PERFORMANCE EVALUATION OF AC MOTOR DRIVES THROUGH MATRIX CONVERTER-AN INDIRECT SPACE VECTOR MODULATION APPROACH

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ABSTRACT

This paper addressed to study about the performance of polyphase AC motor drives fed by a three phase matrix converter through an indirect space vector modulation technique under various load conditions. Invention of direct transfer of Power conversion is convenient method to eliminate DC link filter. Most of the Speed control method of AC drive has DC link filter which play an important role in rectifier fed inverter system. MATLAB/Simulink modeling and simulation of three phase induction motor drive fed by a three-phase direct matrix converter feeding a various load conditions is presented. The model has been performed with different switching frequency of matrix converter. The simulation results of various loads condition like rotor speed, stator current, input line current, output phase voltage, etc. are presented in term of waveform to confirm the input currents has sinusoidal and maximum output voltage per input voltage ratio is 0.866 with regard to operation under balance supply voltage.

KEYWORDS

Direct Matrix converter, Induction motor, Indirect SVM, Input Filter.

1. INTRODUCTION

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 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 as shown in Fig.1 [1], [2]. Among the most desirable features in power frequency changers are-

- Power circuit is Simple and compact.
- Generation of load voltage with arbitrary amplitude and frequency.
- Sinusoidal waveform of input and output currents.
- Unity power factor operation for any load.
- Regeneration capability.

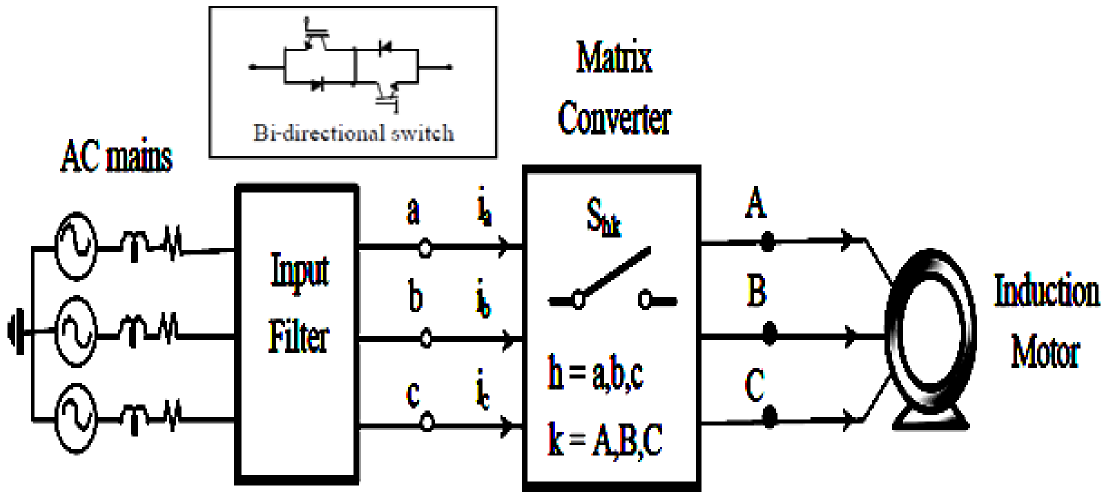


Fig. 1 Three phase matrix converter

2. MATRIX CONVERTER

All above ideal characteristics can be fulfilled by Matrix Converters and this is the reason for the tremendous interest in this converter topology. With the general arrangement of switches as shown in fig.1, the power can be flow in both directions through the converter. Because of the absence of any energy storage element, the instantaneous power input must be equal to the power output, assuming idealized zero-loss switches, the form and the frequency at the two sides are independent, in other words, the input may be three-phase ac and the output dc, or both may be dc, or both may be ac [3]. Therefore, the matrix converter topology is promising for universal power conversion such as- ac to dc, dc to ac, dc to dc or ac to ac.

The matrix converter has several advantages over traditional rectifier-inverter type power frequency converters.

- It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no sub harmonics.
- It has inherent bi-directional energy flow capability, the input power factor can be fully controlled.
- Last but not least, it has minimal energy storage requirements, which allows to get rid of bulky and lifetime- limited energy-storing capacitors.

The matrix converter has also some disadvantages over traditional rectifier-inverter type power frequency converters.

- First of all it has a maximum input output voltage transfer ratio limited to ≡ 87 % for sinusoidal input and output waveforms.
- It requires more semiconductor devices than a conventional AC-AC indirect power frequency converter, since no monolithic bi-directional switches exist and consequently discrete unidirectional devices, variously arranged, have to be used for each bi-directional switch.
- Finally, it is particularly sensitive to the disturbances of the input voltage system. [3], [4].

With nine bi-directional switches the matrix converter can theoretically assume 512 (29) different switching states combinations. But not all of them can be usefully employed. Regardless to the control method used, the choice of the matrix converter switching states combinations to be used must comply with two basic rules, which are-

- The converter is supplied by a voltage source and usually feeds an inductive load.
- The input phases should never be short-circuited and the output currents should not be interrupted.

From a practical point of view these rules imply that one and only one bi-directional switch per output phase must be switched on at any instant. By this constraint, in a three phase to three phase matrix converter 27 are the permitted switching combinations [5].

3. PROPOSED CONTROL SCHEME

The block diagram of the Matrix Converter is represented in Fig 1. Various modulation techniques can be applied to the AC-AC matrix Converter to achieve sinusoidal output voltages and input currents. The object of the modulation strategy is to synthesize the output voltages from the input voltages and the input currents from the output currents [5],[6]. The first modulator proposed for Matrix Converters, known as the Venturini modulation, employed a scalar model. This model gives a maximum voltage transfer ratio of 0.5. An injection of a third harmonic of the input and output voltage was proposed in order to fit the reference output voltage in the input system envelope. This technique is used to achieve a voltage transfer ratio with a maximum value of 0.866. The three phase matrix converter can be represented by a 3 by 3 matrix form because the nine bidirectional switches can connect one input phase to one output phase directly without any intermediate energy storage elements [7]. Therefore, the output voltages and input currents of the matrix converter can be represented by the transfer function T and the transposed TT such as

$$V_0 = T.V_I \tag{1}$$

$$\begin{bmatrix} V_A \\ -V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2}$$

$$I_I = T^T . I_O \tag{3}$$

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \end{bmatrix} . \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \tag{4}$$

where Va, Vb and Vc are input phase voltages, VA, VB and VC are output phase voltages, Ia, Ib and Ic are input currents and IA, IB and IC are output currents. Although several modulation strategies have been proposed since Venturini announced a closed mathematical solution for the transfer function T in early 1980, the indirect space vector modulation is gaining as a standard technique in the matrix converter modulations. The indirect space vector modulation (indirect SVM) was first proposed by Borojevic et al in 1989, where 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.2 [8]. Inverter stage has a standard 3φ 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.

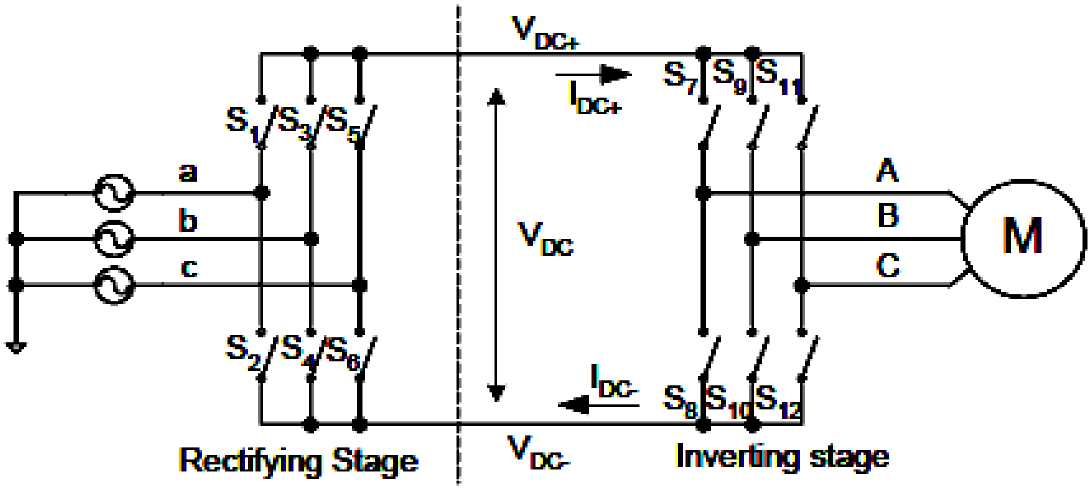


Fig. 2 The equivalent circuit for induction modulation

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 as shown in fig. 3.

$$T = I \cdot R \qquad (5)$$

$$\begin{bmatrix} S_{aA} & S_{bA} & S_{cA} \\ S_{aB} & S_{bB} & S_{cB} \\ S_{aC} & S_{bC} & S_{cC} \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \qquad (6)$$

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.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (7)$$

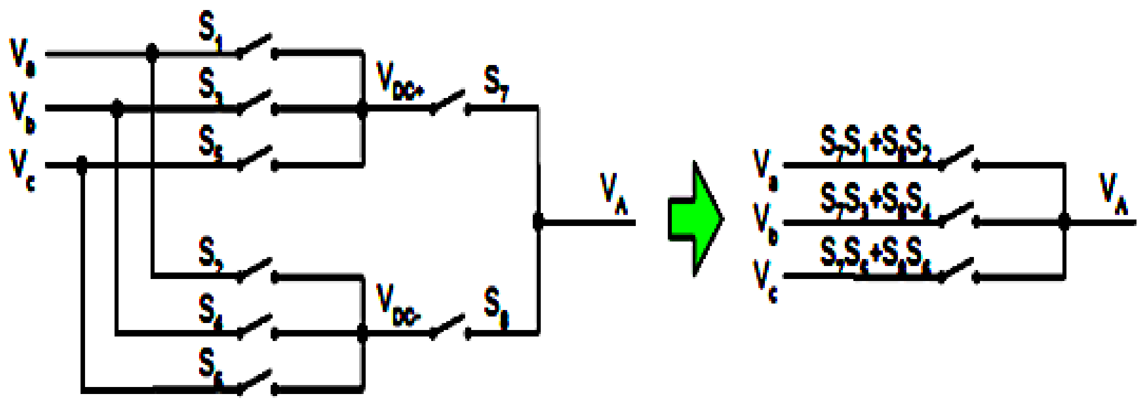
$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7.S_1 + S_8.S_2 & S_7.S_3 + S_8.S_4 & S_7.S_5 + S_8.S_6 \\ S_9.S_1 + S_{10}.S_2 & S_9.S_3 + S_{10}.S_4 & S_9.S_5 + S_{10}.S_6 \\ S_{11}.S_1 + S_{12}.S_2 & S_{11}.S_3 + S_{12}.S_4 & S_{11}.S_5 + S_{12}.S_6 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (8)$$

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 [9].

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.

A. 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 in Fig. 4 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



Phase A of back to back equivalent model **Phase A of matrix converter**

Fig. 3 Transformation from equivalent circuit to matrix converter in phase

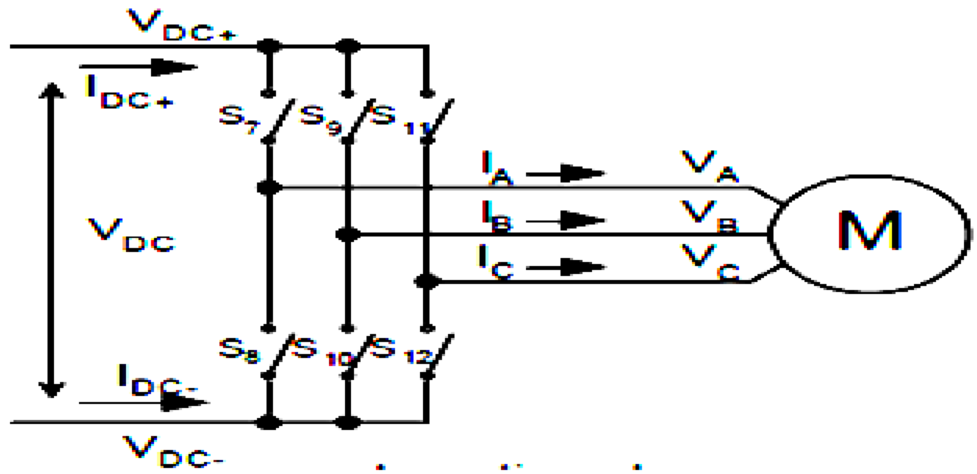
$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_7 & S_8 \\ S_9 & S_{10} \\ S_{11} & S_{12} \end{bmatrix} \begin{bmatrix} V_{DC+} \\ V_{DC-} \end{bmatrix} \qquad (9)$$

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

Then the output voltage space vector Vout and output current space vector Iout are expressed as space vectors using the transformation such as

$$V_{OUT} = \frac{2}{3}\left(V_A + V_B e^{j\frac{2\pi}{3}} + V_C e^{j\frac{4\pi}{3}}\right) \qquad (11)$$

$$I_{OUT} = \frac{2}{3}(I_A + I_B e^{j\frac{2\pi}{3}} + I_C e^{j\frac{4\pi}{3}}) \qquad (12)$$



Inverting stage

Fig. 4 Inverter stage from the equivalent circuit

The inverter switches, S7 to S12 can have only eight allowed combinations to avoid a short circuit through three half bridges. The eight combinations can be divided into six nonzero output voltages which are active vector V1 to V6 and two zero output voltages which are zero vector V0. In addition, the amplitude and angle of the output voltage space vectors are evaluated for six active vectors and two zero vectors.

The voltage space vector V_1 [100] indicates that output phase V_A is connected to positive rail V_{DC+} and the other phase V_B , V_C are connected to negative rail V_{DC-} and its vector magnitude is calculated from

$$V_1 = \frac{2}{3}(V_A + V_B e^{j\frac{2\pi}{3}} + V_C e^{j\frac{4\pi}{3}})$$

$$= \frac{2}{3}(\frac{2}{3}V_{DC} - \frac{1}{3}V_{DC}e^{j\frac{2\pi}{3}} - \frac{1}{3}V_{DC}e^{j\frac{4\pi}{3}})$$

$$= \frac{2}{3}V_{DC}\, e^{j\frac{\pi}{6}} \qquad (13)$$

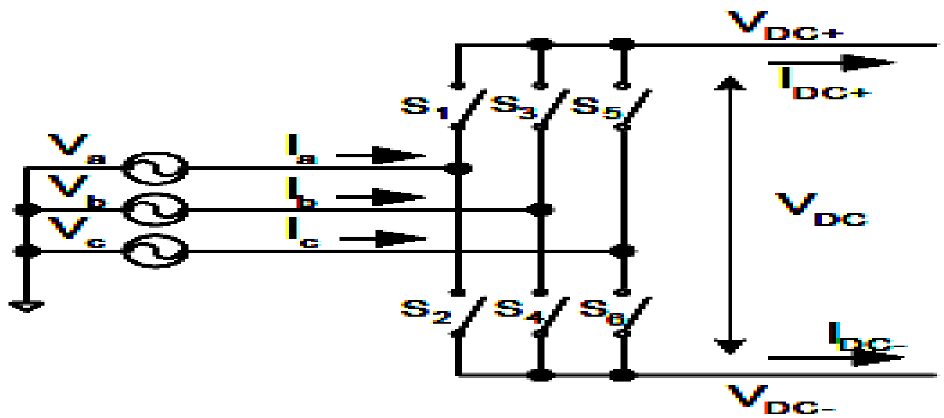
- The input vector sequence is always γδ0.
- When the sum of the current and voltage hexagon sector is odd, the output vector sequence must be αββα0.
- When the sum of the current and voltage hexagon sector is even, the output vector sequence must be βααβ0.
- When the input hexagon sector is odd, the output zero vector must be 000. Otherwise it must be 111.

- The matrix converter has been established as an alternative for the present standard VSI converters for adjustable speed drive applications. In contrast to VSI converters, the matrix converter is a direct type of power converter without any internal energy storage.

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.

B. SVM for Rectifier Stage

This section introduces a graphical interpretation of space vector PWM in the rectifier stage. Likewise the case of inverter stage, the rectifier part of the equivalent circuit in Fig. 5 can be assumed to a standalone current source rectifier (CSR) loaded by a dc current source, IDC.
In the indirect space vector modulation, all quantities are referred to virtual dc link and the virtual dc-link is built by chops of the input voltages. 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 V_{DC} can be derived by using the transposed RT such as



Rectifying stage

Fig.5 Rectifier stage from the equivalent circuit

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} S_1 & S_2 \\ S_3 & S_4 \\ S_5 & S_6 \end{bmatrix} \begin{bmatrix} I_{DC+} \\ I_{DC-} \end{bmatrix} \quad (14)$$

$$\begin{bmatrix} V_{DC+} \\ V_{DC-} \end{bmatrix} = \begin{bmatrix} S_1 & S_3 & S_5 \\ S_2 & S_4 & S_6 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (15)$$

then the input current space vector IIN and input voltage space vector VIN are expressed as space vectors using the transformation such as

$$I_{IN} = \frac{3}{2}\left(I_a + I_b e^{j\frac{2\pi}{3}} + I_c e^{j\frac{4\pi}{3}} \right) \quad (16)$$

$$V_{IN} = \frac{3}{2}\left(V_a + V_b e^{j\frac{2\pi}{3}} + V_c e^{j\frac{4\pi}{3}} \right) \tag{17}$$

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 I1 to I6 and three zero input currents which are zero vector I0. In addition, the amplitude and angle of the input current space vectors are evaluated for 6 active vectors and 3 zero vectors [10].
I1 [ab] indicates that input phase a is connected to the positive rail of the virtual dc-link VDC+ and input phase b is to the negative rail VDC- .Its vector magnitude is calculated from

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

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

$$= \frac{2}{\sqrt{3}} I_{DC} \, e^{-j\frac{\pi}{6}} \tag{18}$$

4. SIMULATIONS AND RESULT

This scheme include reduction in common-mode voltage (peak value), improved harmonic spectrum, reduced switching losses and no more additional switching instants over one sampling period, and simplified implementation via Matlab/Simulink software. The proposed method maintains the active voltage vector and distributes zero vectors equally within a sampling period and reduces square rms of ripple components of input current.
Fig. 6 shows the complete diagram for induction motor fed by a three phase matrix converter through an indirect space vector modulation approach. A Matlab/Simulink model is developed to examine the performance of three phase induction motor as well as three phase matrix converter. The results show that the torque and speed responses are fast and highly dynamic. It is to be noted that the torque ripples have been decreased, moreover, the total harmonic distortion is less than in the conventional method. Hence it is clear that better torque and speed response can be obtained by using this control method and current and voltage response can also be obtained. To confirm the operating principle of the new asynchronous speed drive system, simulations have been carried out on Simulink modeling. In order to show clearly the output voltage obtained from the inverter and rectifier, an LC filter is placed on the input side of the proposed three phase matrix converter.

Case 1. Response of Induction motor for full load condition *(T = 11.9 N-m)*

The result for the above condition are shown in figure 7-11. It is observed that at the very starting point (standstill) rotor current is 90 Amp. and it goes to settle down at 11.6 Amp. in 0.78 sec., stator current is 76.8 Amp. and it goes settle down at 14.7Amp., motor torque responce is rapidly settle down to nearly the load torque and speed reaches at steady state value that is 1719 rpm with in 0.78 second from stanstill condition.

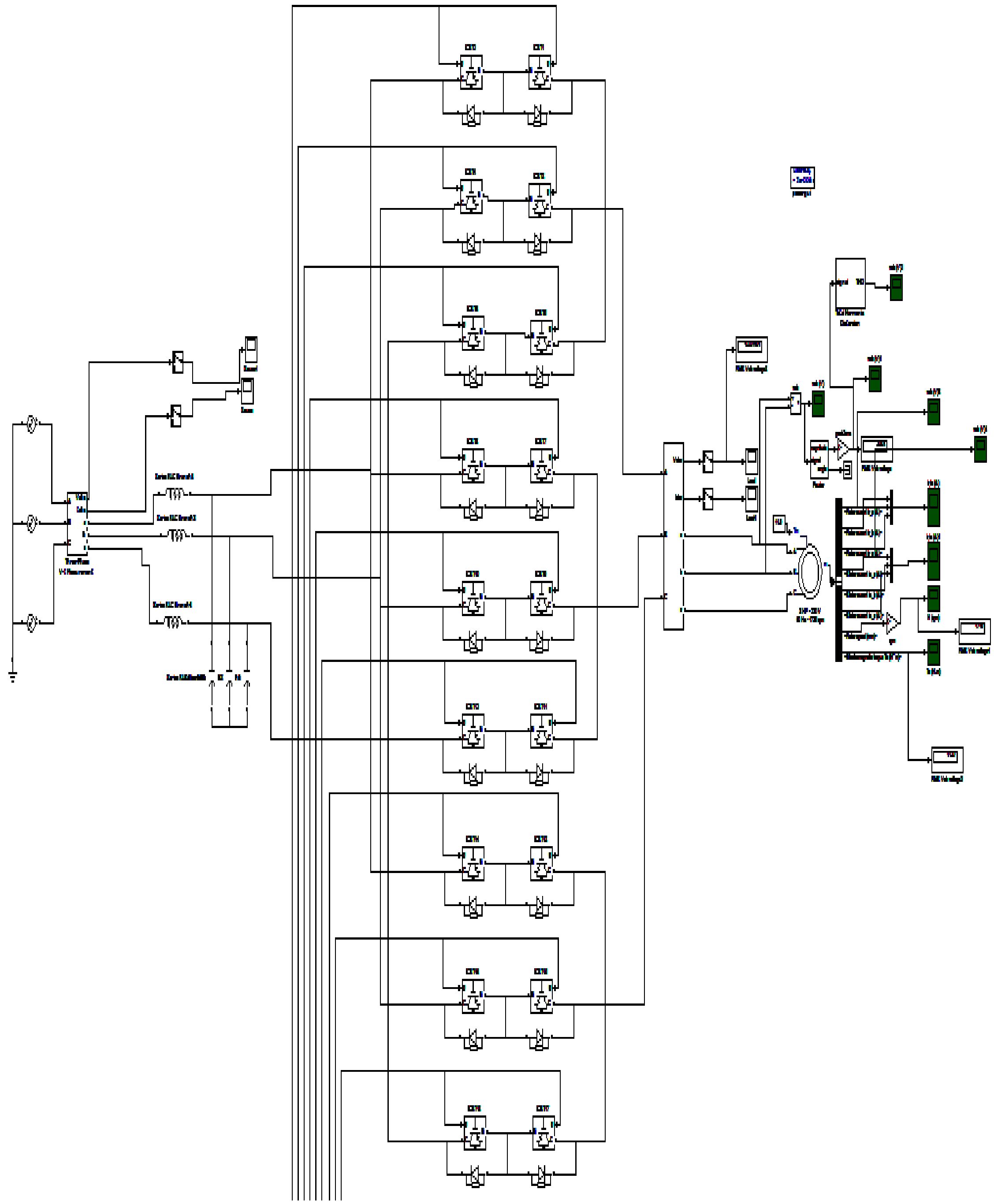


Fig. 6 Simulink Model of three phase induction motor fed by a three phase matrix converter with input LC filter at the input side of the converter

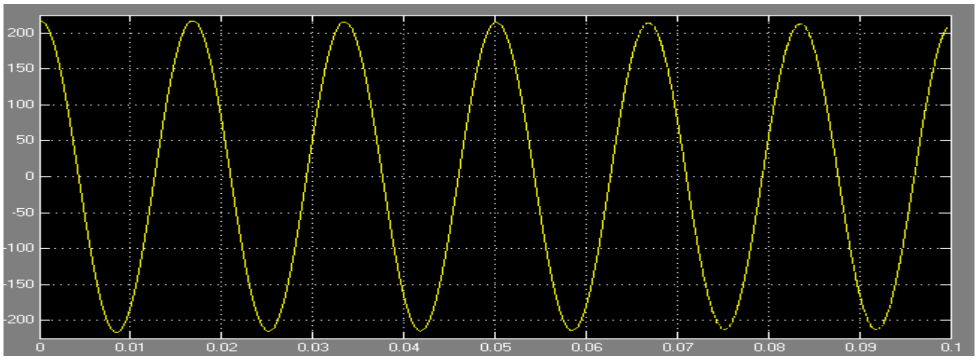


Fig. 7 Input Voltage (Vrms) under full load

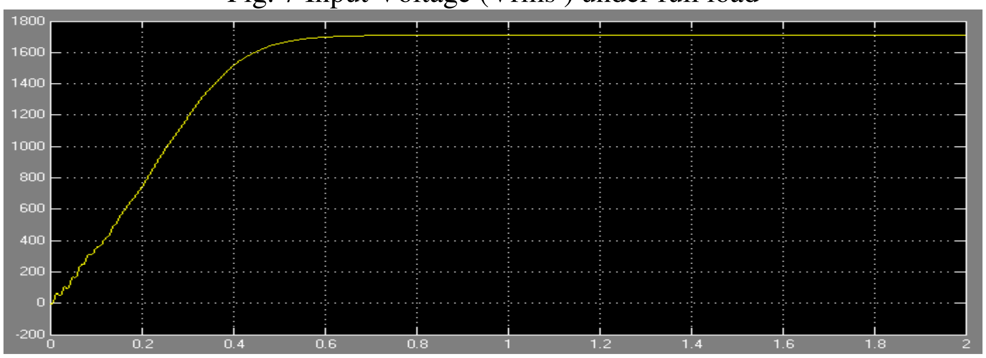


Fig. 8 Rotor Speed Nr under full load condition

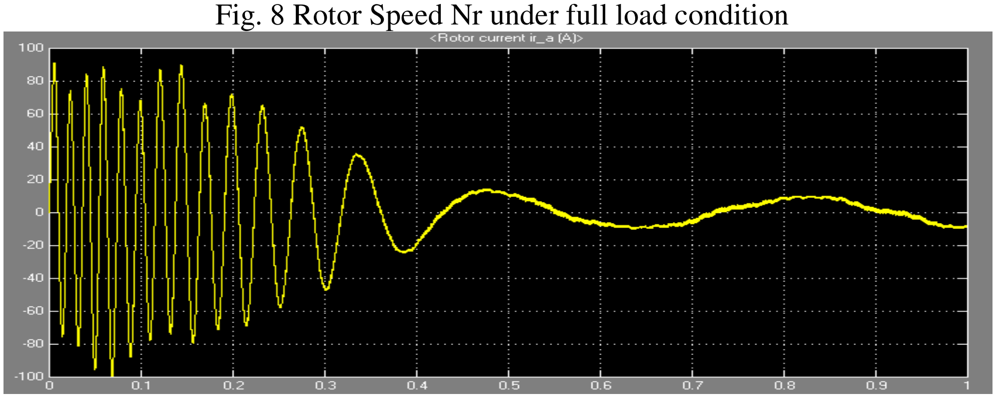


Fig. 9 Rotor current/phase ir

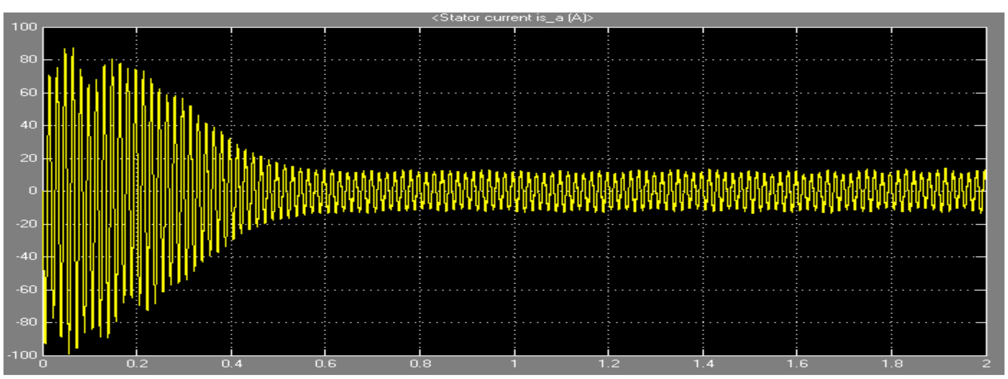


Fig. 10.Stator current/phase is under full load condition

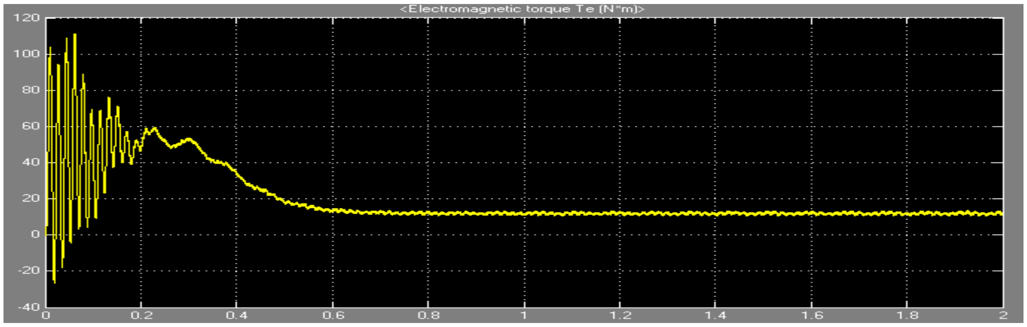


Fig. 11. Electromagnetic Torque Te under full load condition

Case 2. Response of Induction motor for under load condition *(T = 7 N-m)*

The results for the above condition are shown in figure 12-15. It is observed that at the starting point rotor current is 79 Amp. and it goes to settle down at 8.7 Amp. in 0.74 sec., stator current is 78.6 Amp. and it goes settle down at 12.0 Amp., and speed reaches at steady state value from stanstill to 1745 rpm with in 0.74 second.

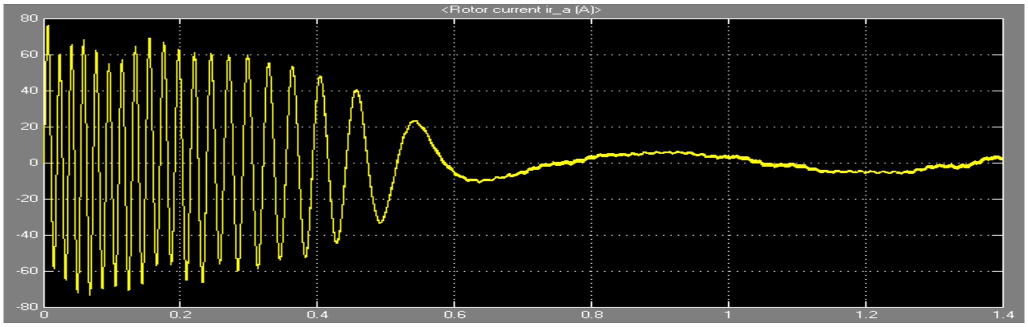


Fig. 12. Rotor current/phase ir for under load condition

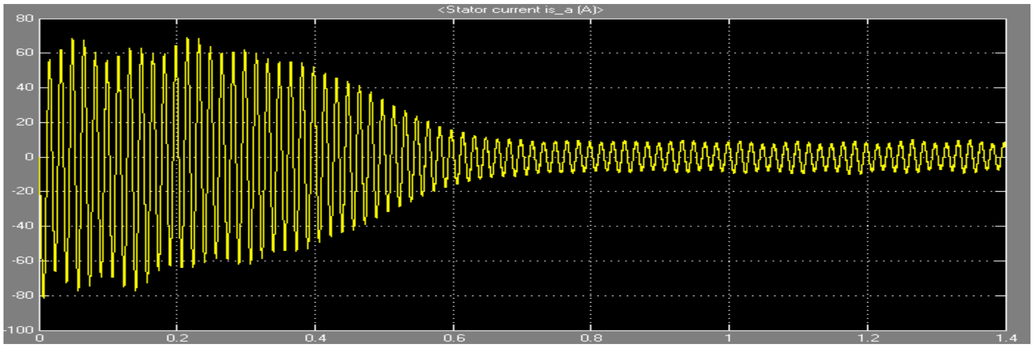


Fig. 13. Stator Current per phase is for under load condition

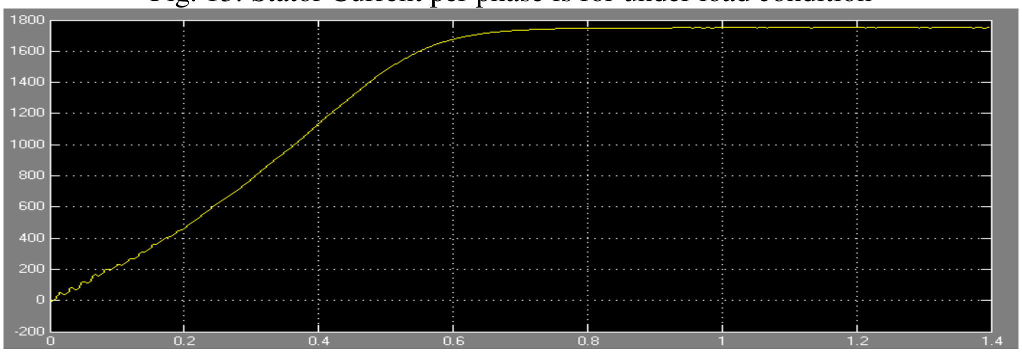


Fig. 14 Rotor Speed in rpm (Nr) for under load condition

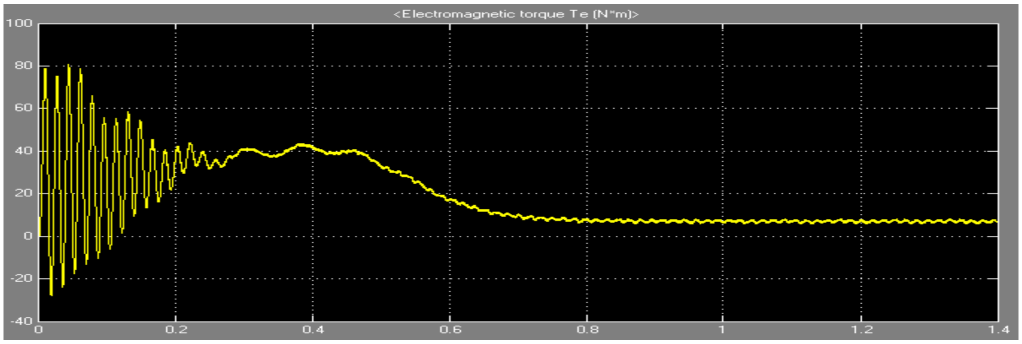


Fig.15 Electromagnetic torque Tem for under load condition

Case 3. Response of Induction motor at No load condition *(T =0 N-m)*

The result for the above condition are shown in figure 16-19. It can be observed that at starting point rotor current is 85.7 Amp. and it goes to settle down at 4.5Amp. in 0.76 sec., stator current is 97.6 Amp. and it goes settle down at 6.7 Amp., torque responce reaches 0 N-m rapidly within the setling time and speed reaches at steady state value that is 1797 rpm with in 0.76 second.

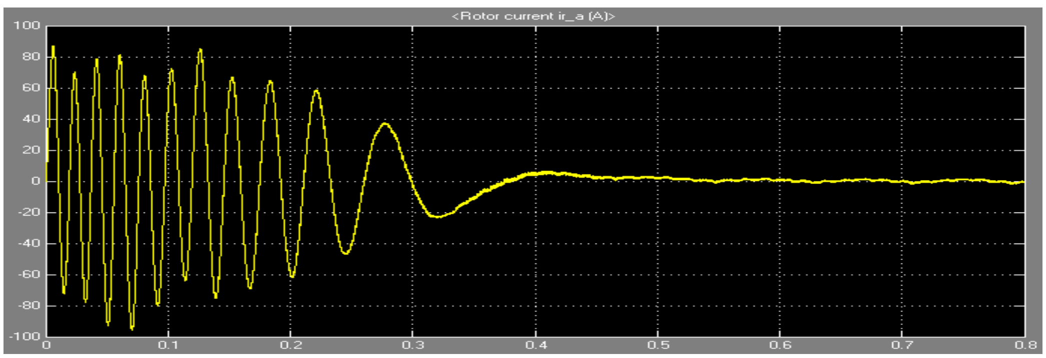


Fig. 16. Rotor current ir at No load condition

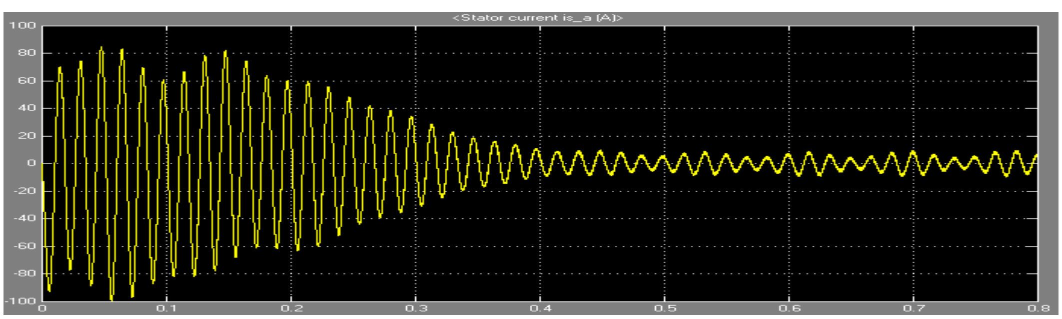


Fig. 17 Stator current/phase is at No load condition

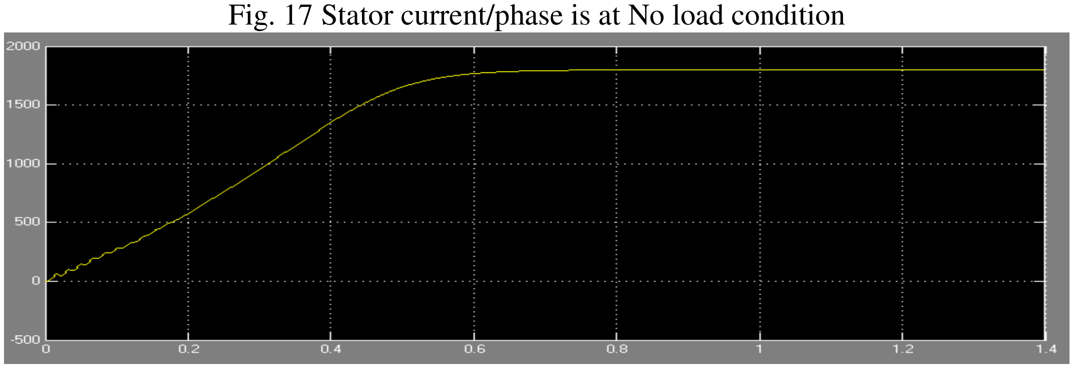


Fig. 18 Rotor speed in rpm Nr at No load condition

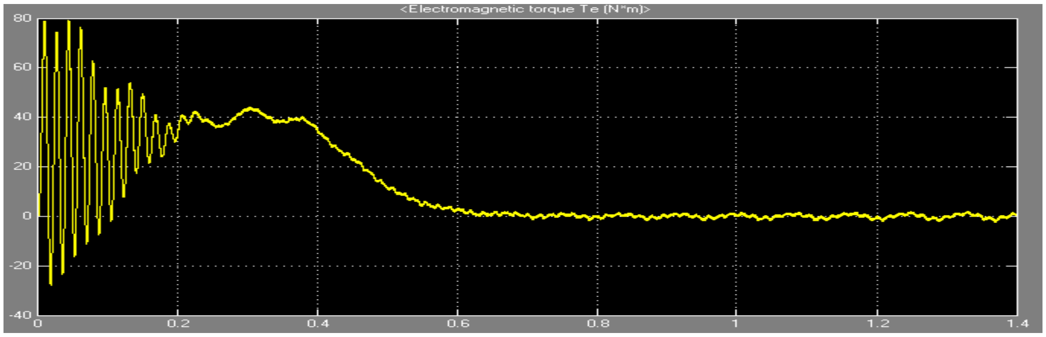


Fig. 19 Electromagnetic torque Tem at No load condition

Case 4. Response of Induction motor at Step load condition *(T =7-11.9 N-m)*

The results for the above condition are shown in 20-23. It can be observed that at starting point rotor current is 83.8 Amp. and it goes to settle down at 8.9 to 12.1Amp. in 1.20 sec., stator current is 76.9 Amp. and it goes settle down at 12.3 to 14.5 Amp., and speed reaches at steady state value that is 1745 to 1719 rpm with in 1.20 second.

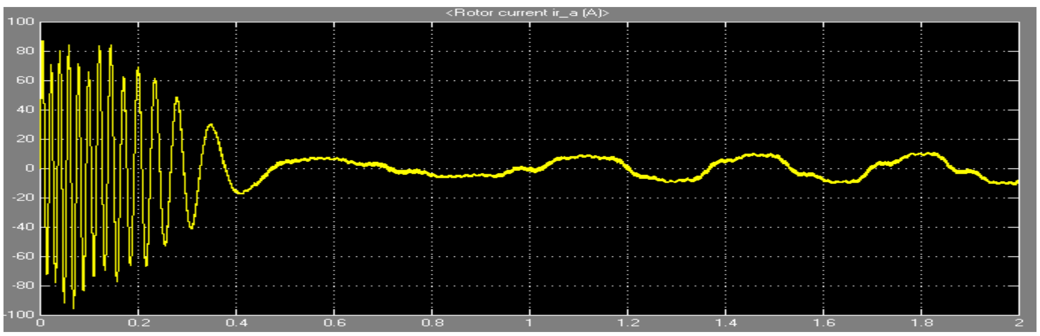


Fig. 20 Rotor Current per phase ir at Step load condition

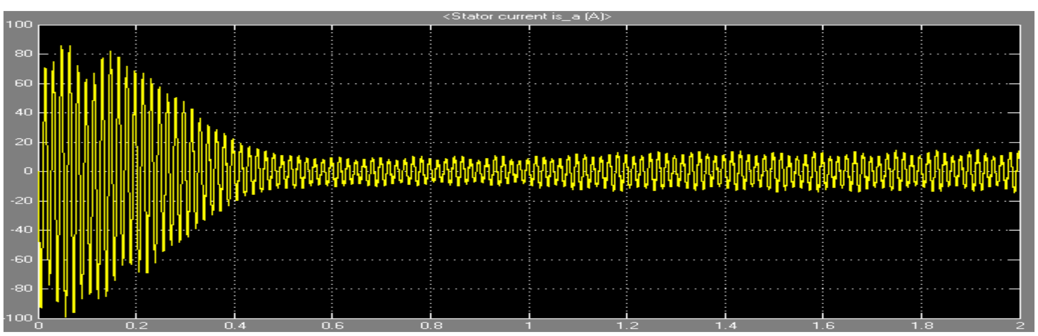


Fig. 21 Stator Current per phase is at Step load condition

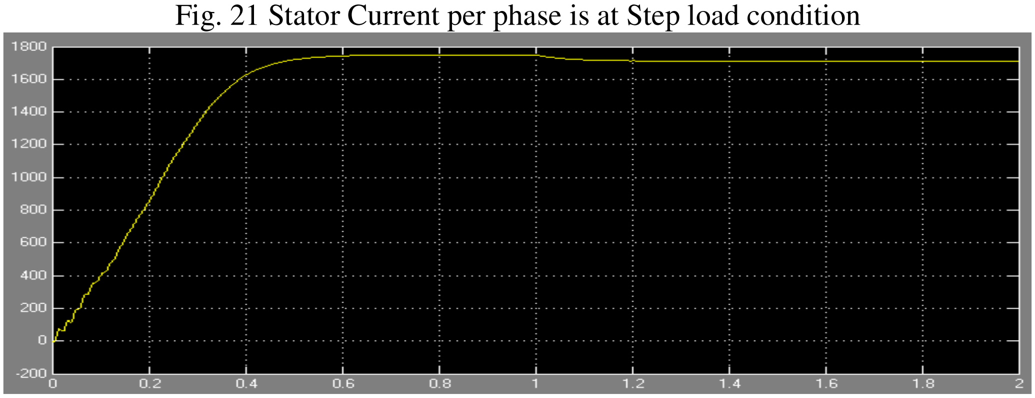


Fig. 22 Rotor speed in rpm Nr at Step load condition

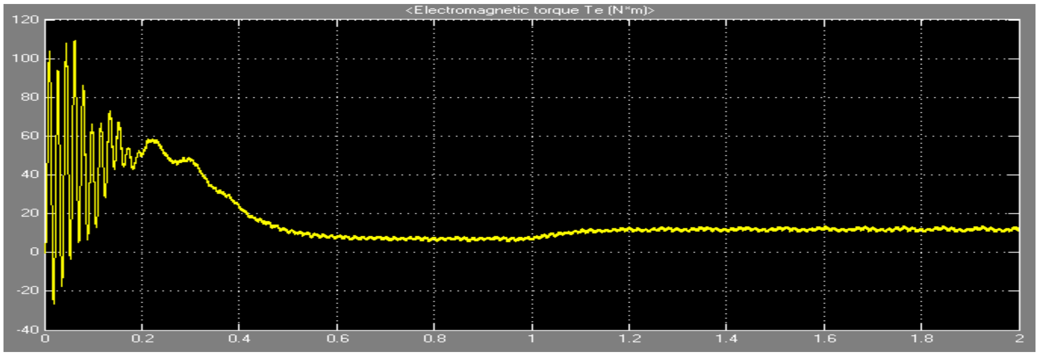


Fig. 23 Electromagnetic torque Tem at Step load condition

Case 5. Response of Induction motor at overload condition *(T =16 N-m)*

The results for the above condition are shown in fig. 24-27. It can be observed that at starting point rotor current is 89.5 Amp. and it goes to settle down at 13.6 Amp. in 0.97 sec., stator current is 81.6 Amp. and it goes settle down at 16.2 Amp., torque responce is settle at 16 N-m and speed reaches at steady state value that is 1797 rpm with in 0.97 second.

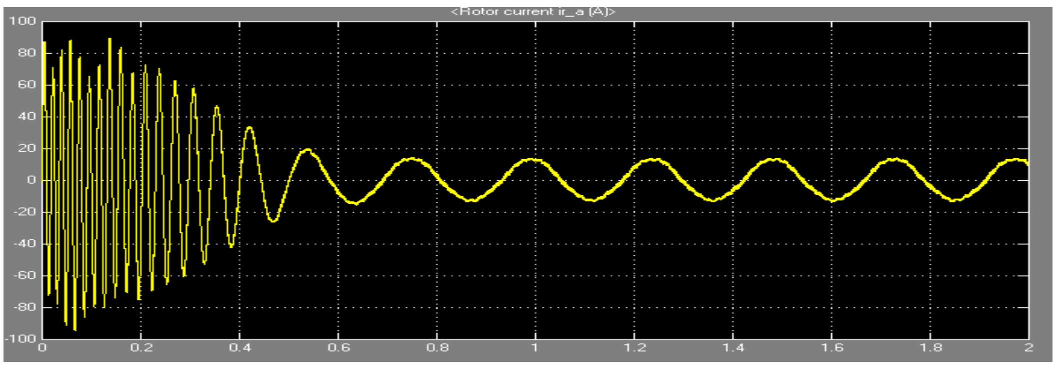


Fig. 24 Rotor Current per phase i_r

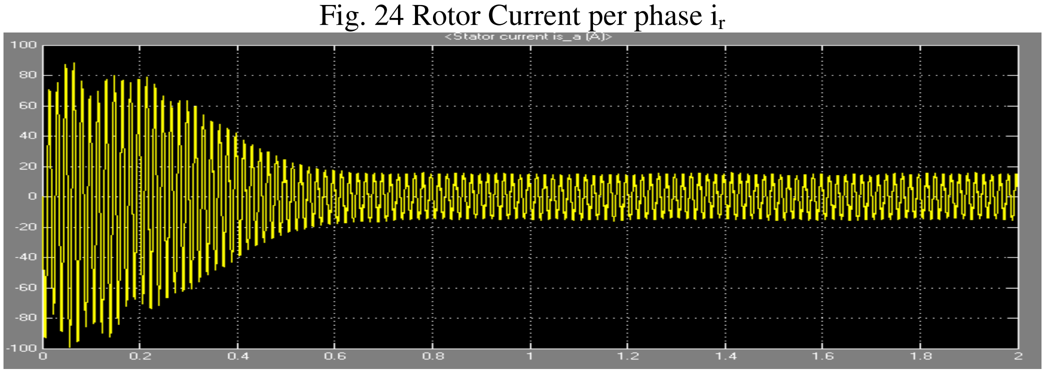


Fig. 25 Stator Current per phase i_s

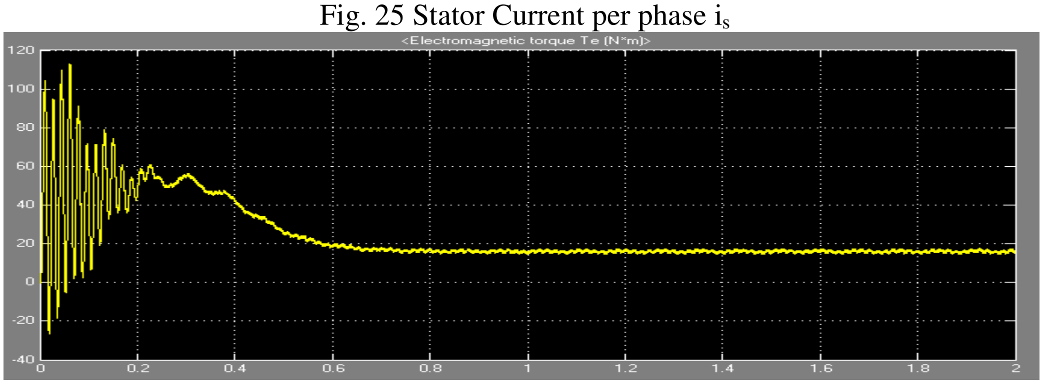


Fig. 26 Electromagnetic torque

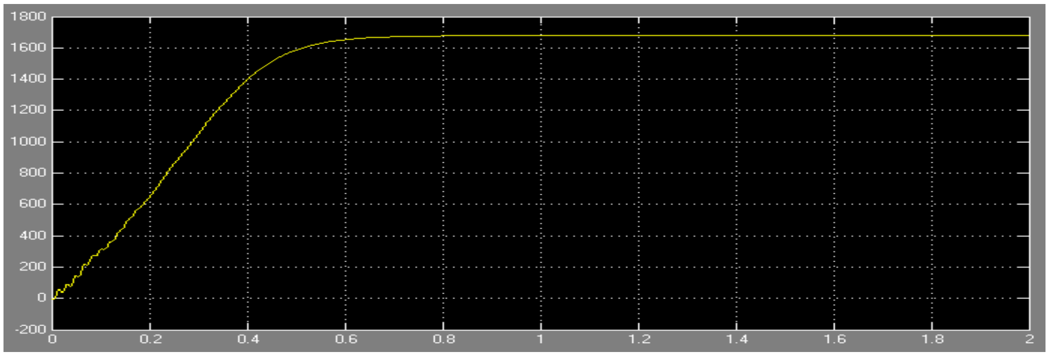


Fig. 27 Rotor speed in rpm Nr

5. COMPARISON OF PERFORMANCE OF AC MOTOR DRIVES

Performance evaluation table for matrix converter fed induction motor drive when motor is subjected to constant load, step load, over load, under load and no load condition is shown in Table I. From this table we conclude that the different parameters of the model are different from each other. From the table the parameters of different load condition can be compared by each other and the performance can be defined by their settling time for the different rotor speed. Rotor current and stator current can also be computed by it.

Table I. Performance Evaluation table for of Matrix converter fed Induction motor drive

PERFORMANCE QUANTITIES	CONSTANT LOAD (11.9 Nm)	STEP LOAD (7Nm to11.9 Nm)	UNDER LOAD (7Nm)	NO LOAD (0Nm)	OVERL OAD (16Nm)
Stator current(amp)	14.7	12.3 to 14.5	12.0	6.7	16.2
Rotor Current (amp)	11.8	8.9 to 12.1	8.7	4.5	13.6
Motor speed (r.p.m)	1719	1745 to 1719	1745	1797	1707
Settling time (second)	0.78	1.20	0.74	0.76	0.96

6. FILTER PARAMETERS

L=0.0010 H
C=0.01118 F

7. CONCLUSION

Simulation model of three phase matrix converter fed induction motor drive is presented. As the matrix converter is a single stage power conversion device, it provides tremendous interest in industrial as well as in domestic application where the variable frequency and variable speed is needed. It is concluded that with the variation of load torque of induction motor and carrier frequency of matrix converter, the output performance of motor is evaluated for its simplicity.

APPENDIX
MOTOR PARAMETERS

Voltage	220 V
Nominal Power	2238 W
Frequency	60 Hz.
Pole Pair	2
Torque	11.9N-m.
Speed	1725 r/min.
Rotation Inertia	0.089 Kg·m².
Stator Resistance (Rs)	0.435 Ω.
Rotor Resistance (R'r)	0.816 Ω.
Stator Inductance (Ls)	0.004 H
Rotor Resistance (L'r)	0.004 H
Mutual Inductance (Lm)	0.06931H

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