mathematical representation of rectifier switching pattern in matrix form is [11]:

$$S_I = \begin{bmatrix} S_{I11} & S_{I12} \\ S_{I21} & S_{I22} \\ S_{I31} & S_{I32} \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} v_{AB} \\ v_{BC} \\ v_{CA} \end{bmatrix} = \begin{bmatrix} S_{I11} & S_{I12} \\ S_{I21} & S_{I22} \\ S_{I31} & S_{I32} \end{bmatrix} \times \begin{bmatrix} V_{DC} \\ -V_{DC} \end{bmatrix} \quad (8)$$

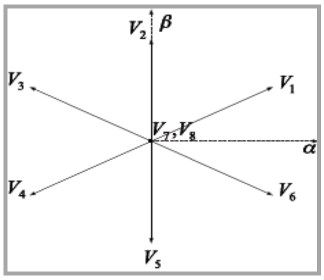


Figure 7: Inverter Voltage Vectors

Table 3: Inverter Switching Functions

Vectors	S_{I11}	S_{I12}	S_{I21}	S_{I22}	S_{I31}	S_{I32}	v_A	v_B	v_C	v_{AB}	v_{BC}	v_{CA}	V_0	δ_0	I_{DC}
V_1	1	0	0	1	0	1	V_D	V_C	V_C	V_{DC}	0	$-V_{DC}$	$\surd 2I_{DC}$	30	I_A
V_2	1	0	1	0	0	1	V_D	V_D	V_C	0	V_{DC}	$-V_{DC}$	$\surd 2I_{DC}$	90	$-I_C$
V_3	0	1	1	0	0	1	V_C	V_D	V_C	$-V_{DC}$	V_{DC}	0	$\surd 2I_{DC}$	150	I_B
V_4	0	1	1	0	1	0	V_C	V_D	V_D	$-V_{DC}$	0	V_{DC}	$\surd 2I_{DC}$	-150	$-I_A$
V_5	0	1	0	1	1	1	V_C	V_C	V_D	0	$-V_{DC}$	V_{DC}	$\surd 2I_{DC}$	-90	I_C
V_6	1	0	0	1	1	0	V_D	V_C	V_D	V_{DC}	$-V_{DC}$	0	$\surd 2I_{DC}$	-30	$-I_B$
V_7	1	0	1	0	1	0	0	0	0	0	0	0	0	-	0
V_8	0	1	0	1	0	1	0	0	0	0	0	0	0	-	0

4. MATLAB/SIMULINK Circuits

4.1 DFIG System with Back to Back Converter

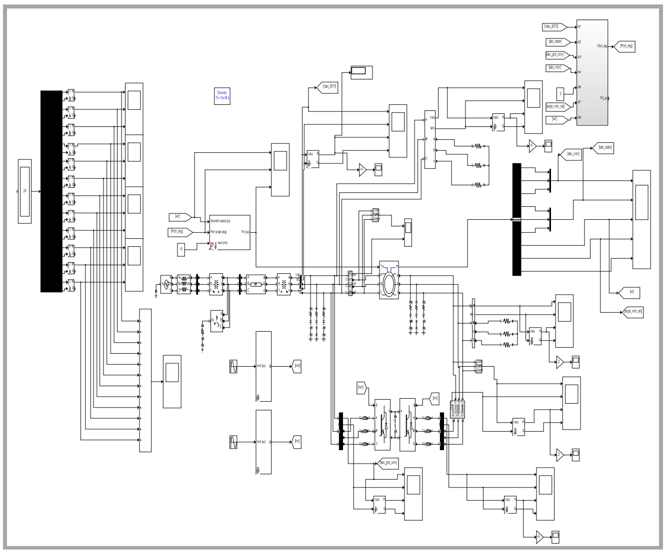


Figure 8: Circuit Diagram of DFIG System with BTB

4.2 DFIG System with Matrix Converter

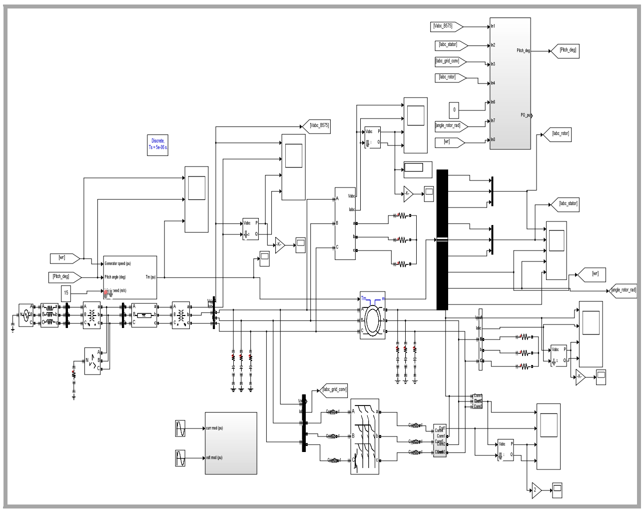
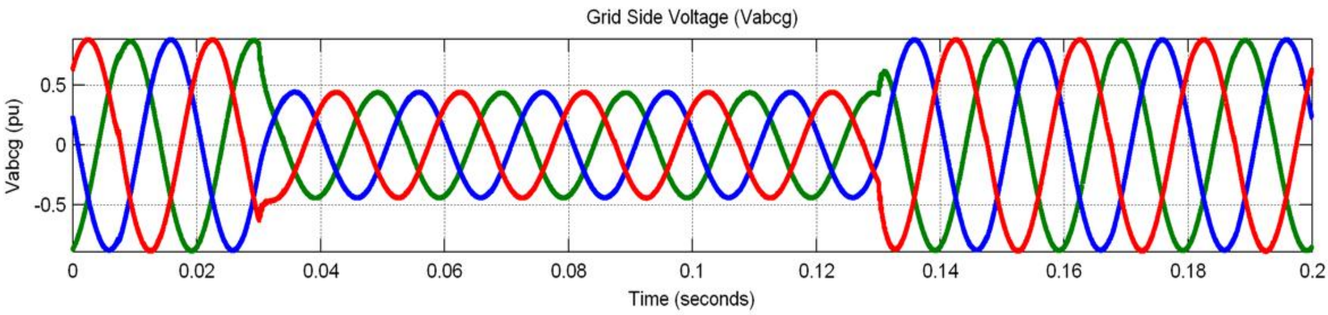
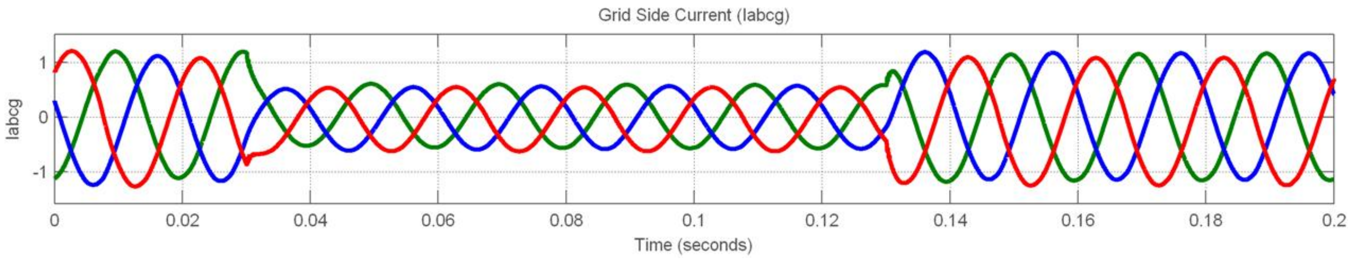


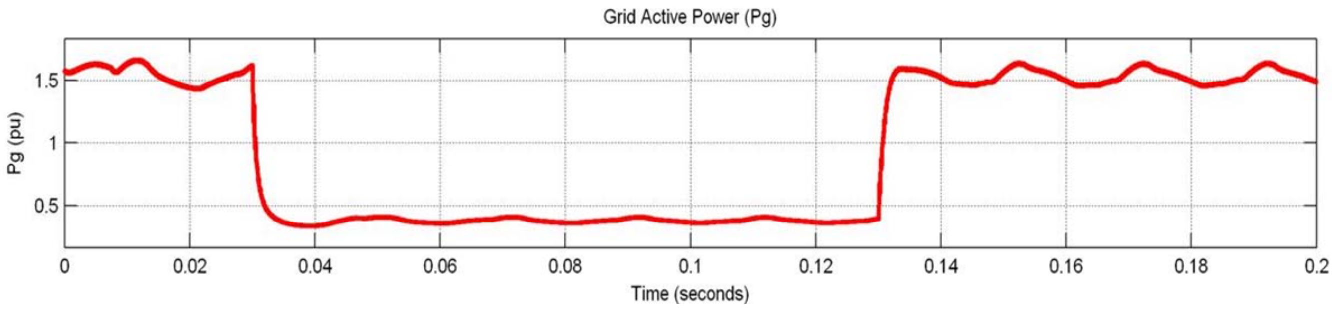
Figure 9: Circuit Diagram of DFIG System with MC

5. Simulation Results

5.1 DFIG System with Back to Back Converter







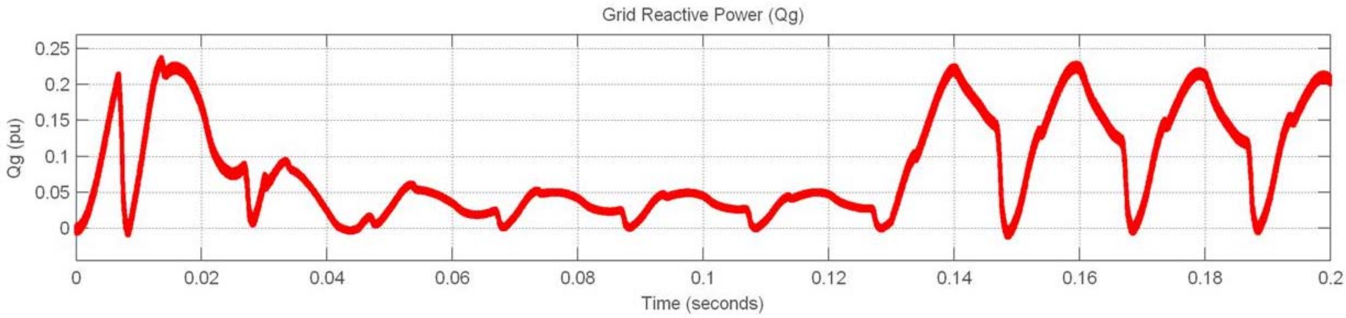


Figure 10: Grid side output waveforms

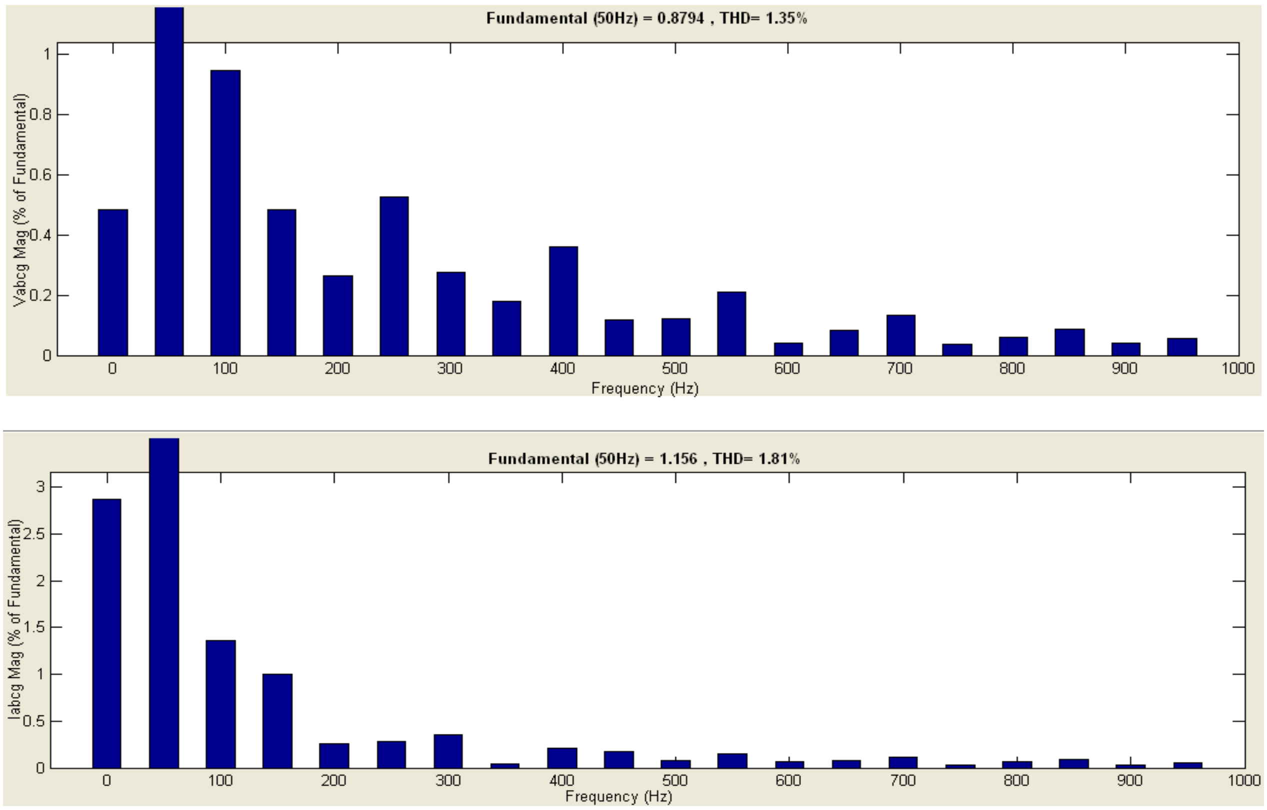
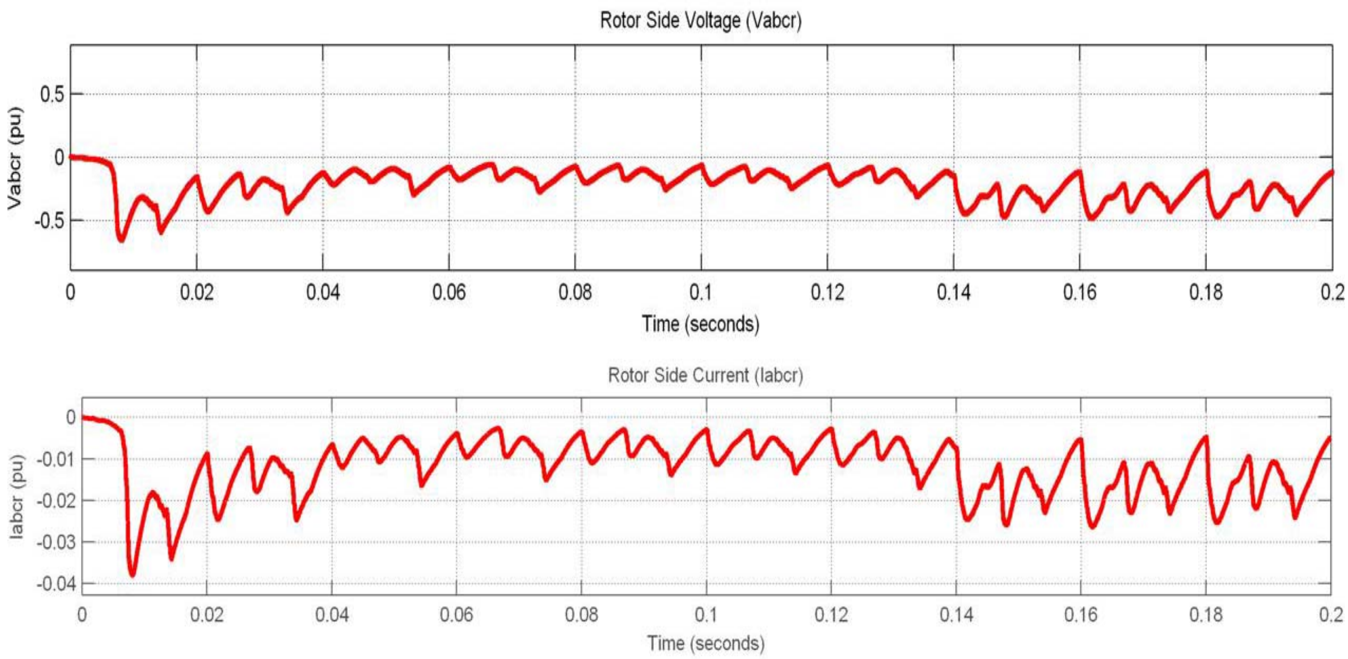


Figure 11: FFT window of grid voltage & grid current



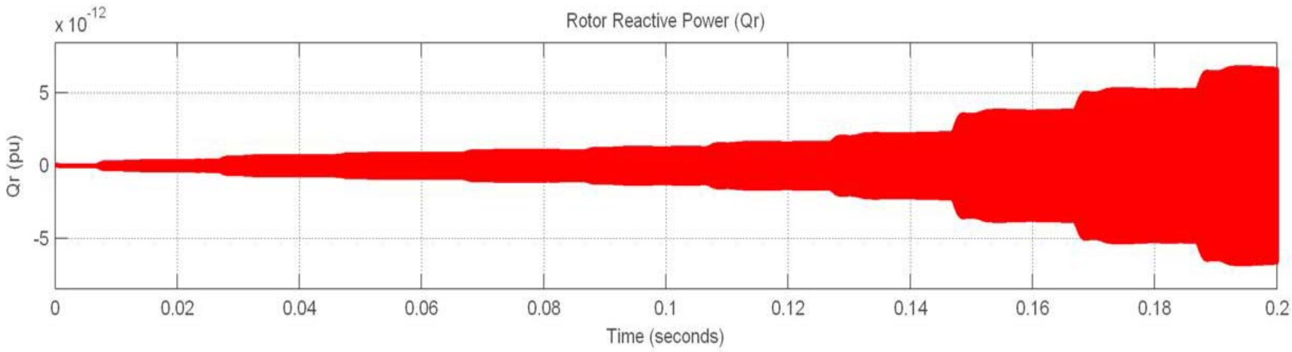


Figure 12: Rotor side output waveforms

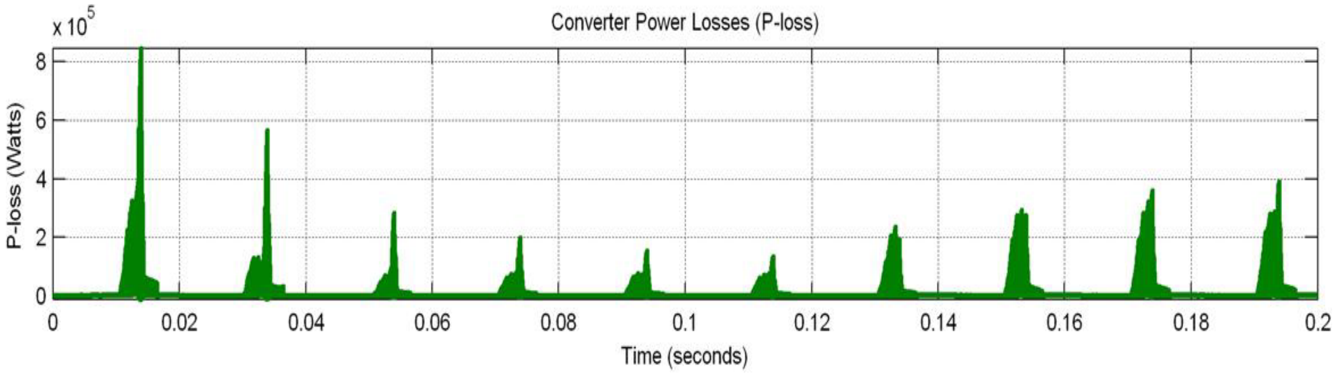
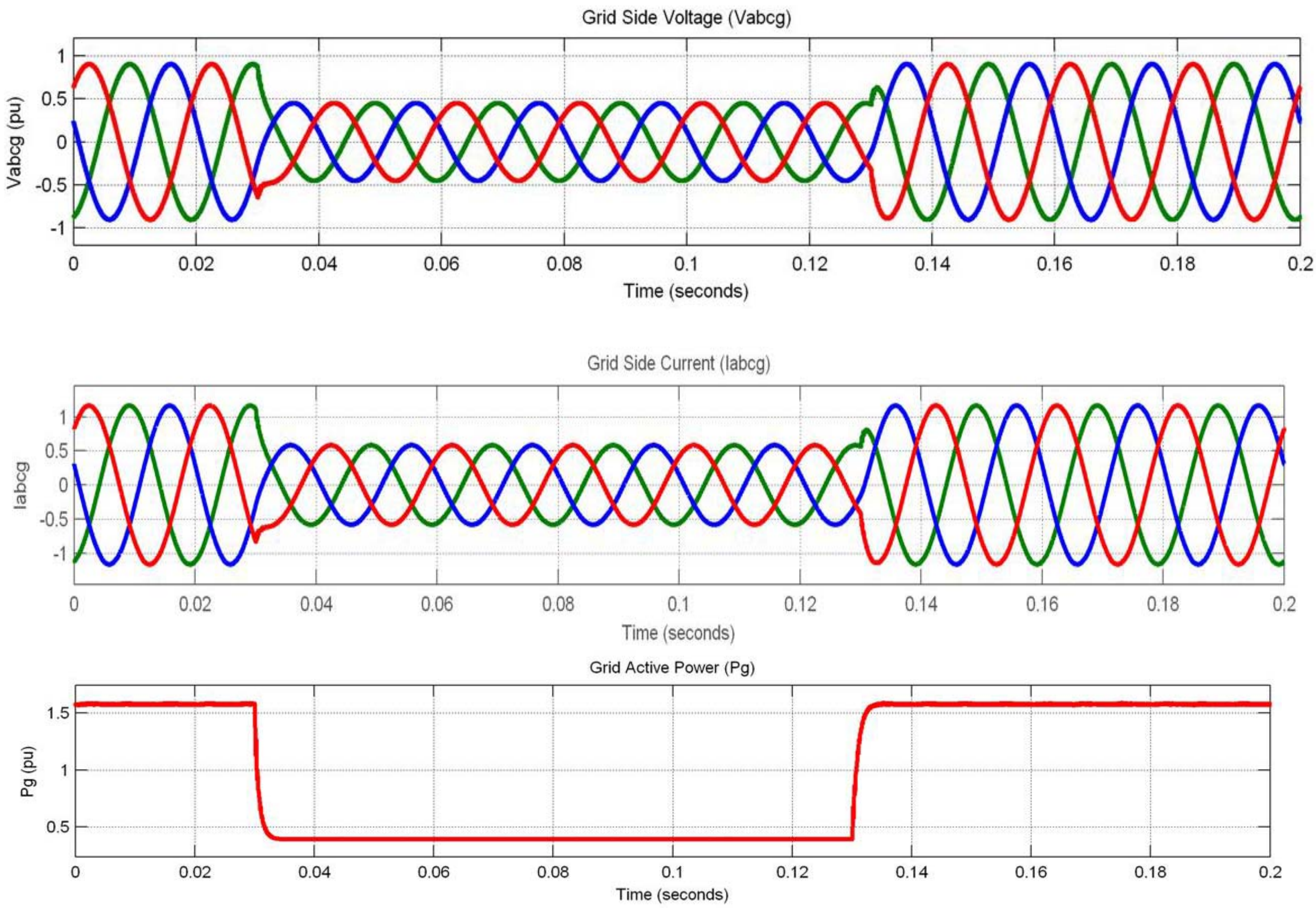


Figure 13: BTB Converter Losses

5.2 DFIG System with Matrix Converter



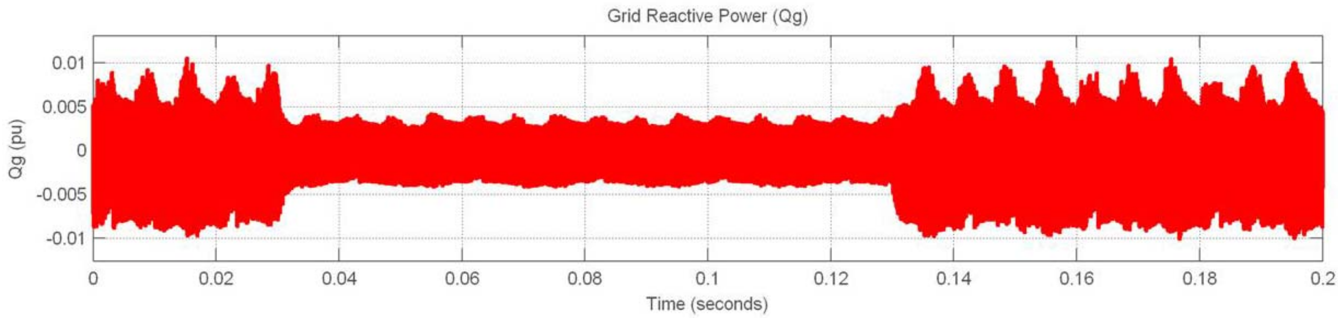


Figure 14: Grid side output waveforms

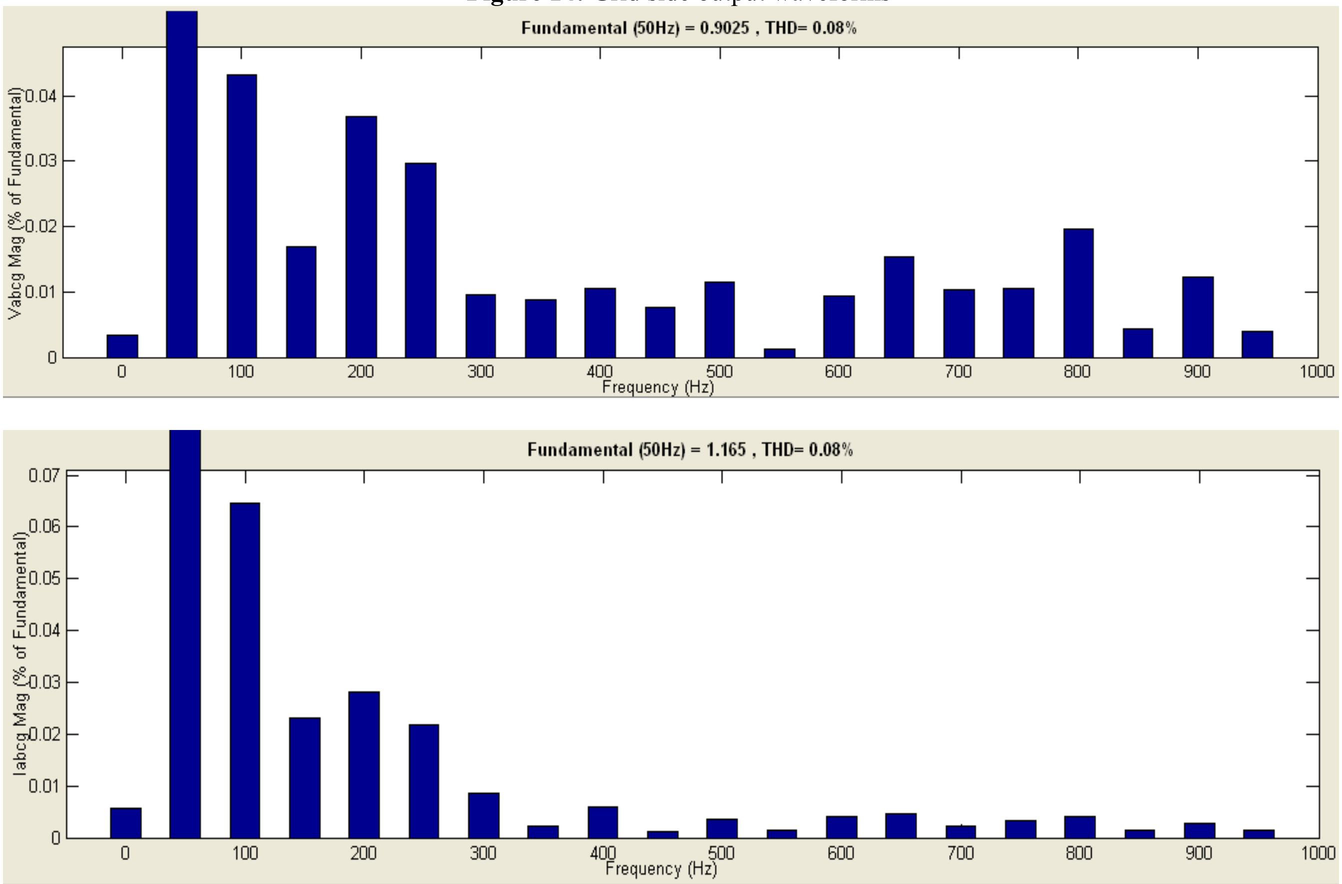
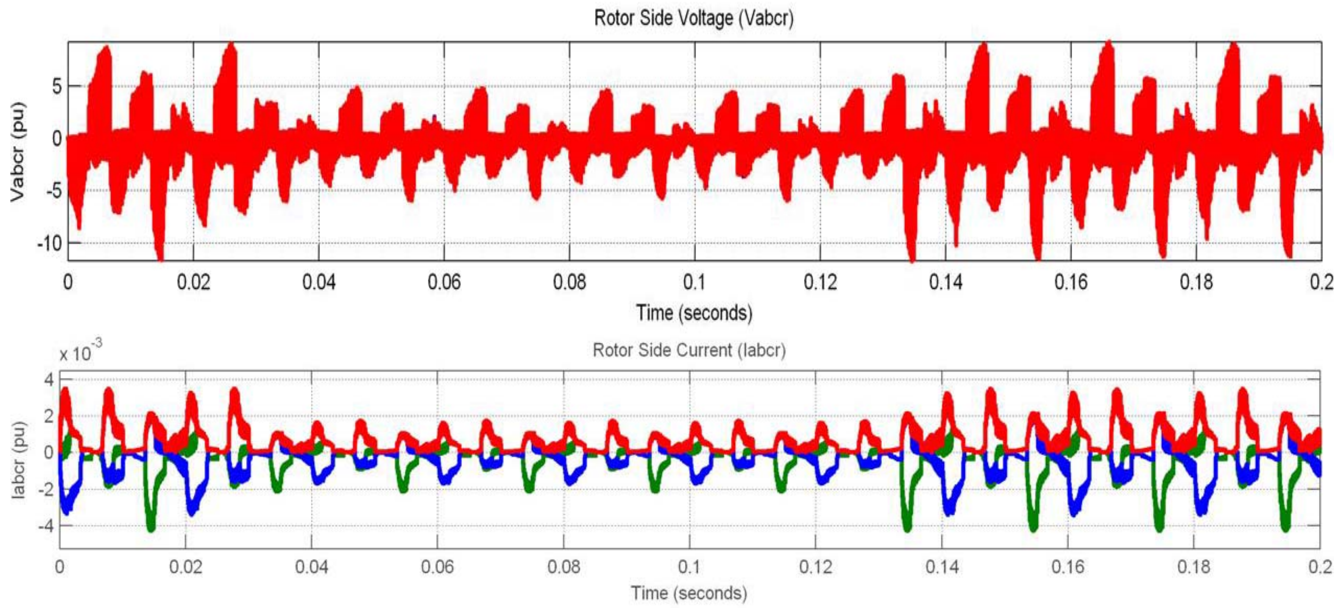


Figure 15: FFT window of grid voltage & grid current



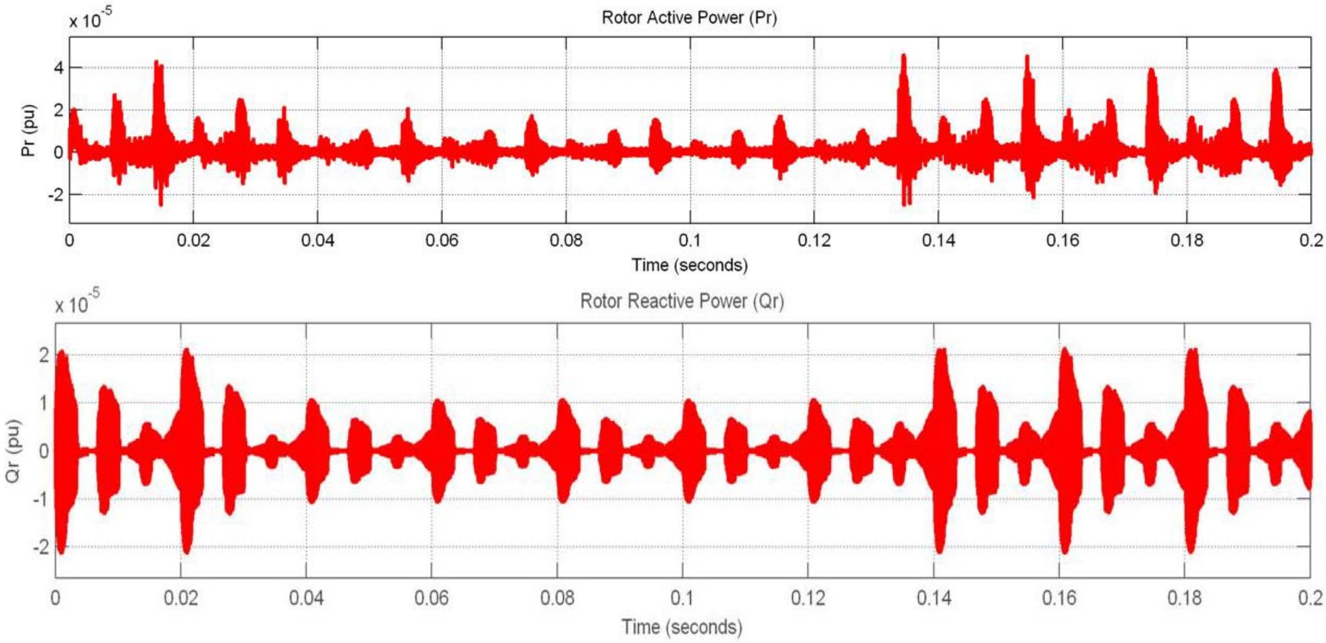


Figure 16: Rotor side output waveforms

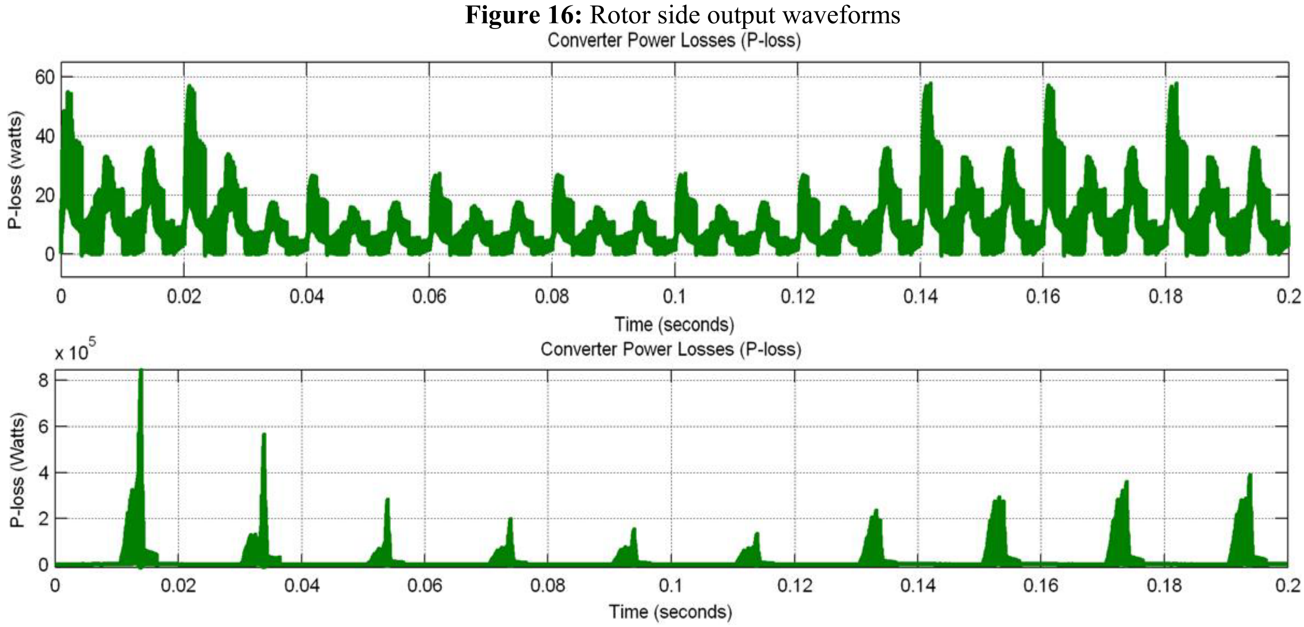


Figure 17: Matrix Converter Losses

6. Comparison of Both Converters

As we are comparing the both converters from the above results both are differentiated as shown in bellow table.

Table 4: BTB Vs MC Comparison

System Parameters	*BTB*	*MC*
No. of switches	12	9 (back to back)
Losses	0-800 (KW)	0-58 (W)
DC-Link Capacitor	12µF	No
THD (%)	1.81%	0.08%
Voltage Mag. at fundamental freq.	0.8794 (pu)	0.9025 (pu)
Current Mag. at fundamental freq.	1.156 (pu)	1.165 (pu)
Base Power	9 (MW)	9 (MW)
Total output Power	13-14.4 (MW)	14.4 (MW)
Conversion	AC-DC-AC (2-stages)	AC-AC (Single-stage)

- MC provides low-distortion sinusoidal input and output waveforms, bi-directional power flow, and controllable input power factor [12]
- The dc-link capacitor in BTB is heavy and bulky, increases the cost, and reduces the overall lifetime of the system [13].
- The main advantage of the MC is in its compact design which makes it suitable for applications

Where size and weight matter, such as in aerospace applications.

7. Conclusions

From the comparison of both converters we can observe that matrix converter is efficient one to design DFIG system for variable wind speeds. In order to track maximum power, MC adjusts the induction generator terminal frequency, and thus the turbine shaft speed. MC adjusts the reactive power transfer at the grid interface to achieve voltage regulation or power factor correction. MC is highly controllable and allows independent control of the output voltage magnitude, frequency, and phase angle, as well as the input power factor. Compared with the DC-link AC/AC converter systems, an advantage of the MC is elimination of the DC-link, including bulky capacitors. The MC structure is inherently capable of a four-quadrant operation. Finally this paper concludes that BTB has high converter losses, lesser magnitudes of voltage and current's, higher THD% and lesser total output power than MC so that this paper proposes DFIG system with MC with efficient results.

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