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Optimum Amplitude Venturini ModulationBased Matrix Converter Fed Induction Motor Drive.

SrikanthYerra[1], Kumaravel S[2], M.Krishna[3], A.Hema Chander[4]
[1,3,4]*GVP college of engineering for women, Madhurawada,Visakhapatnam,India*
[2]*Dept. of Electrical Engineering.National Institute of Technology Calicut,Calicut,Kerala, India*

Abstract**:** *Electrical Drives play a vital role in domestic and industrial applications throughout the world. Electrical drive offers a convenient means for controlling the operation of different equipment used in industry. In the present scenario almost 80% industrial drives are asynchronous induction motor based drives. In general the speed control of induction motor is achieved by employing converter topologies like AC-DC-AC, cyclo-converter etc. However, these converter topologies have several issues such as DC link capacitor losses, bulky size of the converter etc. The proposed Matrix Converter (MC) is one of the new power converter topologiesthat eliminate DC link capacitor and converts fixed frequency power supply to variable frequency in single stage.Modeling and simulation of a typical 3HP, 415V, 3-phase Matrix Converter fed Induction Motor drive is presented in this paper. Current THD analysis shows the promising performance of the proposed converter topology for induction motor drive.*

Key words**:** *Asynchronous induction motor,Matrix Converter, solid state drives, ac-dc-ac converter*

I. Introduction

Most of the production equipment used in modern industrial undertakings consists of three important components, namely the prime mover, the energy transmitting device and the actual apparatus or equipment[1]. The function of the prime mover and the energy transmitting device is to impart the motion and operate actual apparatus. The most commonly used prime mover is, of course an electric motor, since it is far superior in performance to steam, hydraulic, diesel and other types of engines. Electric motors are often operated directly from a supply line, under their own inherent speed- torque characteristics and their operating conditions are dictated by the mechanical loads connected to them.

However in many applications the motors are provided with control equipment by which their characteristics can be adjusted and their operating conditions with respect the mechanical load varied to suite specific speed torque requirements. The most common control adjustment is of motor speed, but torque and acceleration or deceleration can also be adjusted. The control equipment usually consists of relays, contactors, master switches and solid state devices such as diodes, transistors and thyristors which are used in power converters.

AC drives are also known by various other names such as Adjustable Speed Drives (ASD) or Adjustable Frequency Drives (AFD)or Variable Frequency Drives (VFD). Different types of converter topologies are used for changing the frequency of the electrical supply like rectifier-inverter fed systems [2-3].Pulse Width Modulated (PWM)voltage source inverter; Back-to-Back Voltage Source Inverter (VSI) and Current Source Inverter (CSI) are the different types of AC-AC converter topologies that can change the supply frequency. A DC link capacitor is used in the case of VSI and DC link inductor is used in the case of CSI for decoupling the twoAC power conversion stages and ensures the independent control of two stages [4]. But size of the energy storage element is very large and also has the limitedspan of life time.

The proposed Matrix Converter (MC) can overcome the disadvantages associated with the conventional system. The most important characteristics of the matrix converter are [5]:

- Simple and compact power circuit
- Generation of load voltage with arbitrary amplitude and frequency
- Sinusoidal input and output currents
- Energy regeneration aptitude to the mains and
- Controllable of input displacement factor regardless of the load

These highly attractive characteristics are the reason for the present tremendous interest in this topology.

The MC, depending on the kind of power supplies (voltage or current), which can work as a Voltage Source Matrix Converter (VSMC) or a Current Source Matrix Converter (CSMC), respectively. Matrix converter in VSMC mode is discussed much by the researchers, and commonly this structure is referred as a matrix converter. Modeling and simulation of Voltage Source Matrix converter fed Induction Motor drive is presented in this paper.

II. Voltage Source Matrix Converter

Matrix converter is a single-stage converter which has an array (m x n) of bidirectional power switches connect directly between an m-phase voltage source and an n -phase load [6-7], [9-10]. Matrix converter of 3×3 bidirectional switches, shown inFig. 1, is the most important converter which connects a three-phase source to a three phase load.

Matrix converter with nine bi-directional switches has theoretically 512 (2^9) different switching combinations. Regardless to the control method used, the choice of the matrix converter switching state combinations must comply the following two basic rules.

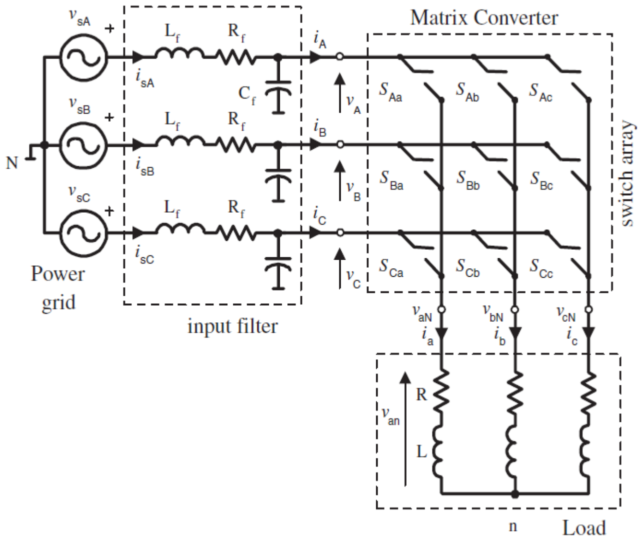


Fig. 1. Basic power circuit of the MC with input filter [10].

- Input phases should never be short-circuited when the converter is supplied by a voltage source.
- The output currents should not be interrupted for the inductive load.

These rules imply that only a 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(3x3x3) switching combinations are permitted.

III. Modelling Of A Matrix Converter Drive

Modeling of a matrix converter with a modulation strategy, source filter, and an induction motor drive is presented in this section.

*A. **Modeling of Matrix Converter using OAVM modulation strategy**.*

Optimum Amplitude Venturini Modulation (OAVM) method is used to generate switching pulses for the Matrix Converter. In the basic topology of the MC shown in Fig. 1v_{si},$_{[i = \{A, B, C\}]}$are three phase source voltages, $i_{si}$are three phase source currents, v_{jn}, $_{[j = \{a, b, c\}]}$are the load voltages with respect to the neutral point 'n' of the star connected load and, i_j, are the load currents. v_{iN},are the MC input voltages, i_i, are the MC input currentsandv_{jN}, are the load voltages with respect to the neutral point N of the source.

Each switch S_{ij}connects/disconnects phase $i$of the input stage to phase $j$of the loadwithproper combination of the conduction states of the switches to get synthesized output voltage v_{jN}. Each switch is characterized by a switching function, defined as follows:

$$S_{ij}(t) = \begin{cases} 0 & Switch\ S_{ij}\ is\ open \\ 1 & Switch\ S_{ij}\ is\ closed \end{cases} \tag{1}$$

$$\sum_{i=A,B,C} S_{ij}(t) = 1 \tag{2}$$

If t_{ij} is the conduction time of the switch S_{ij} and T_s is the switching period, then duty cycle is expressed as:

$$m_{ij}(t) = \frac{t_{ij}}{T_s} \tag{3}$$

Hence, modulation matrix is given as:

$$M(t) = \begin{bmatrix} m_{Aa}(t) & m_{Ba}(t) & m_{Ca}(t) \\ m_{Ab}(t) & m_{Bb}(t) & m_{Cb}(t) \\ m_{Ac}(t) & m_{Bc}(t) & m_{Cc}(t) \end{bmatrix} \tag{4}$$

Under ideal conditions, the three-phase sinusoidal input voltages of the MC is expressed as:

$$v_{si}(t) = v_{sim} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t + 2\pi/3) \\ \cos(\omega_i t + 4\pi/3) \end{bmatrix} \tag{5}$$

Where v_{sim} is maximum value of the source voltage. Each output phase voltages with respect to the neutral point 'N' of the sourceis expressed as:

$$[v_{jN}(t)] = [M(t)][v_{iN}(t)] \tag{6}$$

Similarly, the input current is expressed as:

$$[i_i(t)] = [M(t)]^T [i_j(t)] \tag{7}$$

The amplitude of the output voltage is limited to 50 % of the input voltage in the conventional approach of Venturini Modulation method. To obtain maximum voltage transfer ratio, third harmonics of the input voltage are added and third harmonics of the output voltages are subtracted with the target output phase voltages as given in Eqn. (8).

$$[v_{jN}(t)] = q v_{iNm} \begin{bmatrix} cos(\omega_o t) - \frac{1}{6} cos(3\omega_o t) + \frac{1}{2\sqrt{3}} cos(3\omega_i t) \\ cos\left(\omega_o t + \frac{2\pi}{3}\right) - \frac{1}{6} cos(3\omega_o t) + \frac{1}{2\sqrt{3}} cos(3\omega_i t) \\ cos\left(\omega_o t + \frac{4\pi}{3}\right) - \frac{1}{6} cos(3\omega_o t) + \frac{1}{2\sqrt{3}} cos(3\omega_i t) \end{bmatrix} \tag{8}$$

Where, q is the voltage gain or voltage transfer ratio which is having maximum value of 0.866 and v_{iNm} is maximum value of matrix converter input voltage. In the OAVM method, the algorithm given in the Eqn. (9) is used.

$$m_{ij} = \frac{1}{3}\left[1 + \frac{2 v_{iN} v_{jN}}{v_{iNmax}^2} + \frac{2q}{3q_m} \sin(\omega_i t + \beta_i) \sin(3\omega_i t)\right] \tag{9}$$

Where, $\beta_i = 0, \frac{2\pi}{3}, \frac{4\pi}{3}$.

The above eqns.are simulated in MATLAB/Simulink to generate switching pulses for the Matrix converterand the waveform obtained from the simulation is shown in Fig. 2. From the Fig. 2, it is clear that only one switch per output phase is turned ON at any instant.Logic decisions used to generate the switching functions are $S_{Aj} = A$, $S_{Bj} = not(A) AND B$ and $S_{Cj} = not(A) AND not(B)$.

B. *Modelling of a three phase squirrel cage induction motor*

Dynamic simulation of a three phase squirrel cage induction motor is carried out in MATLAB/Simulink platform. Model of the motor is developed in stationary reference frame which is based on the *T*-type *d-q* model as shown in Fig. 3. This model can be effectively used for matrix converter with different modulation schemes.All analysis and simulation are based on the d-q or dynamic equivalent circuit of the induction motor represented in the stationary reference frame [8]. It is noted that, all quantities in Fig. 3.are referred to the stator.

Here, *d* is the direct axis, *q* is the quadrature axis,$v_{ds}$is the *d*-axis stator voltage,$v_{qs}$is the q-axis stator voltage,$v_{dr}$is *d*-axis rotor voltage,$v_{qr}$is *q*-axis rotor voltage,$i_{ds}$is the *d*-axis stator current,$i_{qs}$is the *q*-axis stator current,$i_{dr}$is *d*-axis rotor current,$i_{qr}$is *q*-axis rotor current,$R_s$is the stator resistance,$R_r$is the rotor resistance,$\omega_e$is the angular velocity of the reference frame, and $\omega_e = 0$ for stationary reference frame.$\omega_r$is the angular velocity of the rotor, and λ_{ds}, λ_{dr}, λ_{qs}, and $\lambda_{qr}$are flux linkages.

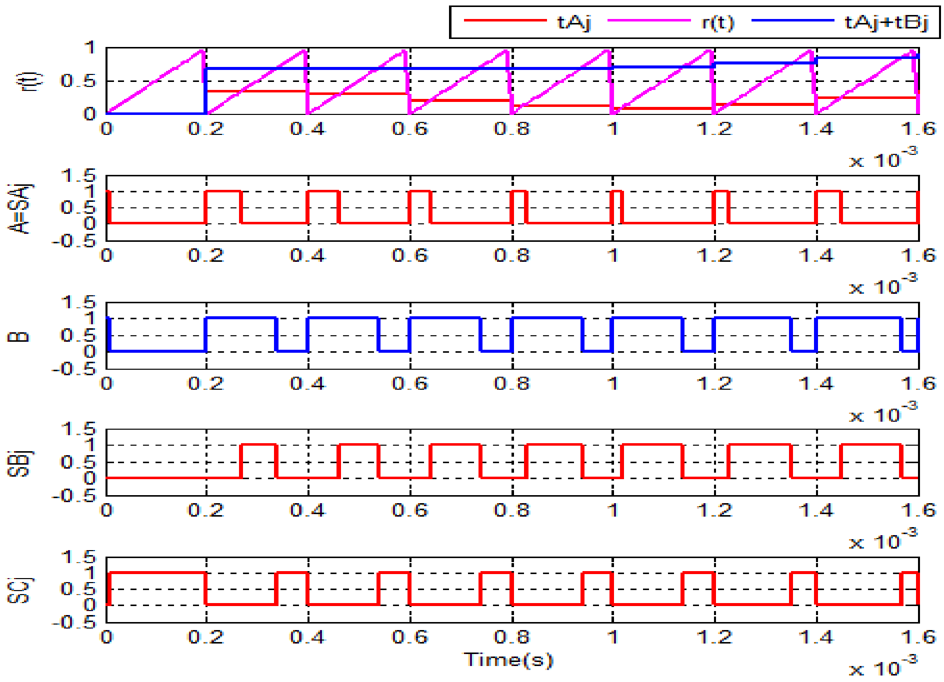


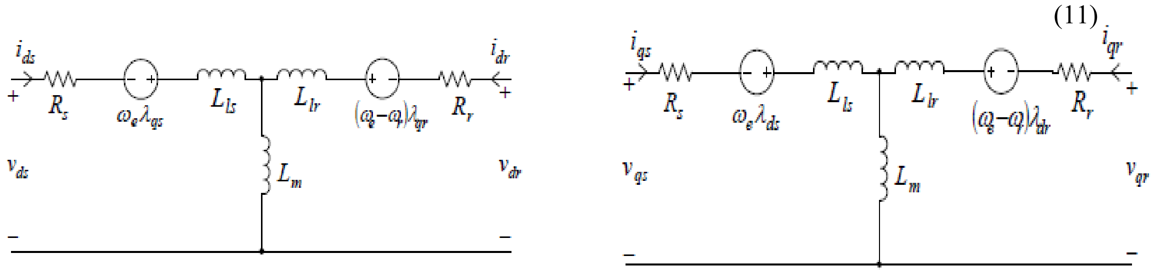
Fig. 2.Synthesis of Gate signals of the power switches connected to the same output phase.

The differential equations obtained from the analysis of the circuits shown in Fig. 3 are as follows:

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt}, \quad (10)$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt}, \quad (11)$$

(11)



(a) (b)

Fig. 3.d-q equivalent circuit of the Induction Motor.
(a) d-axis equivalent circuit. (b) q-axis equivalent circuit [11].

$$v_{dr} = 0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} + \omega_r \lambda_{qr}, \quad (12)$$

$v_{qr} = 0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} - \omega_r \lambda_{dr},$ (13)

For squirrel cage induction motor the rotor voltage in Eqn. (12) and Eqn. (13) being zero. The flux linkages in Eqn. (10) –(13) can be written as:

$\lambda_{ds} = L_s i_{ds} + L_m i_{dr},$ (14)

$\lambda_{qs} = L_s i_{qs} + L_m i_{qr},$ (15)

$\lambda_{dr} = L_r i_{dr} + L_m i_{ds},$ (16)

$\lambda_{qr} = L_r i_{qr} + L_m i_{qs}$ (17)

Where, $L_r$is the rotor self-inductance,$L_s$is the stator self-inductance, $L_m$is the magnetizing inductance, $L_{lr}$is the rotor leakage inductance, and$L_{ls}$is the stator leakage inductance. The self-inductances in Eqn. (14) – (17) can be expressed as:

$L_s = L_m + L_{ls},$ (18)

$L_r = L_m + L_{lr}$ (19)

From Eqn. (10)– (13) the flux linkages can be expressed as:

$\lambda_{ds} = \int(v_{ds} - R_s i_{ds}),$ (20)

$\lambda_{qs} = \int(v_{qs} - R_s i_{qs}),$ (21)

$\lambda_{dr} = \int(-R_r i_{dr} - \omega_r \lambda_{qr}),$ (22)

$\lambda_{qr} = \int(-R_r i_{qr} - \omega_r \lambda_{dr})$ (23)

From Eqn. (14) – (17) the currents can be written as:

$i_{ds} = \frac{\lambda_{ds} - L_m i_{dr}}{L_s},$ (24)

$i_{qs} = \frac{\lambda_{qs} - L_m i_{qr}}{L_s},$ (25)

$i_{dr} = \frac{\lambda_{dr} - L_m i_{ds}}{L_r},$ (26)

$i_{qr} = \frac{\lambda_{qr} - L_m i_{qs}}{L_r}.$ (27)

The electromagnetic torque of the machine can be written as:

$T_e = \frac{3}{2}\frac{P}{2} L_m [i_{qs} i_{dr} - i_{ds} i_{qr}]$ (28)

Where,P is the number of poles and $T_e$is the electromagnetic torque.Neglecting mechanical damping, the torque and rotor speed are related by:

$\frac{d\omega_r}{dt} = \frac{P}{2J}(T_e - T_L)$ (29)

Where,$T_L$is the load torque and $J$is the inertia of the rotor and connected load.Three-phase voltages can be converted to the two-phase stationary reference frame using the following relationship:

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (30)$$

Two phase d-q currents can be converted back to three phase abc form using the following transformation.

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \quad (31)$$

IV. Simulation Of Matrix Converter Drive

Simulation has been carried out in MATLAB/Simulink platform using Eqn. (6) – (9)and (20) – (31). The subsystem is developed using basic Simulink blocks such as the integrator, gain, sum, etc.After the successful development of all the equations as subsystems, the overall simulation of the proposed matrix converter drive is developed by integrating the subsystems as shown in Fig. 4.

V. Simulation Results

The parameters of Matrix Converter fed Induction Motor Drivegiven in Table I is used in simulation. Simulation is carried out at half load, three fourth and full loads of the induction motor for a period of 10 sec. At no load, the speed of the Induction motor is near to synchronous speed. A load torque T_L of 7 N-m, 10.5 N-m, and 14.5 N-m is applied at time 2 sec, 4.5 sec, and 7 sec. respectively. Variable frequency power supply was given as input to the induction motor to vary the speed of the induction motor. Simulation results have been presented for the output frequencies of 30 Hz and 40 Hz from a fixed input frequency of 50 Hz.

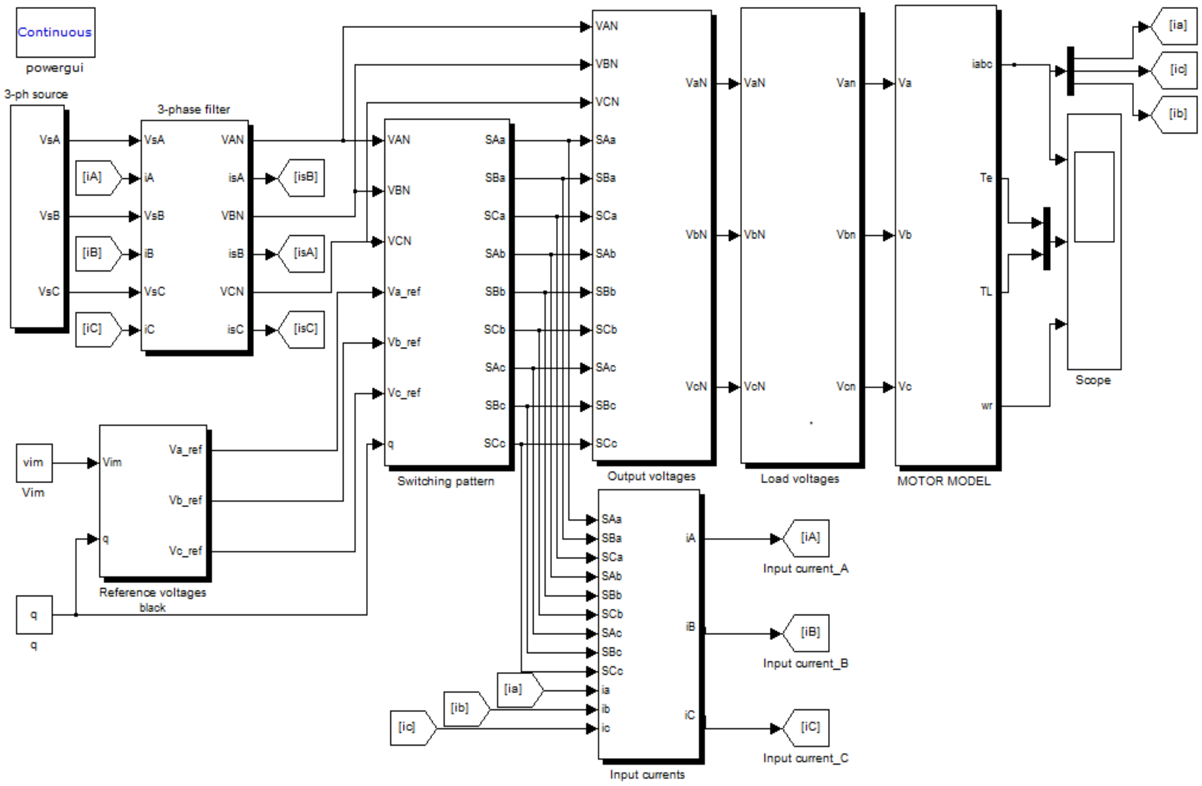


Fig. 4 MATLAB/Simulink model of threephase to three phase matrix converter fed Induction Motor drive.

TABLE I. PARAMETERS USED IN THE SIMULATION

Parameter	**Rating**
Filter inductance	3mh
Filter capacitance,	25µF
Filter resistance,	1Ω
Rated Power of IM	2.2 Kw
Full load torque	14.5 N-m
Moment of inetia (J)	0.03 kg-m^2
Stator resistance (Rs)	1.573 Ω
Rotor resistance (Rr)	2.7914 Ω
Stator inductance (Ls)	0.3942 H
Rotor inductance (Lr)	0.3942 H
Mutual inductance (Lm)	0.378 H
Leakage inductances (Lls&Llr)	0.0162 H
Number of poles (P)	4
Rated Voltage (V_{L-L})	415 V
Rated Frequency	50 Hz

Fig. 5 shows the load current, load torque, electromagnetic torque, and rotor speed of the induction motor at the output frequency of 30Hz. The no load speed of the induction motor is around 900 rpm and the speed of the motor is 842 rpm, 858 rpm and 873 rpm at full load, three fourth load and half load respectively.

Similarly Fig. 6 shows the load current, torque, and rotor speed of the induction motor at the output frequency of 40Hz. The no load speed of the induction motor is around 1200 rpm and the speed of the motor was 1146 rpm, 1162 rpm and 1175 rpm at full load, three fourth load and half load respectively.

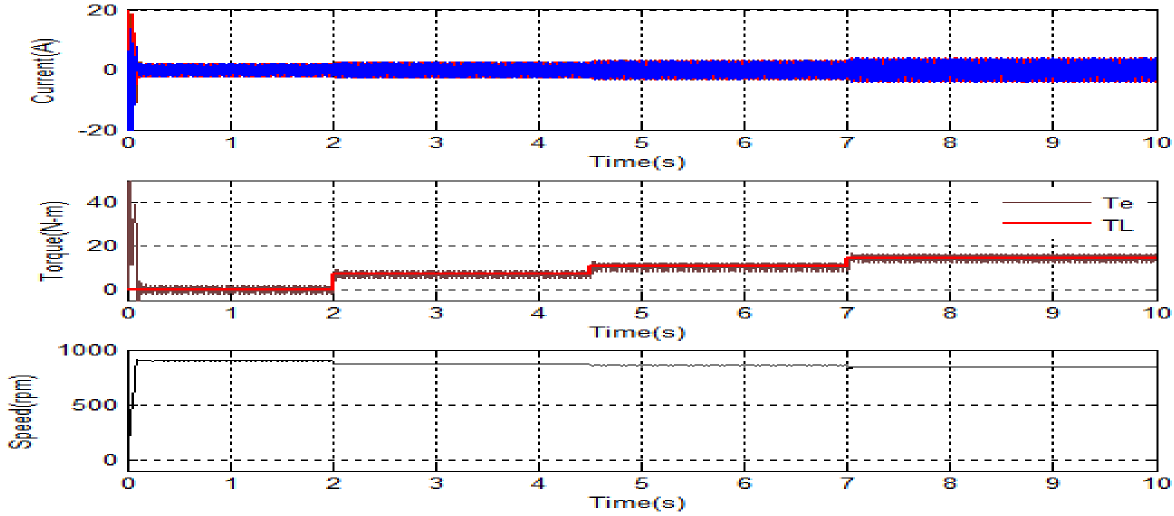


Fig. 5 Load current, Torque, and rotor speed of the induction motor at 30Hz.

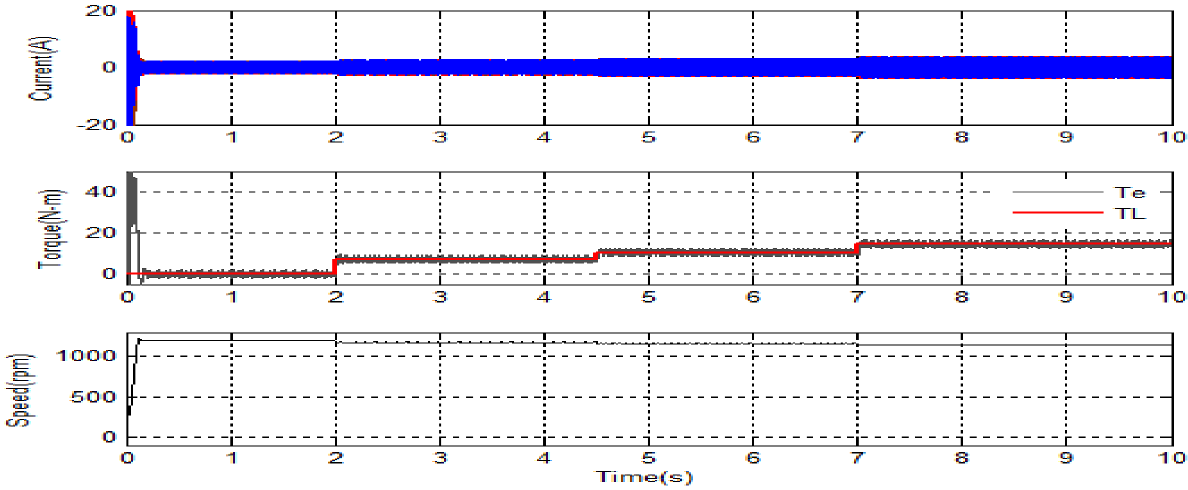


Fig. 6 Load current, Torque, and rotor speed of the induction motor at 40Hz.

THD analysis is done for both the input and output currents. Fig. 7 shows the THD analysis of input current The Total Harmonic Distortion (THD) of the input current is found to be 2.09% which is below the acceptable level.Fig. 8 shows the THD analysis of the output current at 30 Hz and 40 Hz.The THD of the output current is 1.13% and 1.51% for 30 Hz and 40 Hz frequencies respectively.

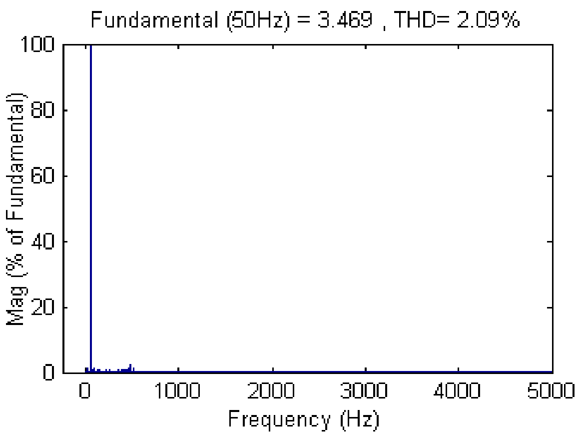
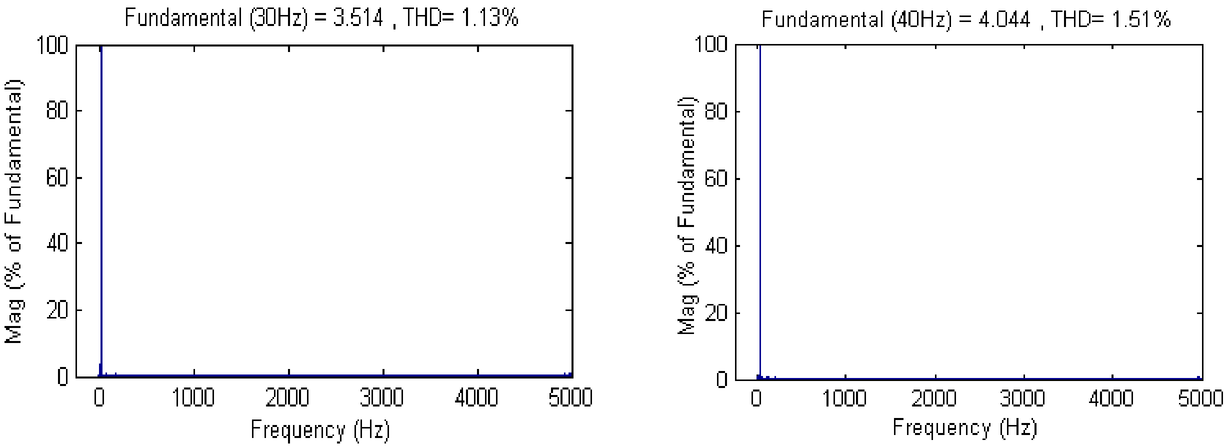


Fig. 7 THD analysis for the input current.



(a) (b)

Fig. 8THD analysis of output current (a) at 30 Hz. (b) at 40Hz

VI. Conclusion

Modelling and dynamic simulation in MATLAB/Simulinkof the matrix converter fed induction motor drive isdiscussed in this paper. Modulation strategies and fundamental mathematical equations of the MC and induction motor have been presented clearly. Variable frequency output is produced from a fixed frequency input of 50Hzusing a three phase matrix converter and fed to the induction motor to control the speed. Simulation results prove that, THD of the output current is below the acceptable level. The value of current THD for source current is 2.09% and output current is 1.13% for 30Hz frequency operation of the matrix converter fed induction motor drive.

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