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SIMULATION OF MATRIX CONVERTER-FED PERMANENT MAGNET SYNCHRONOUS MOTOR WITH NEURAL FUZZY CONTROLLER

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ABSTRACT: *Converting and controlling the electrical energy are one of the significant proceedings in electrical engineering. The rapid developments in power electronics converters especially in semi-conductor power devices have led great advances in controlling electrical energy. One of the most interesting devices in the power converter family is matrix converters which provide direct ac-ac power conversion without needing a dc link. With recent developments in magnet materials, permanent magnet synchronous motors (PMSMs) have taken considerable interest in industrial applications due to their outstanding features. In the literature it can be seen that permanent magnet synchronous motor drives have been performed by using various control methods. Fuzzy logic controllers aim to include an expert experience in a necessary controller design to control a system which involves linguistic changes and describes fuzzy rules instead of the complex mathematical model of a system. In this paper, a vector controlled matrix converter-fed PMSM was simulated with ANFIS based neural fuzzy. Simulation has been performed by applying various speed references. Performance of the drive system has been also shown for speed reversal. In addition, behaviour of the drive system with various load conditions was also observed.*

Key Words : *Matrix converter, permanent magnet synchronous motor, neural fuzzy, speed control*

I. INTRODUCTION

Matrix converters which are in the family of direct ac-ac converter topologies consist of bi-directional semiconductor switching elements connected in a matrix form between the input and output lines [1–3]. There are totally nine bidirectional semiconductor switching elements in the three-phase matrix converter as shown in Fig.1. Bidirectional switches enable the power flow in both directions (from supply to load vice-versa) through the matrix converter. Owing to these bidirectional switches, variable amplitude and frequency at the output voltage is achieved by switching the fixed input supply voltage with various modulation algorithms. The amplitude and frequency of output voltage depend on the duty cycle of the bidirectional switches.

Until 1970s, dc motors were used in position and speed control applications because of their simple structure. With F.Blaschke and K. Hasse's vector control theory, it was considered that synchronous and induction motors could be controlled in the same way as dc motors [6-7]. The fundamental of ac motors is to control the phase angle between the motor current and induced voltage. In the ac motor, the amplitude and angle of current vector are controlled by the control algorithm. If the current vector is not completely controlled, the required operation is not achieved and undesired breakups occur in load torque. Synchronous and induction motors controlled by the vector control algorithm can be used in the applications where four-quadrant operation is required.

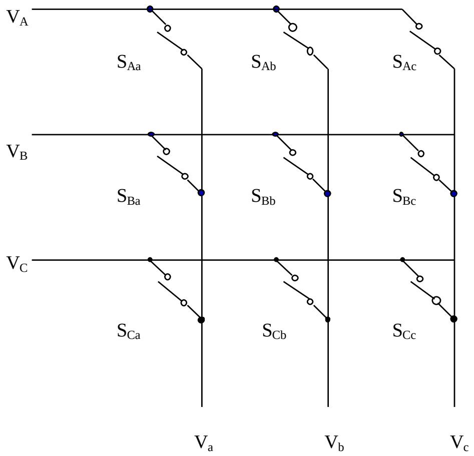


Figure 1. Structure of the matrix converter.

In high-performance permanent-magnet synchronous motor drive systems, features such as not being affected from parameter changes and quick speed response to the speed demand are required [8-9]. The main principal of the vector control is based on decoupling of the current into two components. While one of them is responsible from the torque, the other will be responsible from the flux generation. Vector control of the permanent-magnet synchronous motor is easier than that of the other ac machines since the rotor flux is fixed and does not change with the rated speed [6].

In many industrial applications, under various speed, load and speed reversal conditions, it is required to fulfil the demands of a drive system [7]. A high-performance drive system can be achieved using a matrix converter together with a permanent magnet synchronous motor.

PMSMs can be controlled by classical controllers. These controllers are ones far away from expert experience which is required by all systems as well as P,PI and PID. Fuzzy logic controllers aim to include an expert experience in a necessary controller design to control the system which involves linguistic changes and describes fuzzy rules instead of the complex mathematical model of the system [13–15]. In humans' thinking system, there are intermediate values as well as certain terms such as 0 and 1. The concept of fuzzy logic takes these intermediate values into consideration as well as certain values. Fuzzy logic has an ability to operate about indefinite or incomplete information.

Adaptive-network based fuzzy inference systems (ANFIS) are an artificial intelligence technique which highlights advantages of fuzzy logic (FL) and artificial neural network (ANN) methods, and has been applied in many different fields recently [11].

In this paper, a vector controlled PMSM fed by a three-phase matrix converter was modelled and simulated for various operating conditions such as variable speed and load. The system uses ANFIS based neural fuzzy controller designed in MATLAB environment. Current, speed and torque waveforms of the PMSM were observed for various operating conditions.

II. MODELLING

In this study, modelling and simulation of permanent magnet synchronous motors and a matrix converter was achieved using mathematical models in Simulink/Matlab package program. Speed controller in the vector control algorithm was performed with ANFIS based neural fuzzy controller. Performance of the drive system for variable speed reference including speed reversal operation was observed. The drive system was also operated under various load in order to see the effect of the load changes on motor output currents.

i. Modelling of Permanent Magnet Synchronous Motor

Synchronous motors are made up of two main parts including a stationary part called stator and a moving part called rotor. In order to rotate motor, two fluxes one in the stator and one in the rotor are needed. To generate flux in the rotor of synchronous motor with a three-phase windings available in the stator, either a winding or a permanent magnet is used [12]. Motors which create rotor flux with their permanent magnets placed in the rotor, are known as PMSMs. Mathematical model of motors must be known in order to control them. A vector controlled ac motor driver represents *d* and *q* currents corresponding to field and armature currents, respectively. The coordinate system is generally first converted from three-phase into the α-β fixed reference frame with the Clarke transformation, and then converted to the *d-q* rotating reference frame with the Park transformation [6]. The following equations for V_d ,V_q are obtained from the *d-q* equivalent circuit of PMSM as shown in Fig.2.

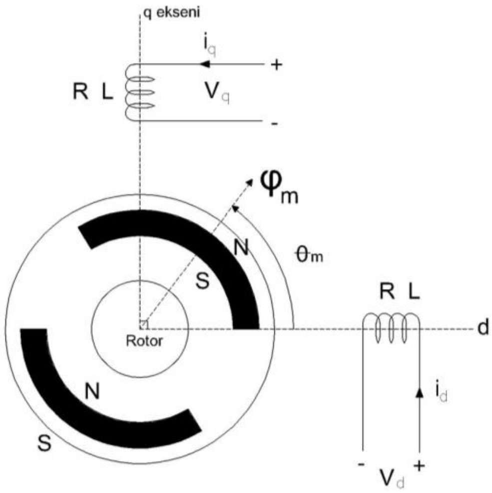


Figure 2. *d-q* axis equivalent circuit of PMSM.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_r \begin{bmatrix} -\psi_q \\ \psi_d \end{bmatrix} \tag{1}$$

where; v_d, v_q are the representations of d-q components of input voltages; L_d,L_q, are d and q axis inductances; ψ_d, ψ_q are d and q axis magnetic fluxes; R represents the stator resistance; and ω_r corresponds to the rotor angular speed.

By rearranging Eq[1], the current components of the motor in the d-q axis can be found by writing in the form of state-space as shown in Eq.[2].

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L_d} & \omega_r \frac{L_q}{L_d} \\ -\omega_r \frac{L_d}{L_q} & -\frac{R}{L_q} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_r \begin{bmatrix} 0 \\ -\frac{\psi_m}{L_q} \end{bmatrix} + \begin{bmatrix} \frac{v_d}{L_d} \\ \frac{v_q}{L_q} \end{bmatrix} \tag{2}$$

Using i_d *and* i_q current components in the rotor reference frame, the electromagnetic torque equation may be simplified as;

$$T_e = \frac{3}{2}\frac{P}{2}\left[\psi_m i_q + (L_d - L_q) i_q i_d\right] \tag{3}$$

where, P represents the pole number. As can be seen from Eq.[3], the electromagnetic torque generated by the motor depends on i_d and i_q currents.

Eqs.[1-3] are mathematical equations of PMSM. By benefiting from these equations, a model of the PMSM shown in Fig. 3 was obtained in MATLAB Simulink.

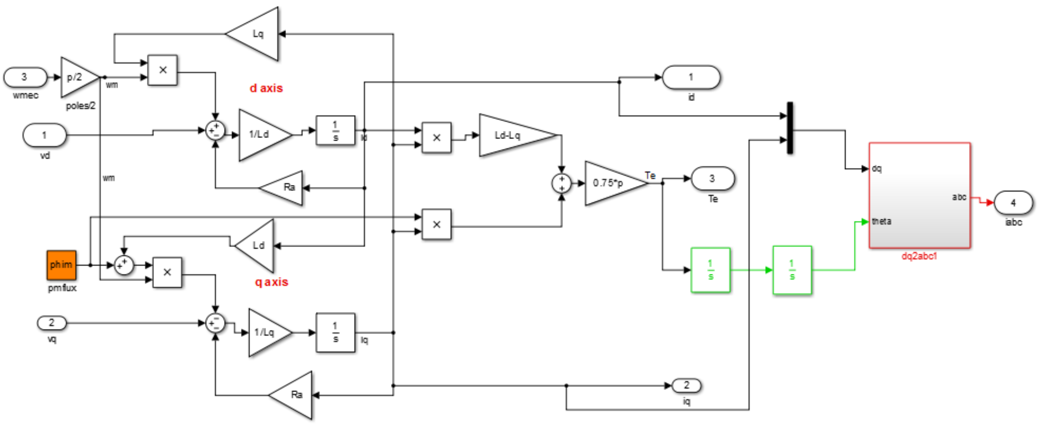


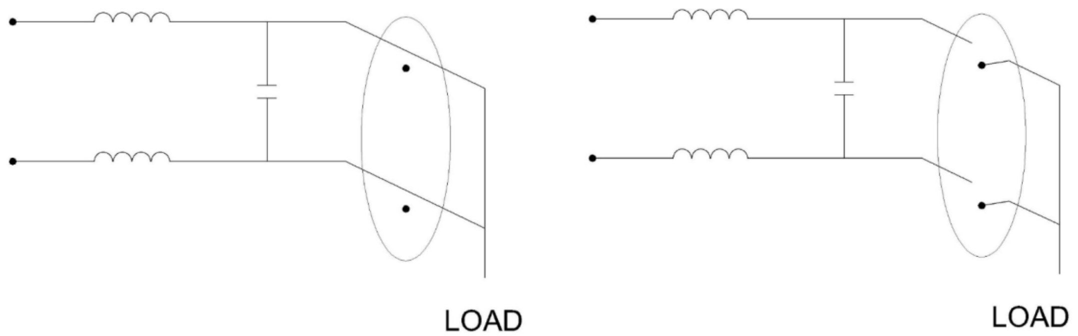
Figure 3. Simulink Model of PMSM

ii. Modelling of Matrix Converter

Matrix converters have capability to convert fixed ac supply into variable ac supply directly without using any intermediate dc link [13]. Power circuit of a three-phase matrix converter consists of nine bi-directional switches ($S_{i,j}$, input phases: i= {A,B,C}, output phases: j= {a,b,c}) which are capable of blocking voltage in both directions. Output voltage is achieved with appropriate combinations of turn-on situations in these switches.

$$S_{ij}(t)=\begin{cases} 0 & S_{ij} \text{ switch is off} \\ 1 & S_{ij} \text{ switch is on} \end{cases} \qquad (4)$$

Commutation action between the switches in the matrix converter must be performed in accordance with two basic rules in any time. These rules can be shown by considering two switches connected to one of the converter output phases. As shown Fig.4 (a), it is necessary to avoid short circuit between the input lines since the converter input is a voltage source. In Fig.4 (b), in case of inductive load, it is necessary to make sure that the output line must be never left open because of the inductive load current.



(a) (b)

Figure 4. States to be avoided (a) State to be avoided at the input of matrix converter, (b) State to be avoided at the output of matrix converter

A three-phase matrix converter consists of 9 bi-directional switches connected in matrix form as shown in Fig.1. Using various switching techniques, these switches allow signals at various frequencies and amplitudes to respond to the requirements of any type of load connected to the output.

Various modulation techniques for the matrix converter have been studied by the researchers. Among these studies, the Venturini modulation method, the scalar method and the space vector modulation method can be listed. In this paper, matrix converter was modelled by using Venturini modulation algorithm. The simplified Venturini algorithm [14], [15] which gives unity input displacement factor is appropriate for real time application. Instead of using zero crossing detection or phase locking system to determine point on the input voltage waveform, the simplified version of Venturini algorithm is defined in terms of three-phase input and output voltages at each sampling instant. In this approach, the input voltages are measured at each sampling period of the modulation algorithm and then the voltage vector magnitude and position are directly determined. For unity input displacement factor the duty cycle for the switch connected between input phase, β and output phase, γ can be defined as;.

$$T_{\beta\gamma} = T_s\left[\frac{1}{3}+\frac{2V_{0\gamma}V_{i\beta}}{3V_{im}^2}+\frac{2q}{9q_m}\sin(\omega_i t+\varphi_\beta)\sin(3\omega_i t)\right] \tag{5}$$

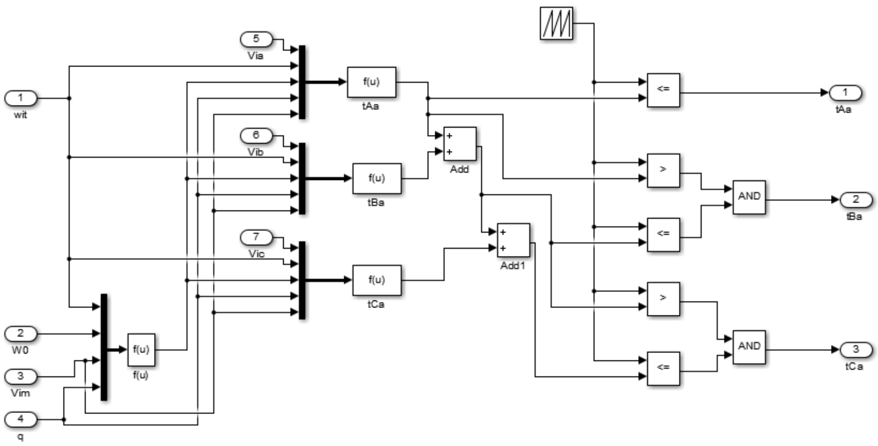


Figure 5. The Matlab/Simulink model of T_{Aa}, T_{Ba}, T_{Ca} blocks

where; φ_β corresponds to input phases, A,B and C (0, 2π/3, 4π/3), q_m is the maximum voltage rate (0.866), q is the desired voltage rate, V_{im} is the peak value of input voltage, T_s is the sampling period, $V_{i\beta}$ is the instantaneous value of the related input voltage and ω_i is the input frequency. Output voltage, $V_{0\gamma}$ is expressed as;

$$V_{0\gamma} = qV_{im}\cos(\omega_0 t+\varphi_\gamma) - \frac{q}{6}V_{im}\cos(3\omega_0 t) + \frac{1}{4}\frac{q}{q_m}V_{im}\cos(3\omega_i t) \tag{6}$$

Where; φ_γ corresponds to output phases a,b,c (0, 2π/3, 4π/3), ω_0 is the output frequency. As can be seen from Eq.[6], there are 3rd harmonics of the input and output frequencies. The reason for this is to have possible maximum voltage rate (0.866).

It is necessary to calculate duty period of a switch in each sampling period to have variable frequency and voltage at the output voltage of the matrix converter, particularly for the systems having closed-loop operations on the speed and torque.

In Sunter-Clare algorithm[16], it is necessary to know the maximum values of input voltage and output voltage in order to calculate the voltage gain, q at each sampling period. The values required by the Sunter-Clare Algorithm can be easily calculated by the following equation [17] ;

$$V_{im}^2 = \frac{4}{9}\left(V_{AB}^2 + V_{BC}^2 + V_{AB}V_{BC}\right) \quad (7)$$

$$\omega_i t = \arctan\left(\frac{V_{BC}}{\sqrt{3}\left(\frac{2}{3}V_{AB} + \frac{1}{3}V_{BC}\right)}\right) \quad (8)$$

$$V_{om}^2 = \frac{2}{3}\left(V_a^2 + V_b^2 + V_c^2\right) \quad (9)$$

$$\omega_0 t = \arctan\left(\frac{V_b - V_c}{\sqrt{3}V_a}\right) \quad (10)$$

$$q = \sqrt{\frac{V_{om}^2}{V_{im}^2}} \quad (11)$$

iii. Modulation Technique

Since methods used for modelling electrical machines are generally based on mathematical theories, they contain lots of machine parameters. In general, machine parameters are assumed to be constant in these models and their changes with temperature, saturation etc are not taken into account. However, several parameters of electrical machines change in accordance with operating conditions and external effects. The effects of parameter changes on the machine model to be designed must be taken into account [18], [19]. An appropriate model including all the effects mentioned above can be developed. However, it will not be still useful enough since it will be very complex and ungraceful. In this work, Fuzzy Logic, Neural Network and their combination Neuro-Fuzzy which are the most common artificial intelligence applications utilised in the analysis of electrical machines were used in the vector control simulation. Five membership functions were formed using the trimpf method as shown in Fig.6. By citing the ANFIS structure, to transfer into the system with the Sugeno model, 5 triangle inputs are determined with the membership limits functions and then the rules are formed. These rules are determined with the membership functions at MATLAB Fuzzy Toolbox using the AND method with the Sugeno model. Output data in the ANFIS editor are obtained after being handled with neural fuzzy.

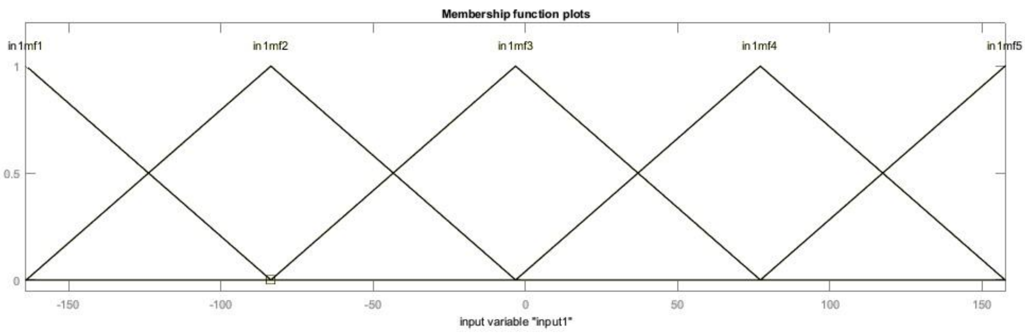


Figure 6. Membership functions for speed controller

III. SIMULATION MODEL

Mathematical model of the PMSM used in the simulation is based on the d-q model on the rotating reference frame. The block diagram of matrix converter-fed PMSM is given in Fig.7. The field-oriented control was used in the simulation.

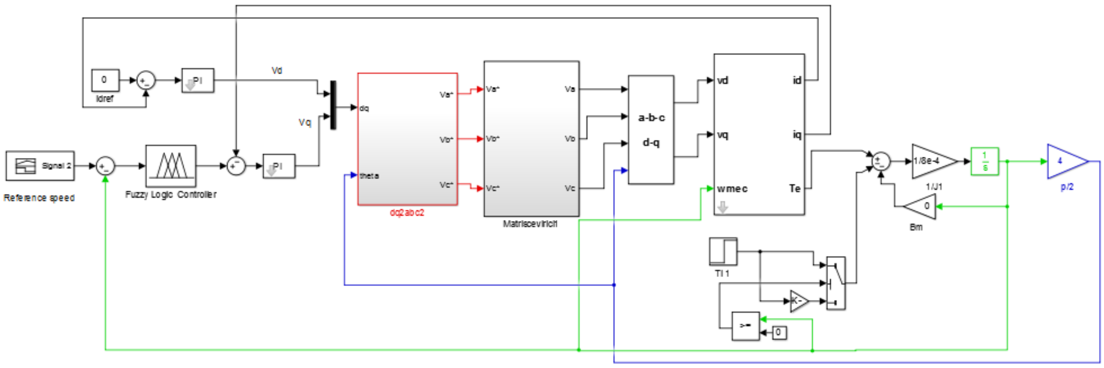


Figure 7. Block diagram of the vector controlled matrix converter-fed PMSM

IV. SIMULATION RESULTS

In order to see the transient and steady-state performance of the drive system, the simulation has been performed for the speed reference of ±750 rpm for a period of 4 seconds as shown in Fig.8 (a). At start-up, the motor reaches the reference value approximately in 80 ms. At speed reversal, the speed of the motor changes from 750 rmp to -750 rpm around 0.1 seconds. The machine was loaded with the rated value of 3 Nm for the first 2 seconds of the period. After 2 seconds the motor load was reduced to 1 Nm and operated for 2 more seconds as seen in Fig.8 (b). The corresponding d-q currents are given in Fig.8 (c). As can be seen the controller holds the magnetizing current around zero because of the permanent magnets. The torque component of the current, i_q follows the load torque and takes a value which is proportional to the torque. The corresponding torque-speed characteristic of the motor is given in Fig.8 (d). The matrix converter used in the simulation has a switching frequency of 5 kHz. The rated power of permanent magnet synchronous motor is 1.1 kW.

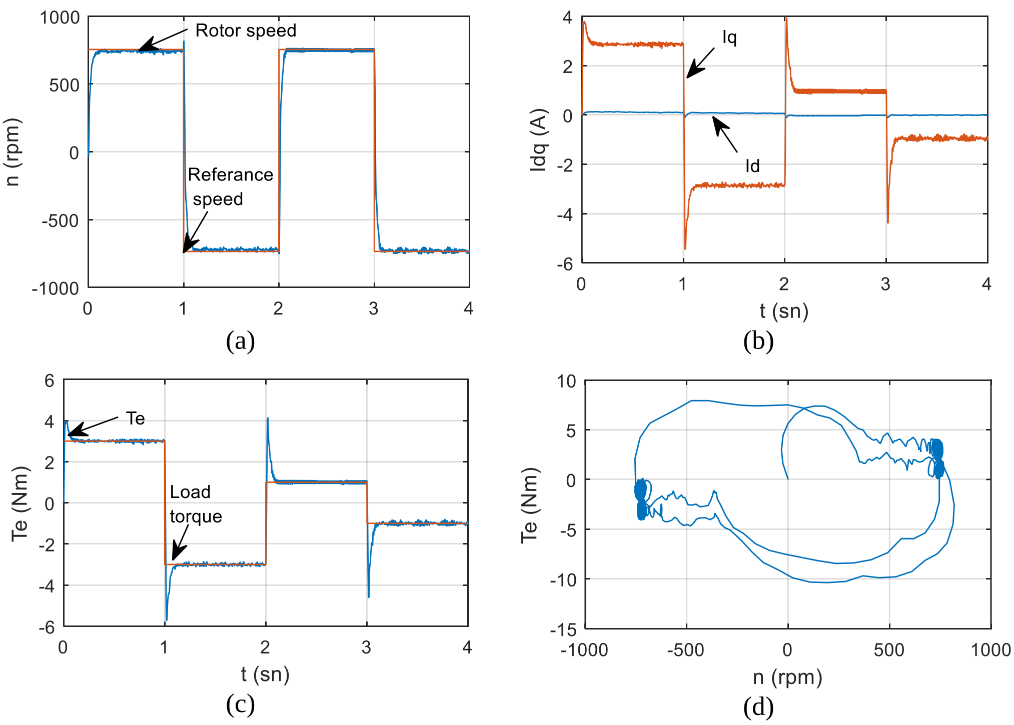


Figure 8. Simulation results on-load. (a) Motor speed, (b) I_d-I_q currents (c) Motor and load torques, (d) Torque- speed characteristic

Fig.9 shows the motor currents and current spectrum. In Fig.9 (a), three-phase motor currents for a period of 4 seconds corresponding to the operating conditions in Fig.8 are given. As can be seen the amplitude of the currents at first 2 seconds is higher than that of the currents after 2nd seconds since at first half of the speed period the machine is loaded more than the second half as stated in Fig.8. The detailed current waveform for the instant at speed reversal (around the 2nd seconds) is illustrated in Fig.9 (b). Fig.9 (c) shows harmonic spectrum of the motor current.

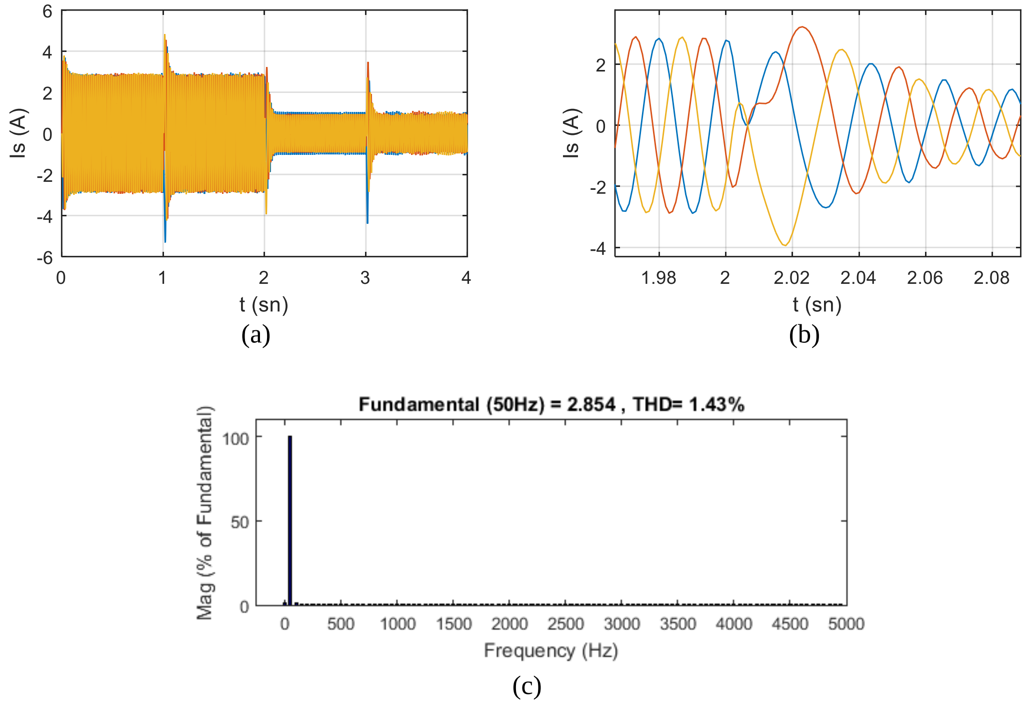


Figure 9. (a) Motor current waveforms and harmonic spectrum.

The output line voltage and motor current waveforms are given in Fig.10(a). As can be seen the output voltage waveform is obtained by chopping the 3-phase input voltage at the switching frequency rate using the proposed modulation algorithm. Fig.10(b) shows harmonic spectrum of the converter output voltage. As expected, in addition to the main harmonic the output voltage waveform has only harmonics around the switching frequency (5 kHz).

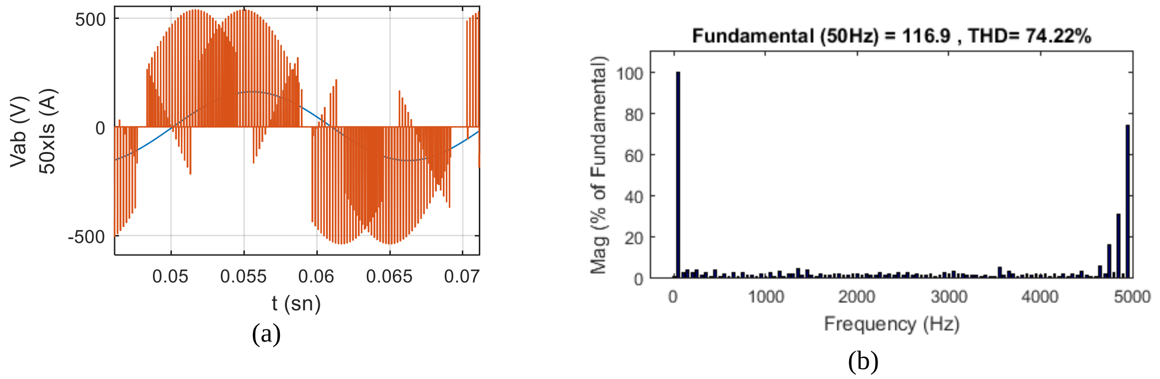


Figure 10. (a) The output line voltage waveform of the matrix converter and motor current (b) The harmonic spectrum of the matrix converter output voltage

CONCLUSIONS

Matrix converter-fed permanent magnet synchronous motor drive with the ANFIS based neural fuzzy controller was modelled and simulated using field-oriented control strategy. The modelling and simulation has been performed in MATLAB/Simulink environment. In the simulation, PMSM which has high power/weight, torque/inertia rates and high efficiency has been controlled by using field oriented control method. In this type of control system, PI controllers are usually used as speed and current controllers. The parameters of PI controllers are manually taken. However, the most suitable parameters can be chosen with the trial-and-error method for the system or the parameters are determined with the estimation method tested in the system. Better results are obtained than the trial-and-error method. In this work, input data were directly taken from the model and error rates were reduced much more than the classical controllers. Output data were also applied to the model directly under the ANFIS based neural fuzzy model. Simulation results have been taken for various load conditions. The reference motor speed was chosen for speed reversal action to demonstrate performance of the drive system. It has been observed from the simulation results that the motor has shown good performance in spite of changes in speed and load conditions.

Motor parameters: 1.1 kW, 220 V, f=50 Hz, 3000 rpm, R_s=2.875 **Ω**, L_d= L_q=8.5 mH, J= 0.175 kg m^2, B=0 Nm s/rd, P=8 Tn=3 Nm

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