Modeling and Control of Variable Pitch and Variable Speed Wind Turbine by using Matrix Converter

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ABSTRACT

In order to meet increasing power demand, taking into account economical and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy. In this paper, The modeling of the Wind Energy Conversion System (WECS) with Matrix converter is proposed.

The matrix converter, as a power electronic converter, is used to interface the induction generator with the grid and control the wind turbine shaft speed. At a given wind velocity, the mechanical power available from a wind turbine is a function of its shaft speed. Through the matrix converter, the terminal voltage and frequency of the induction generator is controlled, based on a constant V/f strategy, to adjust the turbine shaft speed and accordingly, control the active power injected into the grid to track maximum power for all wind velocities. The power factor at the interface with the grid is also controlled by the matrix converter to either ensure purely active power injection into the grid for optimal utilization of the installed wind turbine capacity or assist in regulation of voltage at the point of connection. Furthermore, the reactive power requirements of the induction generator are satisfied by the matrix converter to avoid use of self-excitation capacitors. The Space Vector pulse width Modulation (SVPWM) technique is used for matrix converter to control the generator rotor current.

The Matrix converter is good for controlling torque (load changes in wind turbine), fault current power flow in the lines in WECS. In this paper the controller is tuned for fault current limitations and optimal power flow. The modeling of the complete system is done in MATLAB- SIMULINK.

General Terms

Induction Generator, Matrix converter, Wind Turbine, Variable Speed, Power Control.

Keywords

WECS, FCC, CSCF, PWM, SVPWM,

1. INTRODUCTION

With exhausting of traditional energy resources and increasing concern of environment, renewable and clean energy is attracting more attention all over the world to overcome the increasing power demand. Out of all the renewable energy sources, Wind energy and solar energy are reliable energy sources. Now a day, Wind power is gaining a lot of importance because it is cost- effective, environmentally clean and safe renewable power source compared to fossil fuel and nuclear power generation [23].

A Wind Energy Conversion System (WECS) can vary in size from a few hundred kilowatts to several megawatts. The size of the WECS mostly determines the choice of the generator and converter system. Asynchronous generators are more commonly used in systems up to 2MW, beyond which direct-driven permanent magnet synchronous machines are preferred. A grid connected WECS should generate power at constant electrical frequency which is determined by the grid .Generally Squirrel cage rotor induction generators are used in medium power level grid- connected systems. The induction generator runs at near synchronous speed and draws the magnetizing current from the mains when it is connected to the constant frequency network, which results in constant speed constant frequency (CSCF) operation of generator However the power capture due to fluctuating wind speed can be substantially improved if there is flexibility in varying the shaft speed[23].

In such variable Speed Constant Frequency (VSCF) application rotor side control of grid-connected wound rotor inductio machine is an attractive solution. In double fed induction generator, the stator is directly connected to the three phase grid and the rotor is supplied by two back-to-back PWM converters as shown in Figure1. Such an arrangement provides flexibility of operation at both sub-synchronous and super synchronous speeds [9][10].

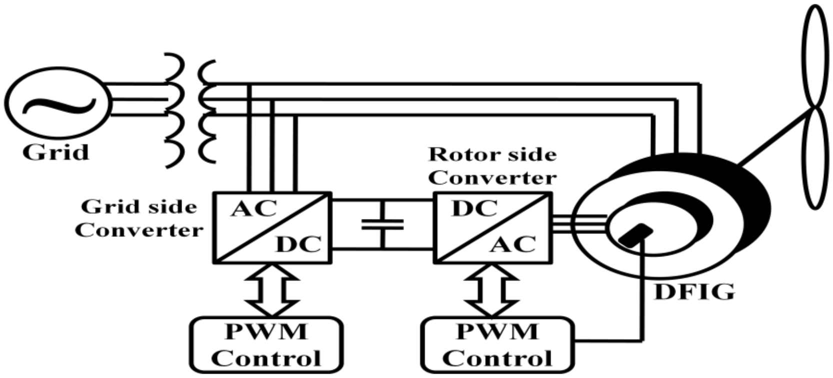

Figure 1: Block diagram of Wind Energy Conversion System

Traditionally, ac voltages and currents having variable amplitude and frequency are generated by PWM modulated Voltage source inverters (PWM-VSI). These inverters need dc power , which is usually supplied by a diode bridge rectifer or a PWM active rectifier. This can be considered indirect power conversion because the topology is based on two types of power conversions via a dc link (capacitor). Indirect power converters perform the ac/ac power conversion by converting ac to dc through a rectifier, and then converting dc back to ac via an inverter. This operation is illustrated below and shown in Figure 2.

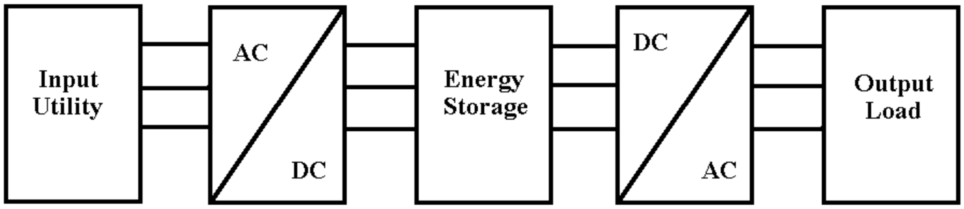

Figure 2 Indirect power conversions

An alternative to indirect power converters is the direct power converter which is known as Matrix converter is as shown in Figure 3. The matrix converter is a Forced Commutated Cyclo-converter (FCC)which uses an array of controlled bidirectional switches as the main power element to create a variable output voltage system with unrestricted frequency. It does not have any dc-link circuit and does not need any large energy storage elements like inductor and capacitor. The key element in a matrix converter is the fully controlled four-quadrant bidirectional switch, which allows high-frequency operation. The matrix converter has no limit on output frequency due to the fact that it uses semiconductor switches with controlled turn-off capability like IGBT, MOSFET, and MCT.

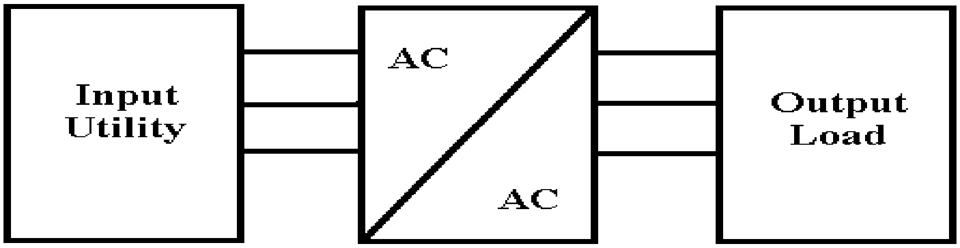

Figure 3 Direct power conversion

However, the simultaneous commutation of controlled bidirectional switches used in matrix converters is very difficult to achieve without generating over current or over voltage spikes that can destroy the power semiconductors. This fact limited the practical implementation in matrix converters. Fortunately, this major problem has been solved with the development of several multistep commutation strategies that allow safe operation of the switches. In 1989, Burany introduced the later-named “semi-soft current commutation” technique [**15**]. The block diagram of WECS with Matrix Converter is shown in Figure 4.

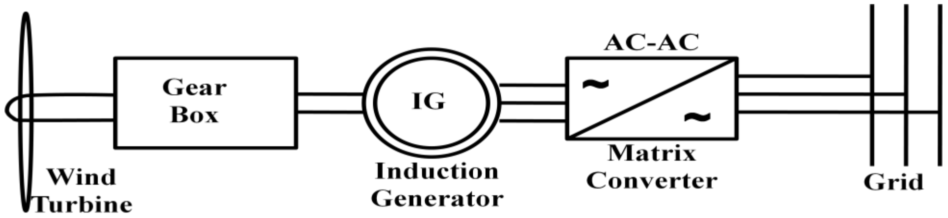

Figure 4 Block diagram of WECS with Matrix Converter

2. MATHEMATICAL MODELING OF THE INDUCTION GENERATOR

The wind generation system studied in this paper consists of two components, the induction Generator (Squirrel cage or slip ring) and the variable speed wind turbine [23]. A detailed description of these two components is given below. The electrical part of the induction generator represented by a fourth-order state space model, which is constructed using the synchronously rotating reference frame (dq-frame), where the d-axis is oriented along the stator flux vector position. The relation between the three phase quantities and the dq components is defined by Park's transformation The voltage equations of the induction generator are

$$V_{ds} = R_s i_{ds} - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \tag{1}$$

$$V_{qs} = R_s i_{qs} - \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \tag{2}$$

$$V_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\psi_{qr} + \frac{d\psi_{dr}}{dt} \tag{3}$$

$$V_{qr} = R_r i_{qr} - (\omega_s - \omega_r)\psi_{dr} + \frac{d\psi_{qr}}{dt} \tag{4}$$

where V_{ds}, V_{qs}, V_{dr}, V_{qr} are the d- and q-axis of the stator and rotor voltages; I_{ds}, I_{qs} ,I_{dr}, I_{qr} are the d- and q-axis of the stator and rotor currents; $\Psi_{ds,}$ $\Psi_{qs,}$ $\Psi_{dr,}$ Ψ_{qr} are the d- and q- axis of the stator and rotor fluxes; ω_s is the angular velocity of the synchronously rotating reference frame; ω_r is the rotor angular velocity; and R_s, R_r are the stator and rotor resistances. The flux equations of the induction generator are

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \tag{5}$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \tag{6}$$

$$\psi_{dr} = L_m I_{ds} + L_r I_{dr} \tag{7}$$

$$\psi_{qr} = L_m I_{qs} + L_r I_{qr} \tag{8}$$

Where L_s, L_r, and L_m are the stator, rotor, and mutual inductances, respectively. From the flux equations (5)–(8), the current equations can be written as

$$I_{ds} = \frac{1}{\sigma L_s}\psi_{ds} - \frac{L_m}{\sigma L_s L_r}\psi_{dr} \tag{9}$$

$$I_{qs} = \frac{1}{\sigma L_s}\psi_{qs} - \frac{L_m}{\sigma L_s L_r}\psi_{qr} \tag{10}$$

$$I_{dr} = \frac{-L_m}{\sigma L_s L_r}\psi_{ds} + \frac{1}{\sigma L_r}\psi_{dr} \tag{11}$$

$$I_{qr} = \frac{-L_m}{\sigma L_s L_r}\psi_{qs} + \frac{1}{\sigma L_r}\psi_{qr} \tag{12}$$

Where $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ is the leakage Coefficient

Neglecting the power losses associated with the stator and Rotor resistances, the active and reactive stator and rotor powers are given by

$$P_s = -V_{ds} I_{ds} - V_{qs} I_{qs} \tag{13}$$

$$Q_s = -V_{qs} I_{ds} + V_{ds} I_{qs} \tag{14}$$

$$P_r = -V_{dr} I_{dr} - V_{qr} I_{qr} \tag{15}$$

$$Q_r = -V_{qr} I_{dr} + V_{dr} I_{qr} \tag{16}$$

And the total active and reactive powers of the DFIG are

$$P = P_s + P_r \tag{17}$$

$$Q = Q_s + Q_r \tag{18}$$

Where positive (negative) values of P and Q mean that the induction generator injects power into (draws power from) the grid. The mechanical part of the induction generator is represented by a first-order model

$$J\frac{d\omega_r}{dt} = T_m - T_e - C_f \omega_r \tag{19}$$

Where C_f is the friction coefficient, T_m is the mechanical torque generated by the wind turbine, and T_e is the electromagnetic torque given by

$$T_e = \psi_{ds} I_{ds} - \psi_{qs} I_{qs} \tag{20}$$

Where positive (negative) values mean the induction machine acts as a generator (motor).

3. MATRIX CONVERTER THEORY

The schematic diagram of the matrix converter is shown in Figure 4 The matrix converter is a single-stage converter which has an array of m×n bidirectional power switches to connect, directly, an m-phase voltage source to an n-phase load. The matrix converter of 3×3 switches has the highest practical interest because it connects a three-phase voltage source with a three-phase load, typically a motor. Normally, the matrix converter is fed by a voltage source and, for this reason the input terminals should not be short circuited. On the other hand, the load has typically an inductive nature and, for this reason, an output phase must never be opened.

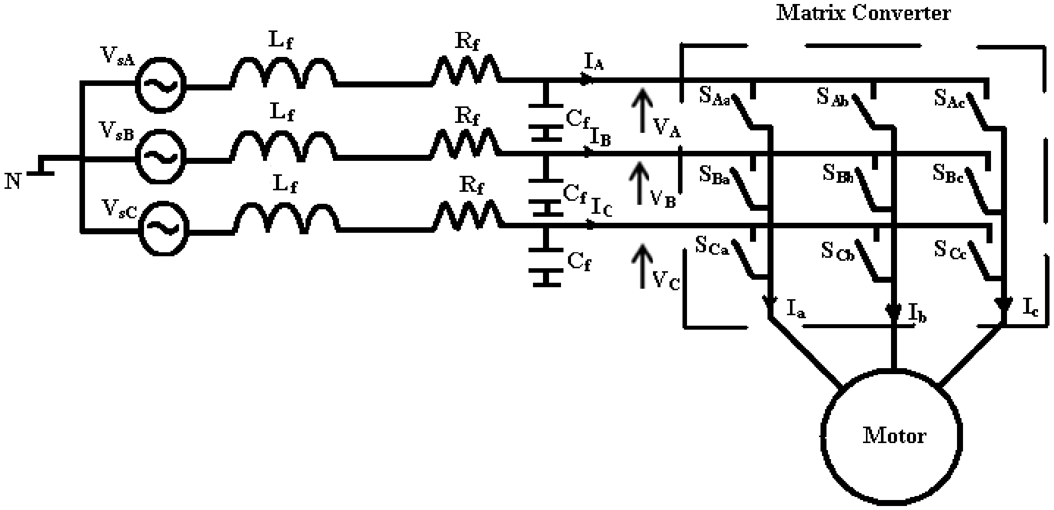

Figure 4. Schematic diagram of Matrix converter

3.1 Space Vector Pulse Width Modulation Technique

The SVPWM is well known and established in conventional PWM inverters, Its application to matrix converters is conceptually the same, but is more complex. With a matrix converter, the SVPWM can be applied to output voltage and input current control. The 27 possible output vectors for a three-phase matrix converter can be classified into three groups with the following characteristics [9][11].

- Group I: Each output line is connected to a different input line. Output space vectors are constant in amplitude, rotating in either direction at the supply angular frequency (Rotating Vectors).
- Group II: Two output lines are connected to a common input line and the remaining output line is connected to one of the other input lines. Output space vectors have varying amplitude and fixed direction occupying one of six positions regularly spaced 60 degrees apart. The maximum length of these vectors is 1.154 times of V_{env} where V_{env} the instantaneous value of the rectified input voltage envelope (Active Vectors).
- Group III: All output lines are connected to a common input line. Output space vectors have zero amplitude (Zero Vectors)

In the SVPWM, the Group I vectors are not used. The desired output is synthesized from the Group II active vectors and the Group III zeros vectors. Again the Group II vectors are further subdivided into three groups based on which output line-to-line voltage is zero.

The voltage space vector of the target matrix converter output voltages and input currents are defined as follows

$$V_0(t) = \frac{2}{3}(V_{ab} + aV_{bc} + a^2V_{ca}) \qquad (21)$$

$$I_i(t) = \frac{2}{3}(I_a + aI_b + a^2I_c) \qquad (22)$$

Where $a = e^{j2\pi/3}$

The Table 1 shows the 27 switching states of the three-phase matrix converter. The first 18 states (±1, ±2, ±3, ±4, ±5, ±6, ±7, ±8, ±9) correspond to the active vectors. 0a, 0b and 0c are the corresponding zero vectors states and the last six states (±10, ±11, ±12) are the rotating vectors.

Table shows all different vectors for output voltages and input currents. The first eighteen space vectors are constant in direction but the magnitude depends on the input voltages and the output currents for the voltage and currents space vectors respectively. On the contrary, the magnitude of the six rotating vectors remains constant and corresponds to the maximum value of the input line-to-neutral voltage vector and the output line current vector, while its direction depends on the angles of the line-to-neutral input voltage vector and the input line current vector.

Table 1. Matrix Converter Space Vectors

State	a b c	V_o	α_o	I_i	β_i
+1	A B B	$2/3\,V_{AB}$	0	$2/\sqrt{3}$	$-\pi/6$
-1	B A A	$-2/3\,V_{AB}$	0	$-2/\sqrt{3}$	$-\pi/6$
+2	B C C	$2/3\,V_{BC}$	0	$2/\sqrt{3}$	$-\pi/2$
-2	C B B	$-2/3\,V_{BC}$	0	$-2/\sqrt{3}$	$-\pi/2$
+3	C A A	$2/3\,V_{CA}$	0	$2/\sqrt{3}$	$7\pi/6$
-3	A C C	$-2/3\,V_{CA}$	0	$-2/\sqrt{3}$	$7\pi/6$
+4	B A B	$2/3\,V_{AB}$	$2\pi/3$	$2/\sqrt{3}$	$-\pi/6$
-4	A B A	$-2/3\,V_{AB}$	$2\pi/3$	$-2/\sqrt{3}$	$-\pi/6$
+5	C B C	$2/3\,V_{BC}$	$2\pi/3$	$2/\sqrt{3}$	$-\pi/2$
-5	B C B	$-2/3\,V_{BC}$	$2\pi/3$	$-2/\sqrt{3}$	$-\pi/2$
+6	A C A	$2/3\,V_{CA}$	$2\pi/3$	$2/\sqrt{3}$	$7\pi/6$
-6	C A C	$-2/3\,V_{CA}$	$2\pi/3$	$-2/\sqrt{3}$	$7\pi/6$
+7	A A B	$2/3\,V_{AB}$	$4\pi/3$	$2/\sqrt{3}$	$-\pi/6$
-7	B B A	$-2/3\,V_{AB}$	$4\pi/3$	$-2/\sqrt{3}$	$-\pi/6$
+8	C C B	$2/3\,V_{BC}$	$4\pi/3$	$2/\sqrt{3}$	$\pi/2$
-8	B B C	$-2/3\,V_{BC}$	$4\pi/3$	$-2/\sqrt{3}$	$\pi/2$
+9	A A C	$2/3\,V_{CA}$	$4\pi/3$	$2/\sqrt{3}$	$7\pi/6$
-9	C C A	$-2/3\,V_{CA}$	$4\pi/3$	$-2/\sqrt{3}$	$7\pi/6$
0a	A A A	0	-	0	-
0b	B B B	0	-	0	-
0c	C C C	0	-	0	-
+10	A B C	V_{imax}	α_o+0	Iomax	β_i+0
-10	A C B	V_{imax}	$-\alpha_o+0$	Iomax	$-\beta_i+0$

+11	C A B	V_{imax}	$\alpha_o+{}^{2\pi}/_3$	Iomax	$\beta_i+{}^{2\pi}/_3$
-11	B A C	V_{imax}	$-\alpha_o-{}^{2\pi}/_3$	Iomax	$-\beta_i-{}^{2\pi}/_3$
+12	B C A	V_{imax}	$\alpha_o+{}^{4\pi}/_3$	Iomax	$\beta_i+{}^{4\pi}/_3$
-12	C B A	V_{imax}	$-\alpha_o-{}^{4\pi}/_3$	Iomax	$-\beta_i-{}^{4\pi}/_3$

4. SIMULATION OF WECS WITHOUT AND WITH MATRIX CONVERTER

The Simulink model of WECS with induction generator and variable pitch and variable speed wind turbine as a prime mover to induction generator (without Matrix Converter) is as shown in Figure 5. At t = 0 instant the pitch angle is 10 degrees and it is changed to 5 degrees at t = 0.25 seconds. The wind velocity at t = 0 instant is 10 m/sec, it is changed to 6 m/sec , 11.25 m/sec, 8 m/sec and 14 m/sec at t = 0.1,0.2,0.3 and 0.5 seconds respectively. The torque developed by wind turbine is applied as load on induction generator. The aerodynamic torque(T_m) and mechanical power (P_o) generated by a wind turbine is given by Equation (23) and Equation (24) respectively.

$$T_m = C_t(\lambda)\left[0.5\frac{\rho\pi R_r^3}{\eta_{gear}}\right]V_w^2 \tag{23}$$

$$P_m = \frac{1}{2}C_p\rho A_r V_w^3 \tag{24}$$

Where P_m is the power in watts, ρ is the air density in g/m^3,C_P a dimensionless factor called power Coefficient, A_r the turbine rotor area in m^2($A_r = \pi R_r^2$, where R_r is the rotor blade radius), η_{gear} is and V_w the wind speed in m/s. The power coefficient is related to the tip speed ratio *(λ)* and rotor blade pitch angle $\boldsymbol{\beta}$ according to Equation (24)

$$C_p = 0.73\left(\frac{151}{\lambda i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda i}} \tag{24}$$

$$\text{Where } \boldsymbol{\lambda_i} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\boldsymbol{\lambda}-\mathbf{0.02}\boldsymbol{\beta}}-\frac{\mathbf{0.003}}{\boldsymbol{\beta}^{\mathbf{3}}+\mathbf{1}}} \tag{25}$$

$$\text{And } \boldsymbol{\lambda} = \frac{\boldsymbol{\omega_r R_r}}{\boldsymbol{V_w}} \tag{26}$$

$$C_t = \frac{C_p}{\lambda} \tag{27}$$

In equation (26), ω_r is the angular speed of the turbine shaft. The theoretical limit for C_P is 0.59 according to Betz's Law, but its practical range of variation is 0.2-0.4.The voltage sag and swell can be produced by using "three phase programmable voltage source" in the simulation.

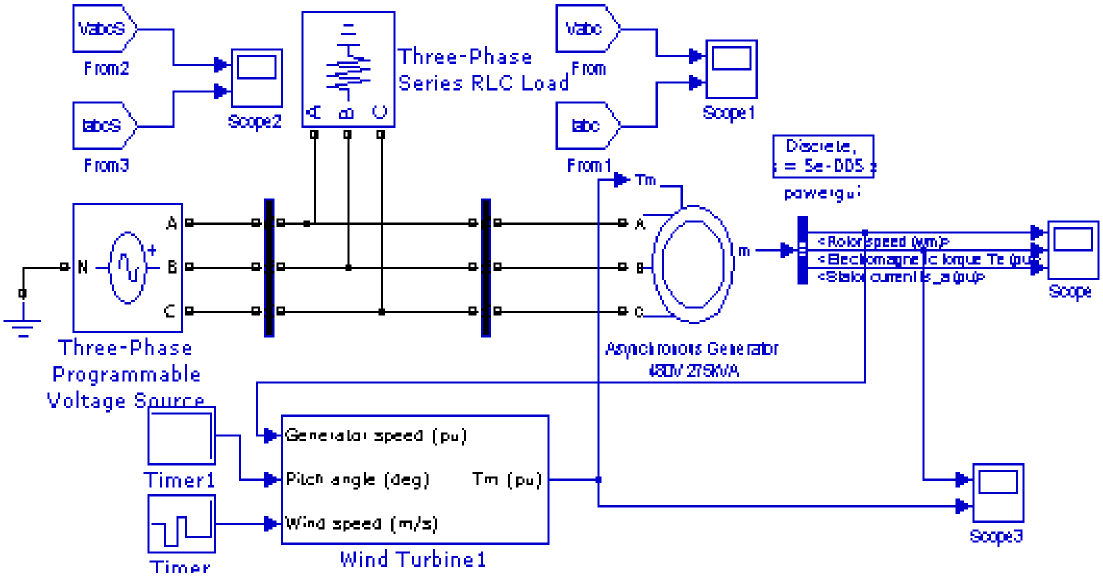

Figure 5 Simulink model of WECS without Matrix Converter

The Simulink model of WECS with induction generator, variable pitch and variable speed wind turbine as a prime mover to induction generator and matrix converter is as shown in Figure 6.

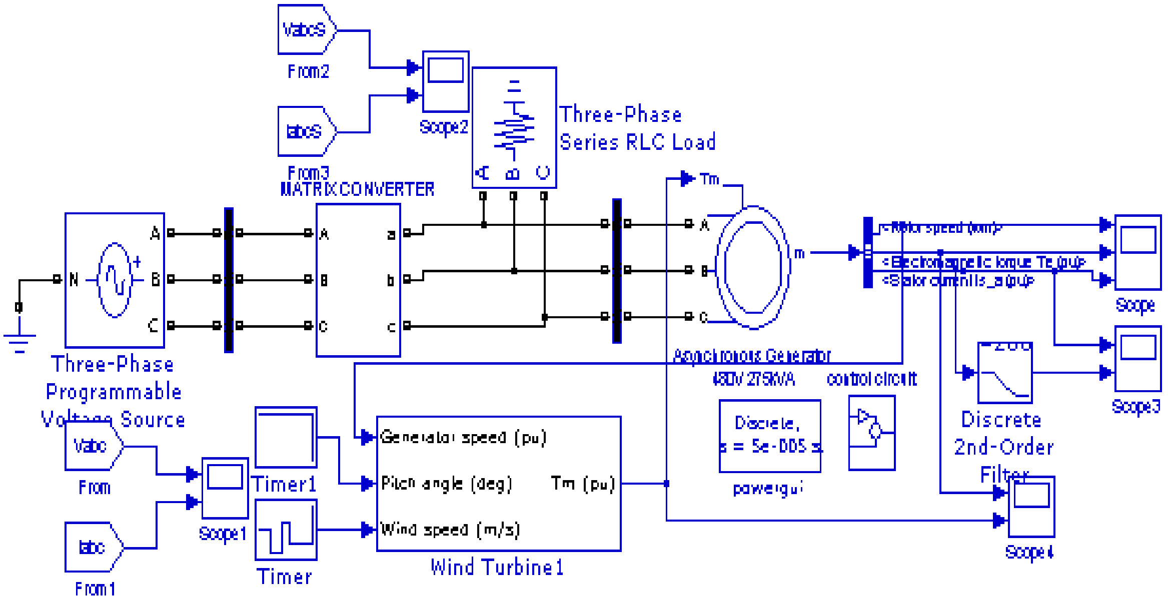

Figure 6 Simulink model of WECS with Matrix Converter

5. SIMULATION RESULTS

The source voltage and source current in above WECS without and with Matrix Converter is as shown in Figure 7 and Figure 8 respectively.

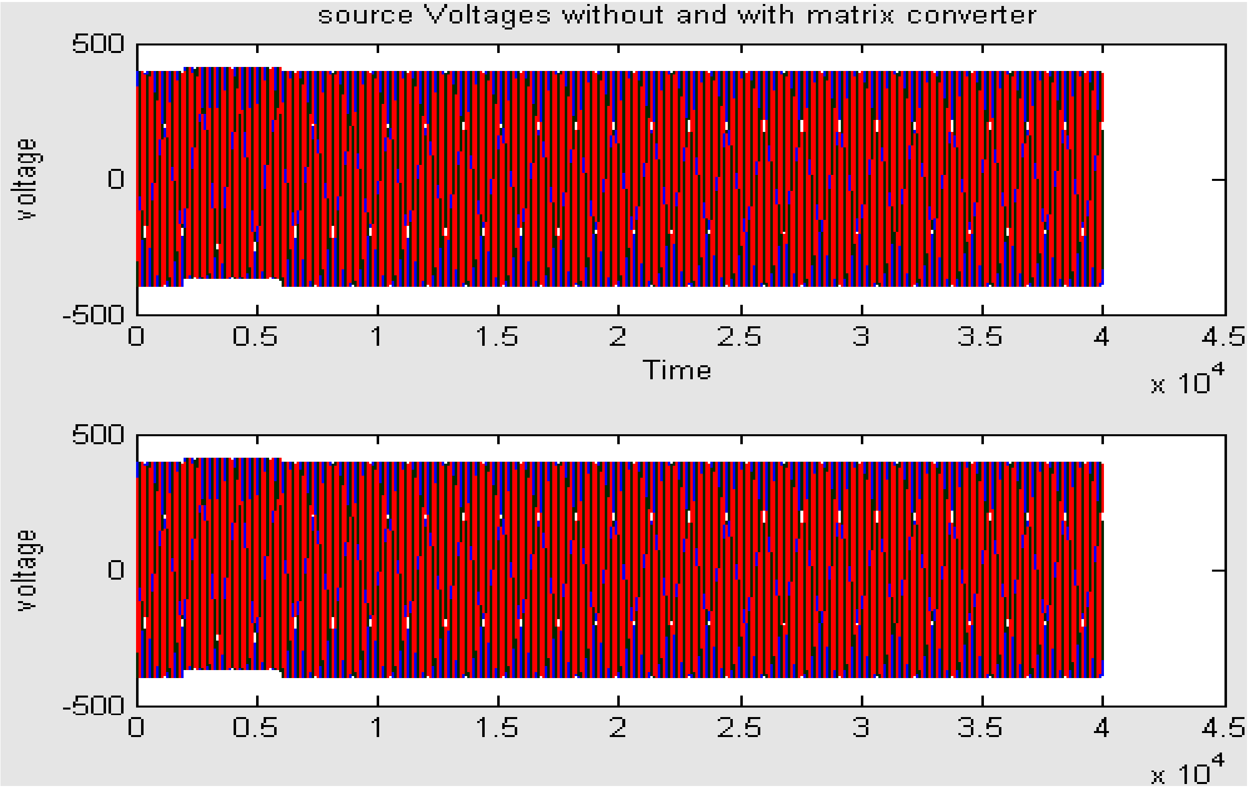

Figure 7. Source Voltages without and with Matrix converter

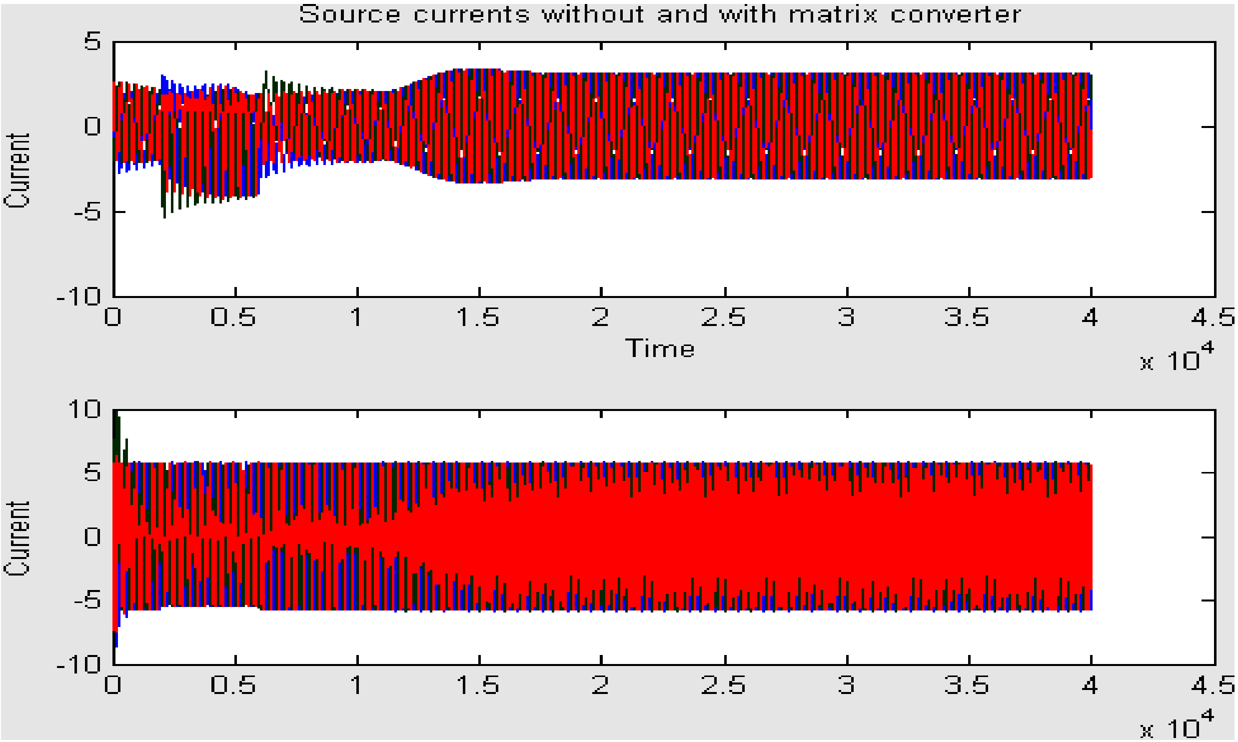

Figure 8 Source Currents without and with Matrix converter

The source current under normal conditions is 5 A. The source current variations are more without matrix converter then with matrix converter during transient state. The effect of source impedance is reduced with matrix converter and it avoids the short circuits in power electronic-devices. The load voltage and load current in above WECS without and with Matrix Converter is as shown in Figure 9 and Figure 10 respectively.

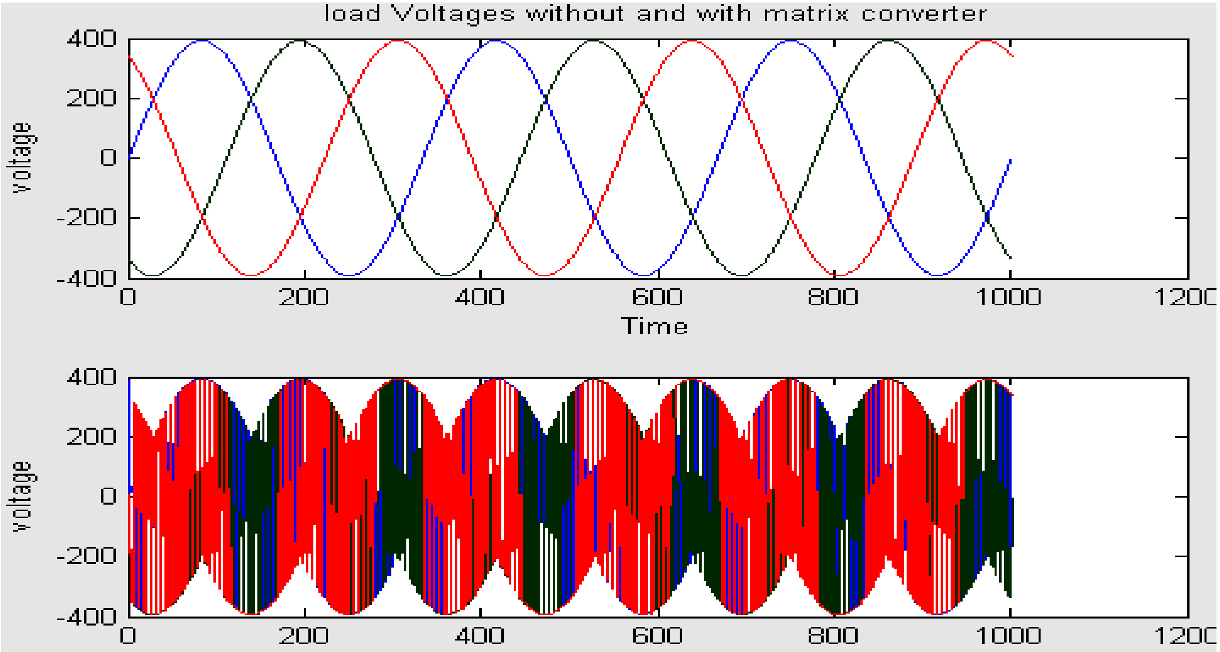

Figure 9 Load Voltages without and with Matrix converter

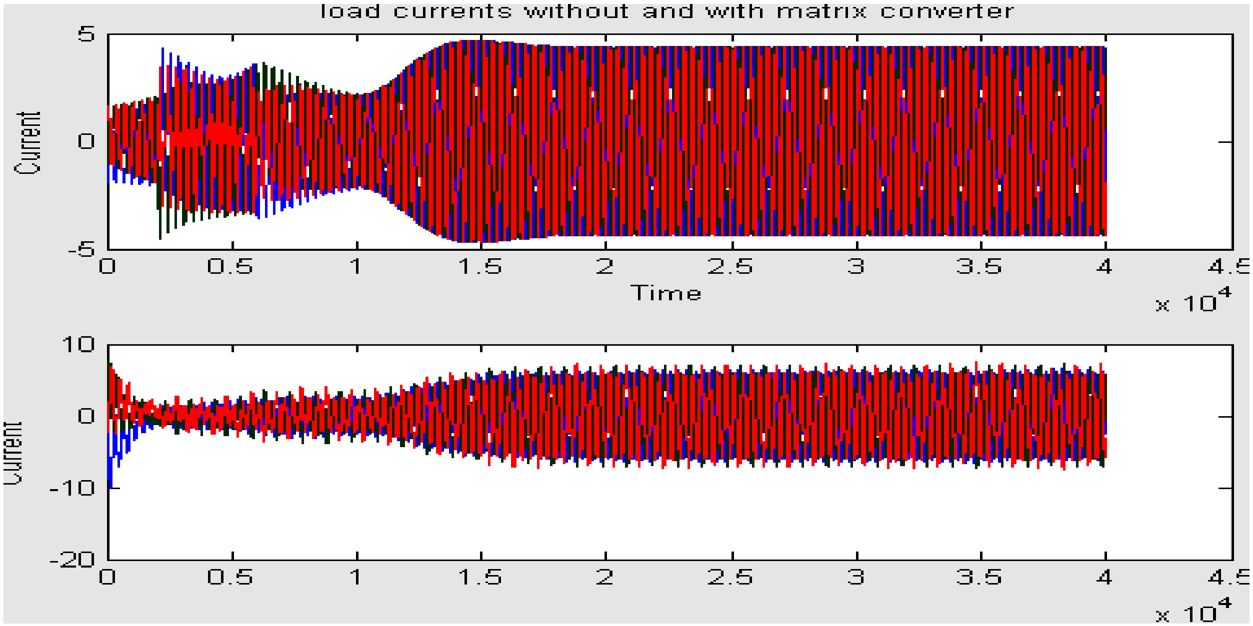

Figure 10 Load currants without and with Matrix converter

From the above two graphs, normal current without any disturbance is 5A. The load current variations are more without matrix converter then with matrix converter during transient state. The Rotor angular torque, Speed, Stator phase current in above WECS without and with Matrix Converter is as shown in Figure 11 , Figure 12 and Figure 13 respectively.

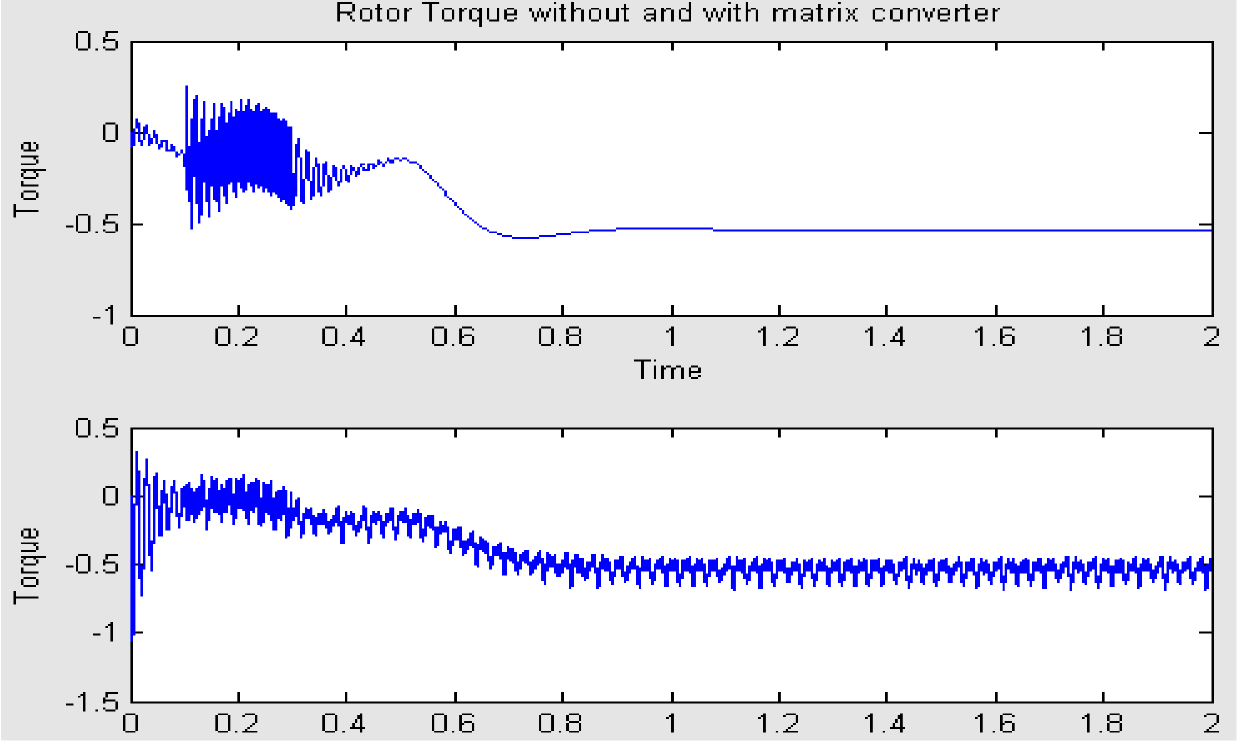

Figure 11 The Rotor angular torque without and with Matrix Converter

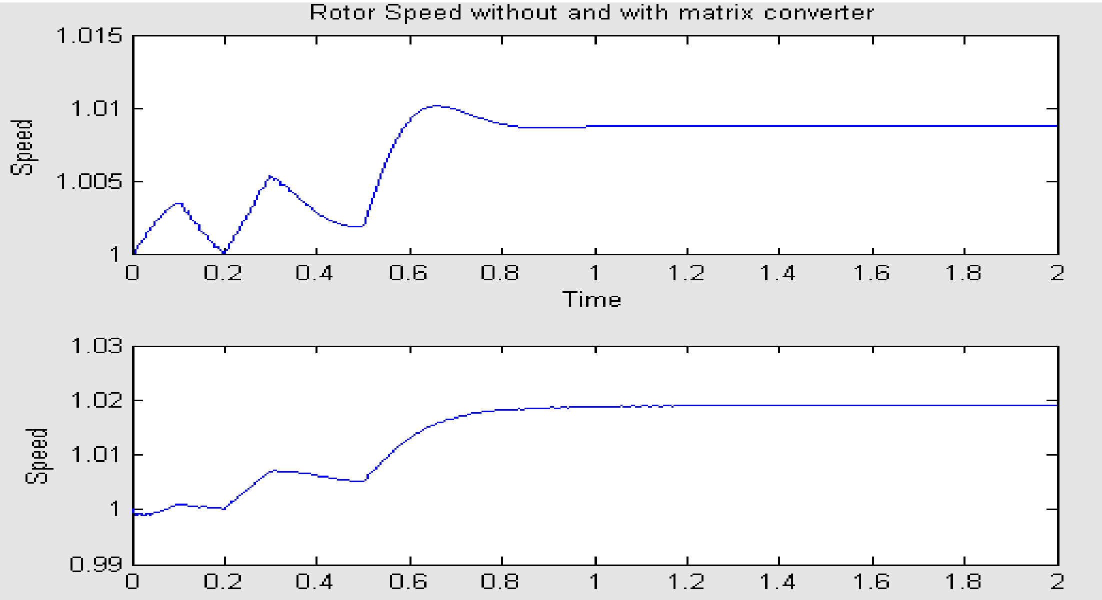

Figure 12 The Rotor angular speed without and with Matrix Converter

The power drawn from the grid under disturbance conditions with matrix converter is very low. Induction machine will be always in generating mode even under disturbance conditions with matrix converter. The stator current variations are very less even under disturbance conditions.

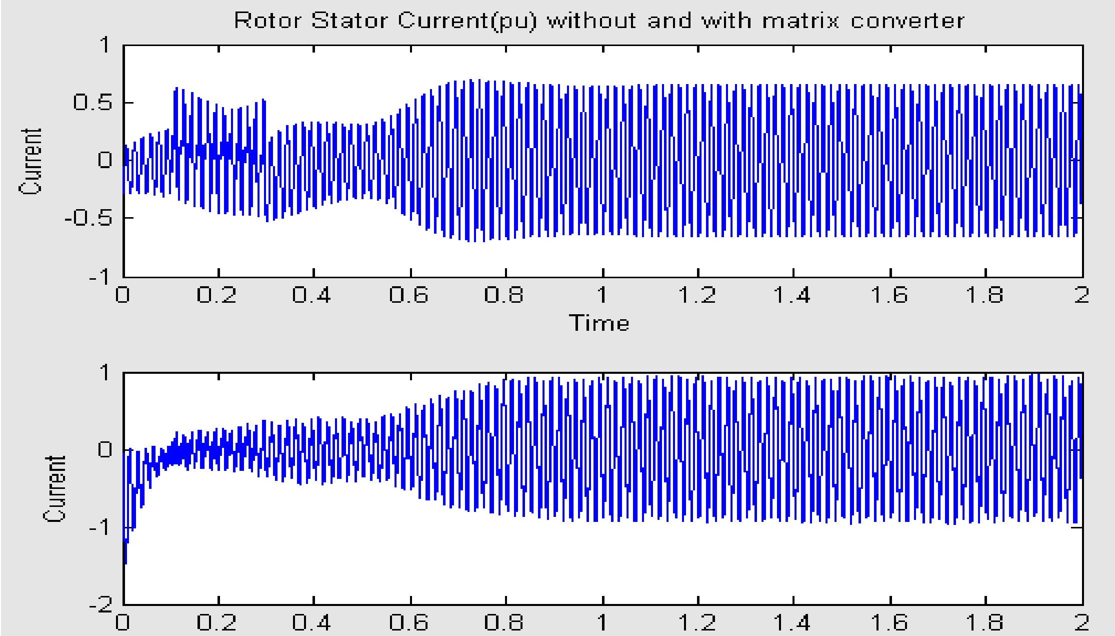

Figure 13 The Stator current (pu) without and with Matrix Converter

The reference and actual speeds in above WECS without and with Matrix Converter is as shown in Figure13 and Figure 14 respectively.

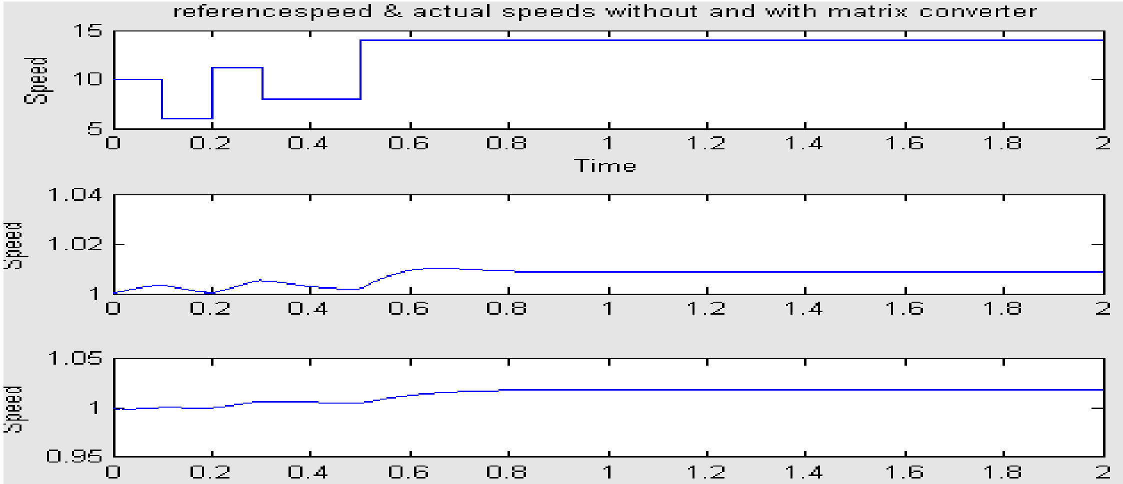

Figure 14 The reference and actual speeds without and with Matrix Converter

Smooth speed control is possible with matrix converter and it protects from the mechanical vibrations.

6. CONCLUSION

The Matrix converter, as an AC/AC converter, satisfies the requirement of providing a sinusoidal voltage on the load side and a sinusoidal current on the source side. Meanwhile, it is possible to adjust the input displacement angle and control the output voltage magnitude and phase angle by properly operating the switches. Since there is no dc-link as compared with a two-stage conventional AC/DC/AC converter, MC can be recognized as a full-silicon structure in a compact design. Also, the structure is inherently capable of a four-quadrant operation, with the output voltage and input current sinusoidal shaped with low distortion.

The matrix controller technique is good for controlling torque (load changes in wind turbine), fault current in the system and in the wind-generator system, power flow in the lines If Source Side Rectifier (AC-DC) is Diode Bridge Rectifier and Grid side controller is IGBT based Voltage Source Converter(VSC), then the former one will induce harmonics into the system along with IGBT VSC controller. So lower and higher order harmonics has to be eliminated by using filters or by other means and it will do only fault clearance or power flow control. But in our technique, matrix converter will take care of all such problems.

The disadvantages of a MC are in the high number of devices in the power circuit (18 switches and 18 diodes) and complexity of topology

Unified Power Flow Controller (UPFC) can be used for power flow control, disturbance clearance and harmonic elimination, but it is not economical. But for matrix controller can be applicable to any power rating with just usage of normal thyristor with anti-parallel diode banks and capacitor without any transformer. Hence it is very cost effective. The controller can be tuned for sags, swells, faults etc.

In this paper the controller is tuned for fault current limitation and optimal power flow. To improve the power quality capacitor rating has to be increased and all thyristors must be replaced with IGBTs.

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