MODELING AND SIMULATION OF A MATRIX POWER ELECTRONIC CONVERTER DRIVING A THREE-PHASE INDUCTION MOTOR

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Abstract – **This paper presents the modeling and simulation of a matrix power electronic converter (MPEC). The modulation algorithm utilized is the Venturini method. The potential use of the matrix converter in industrial applications is shown through simulation of the MPEC driving a three-phase induction motor as a load.**

I. INTRODUCTION

The voltage source inverter (VSI) is widely used as power converter for variable speed drives. However, in recent years, the matrix power electronic converter (MPEC) has been receiving considerable attention as a suitable alternative to VSI.

The MPEC is a forced commutated converter which can perform the power conversion directly from AC mains to the load without any intermediate DC link. The MPEC consistis of an array of bidirectional power swtiches arranged in a matrix manner so that any of the *m* outputs of the converter can be connected to any of the *n* input voltage sources.

The growing interest on MEPC began whith the work of Venturini and Alesina published in 1980 [1] in which they presented the power circuit of the converter as a matrix of bidirectional power switches and a modulation method known as the direct transfer function approach with limited output to input voltage ratio of 0.5. Since then, numerous publications have dealt with modulation schemes in order to increase this gain [3]-[6].

In addition to the lack of a DC link, that makes the MPEC a compact power circuit, other desirable features like sinusoidal input and output currents, regeneration capability and high power factor can be fulfilled by the MPEC. These attractive features make the MPEC to be considered for a variety of industrial applications where energy can be fed back to mains.

This paper deals with modeling and simulation of a MPEC driving an ac motor. The applied modulation algorithm is the Venturini method [1], which enables a unity power factor operation.

II. MPEC BASIC TOPOLOGY

The simplified three-phase to three-phase MPEC topology is shown in fig. 1, where $v_{e1}(t)$, $v_{e2}(t)$ and $v_{e3}(t)$ are the input voltage sources and $v_{o1}(t)$, $v_{o2}(t)$ and $v_{o3}(t)$ are the desirable output voltages given by equation (1):

$$\begin{pmatrix} v_{e1}(t) \\ v_{e2}(t) \\ v_{e3}(t) \end{pmatrix} = V_i \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t + 2\pi/3) \\ \cos(\omega_i t - 2\pi/3 \end{bmatrix} \quad \begin{pmatrix} v_{o1}(t) \\ v_{o2}(t) \\ v_{o3}(t) \end{pmatrix} = V_o \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t + 2\pi/3) \\ \cos(\omega_o t - 2\pi/3 \end{bmatrix} \quad (1)$$

The desirable input and output currents will be:

$$\begin{pmatrix} i_{e1}(t) \\ i_{e2}(t) \\ i_{e3}(t) \end{pmatrix} = I_i \begin{bmatrix} \cos(\omega_i t + \phi_i) \\ \cos(\omega_i t + \phi_i + 2\pi/3) \\ \cos(\omega_i t + \phi_i - 2\pi/3 \end{bmatrix} \quad \begin{pmatrix} i_{o1}(t) \\ i_{o2}(t) \\ i_{o3}(t) \end{pmatrix} = I_o \begin{bmatrix} \cos(\omega_o t + \phi_o) \\ \cos(\omega_o t + \phi_o + 2\pi/3) \\ \cos(\omega_o t + \phi_o - 2\pi/3 \end{bmatrix} \quad (2)$$

Since the input phases of the MPEC are connected to the input voltage supplies, they must not be short-circuited, and due to the inductive nature of the load, the output phases must not be ever left open.

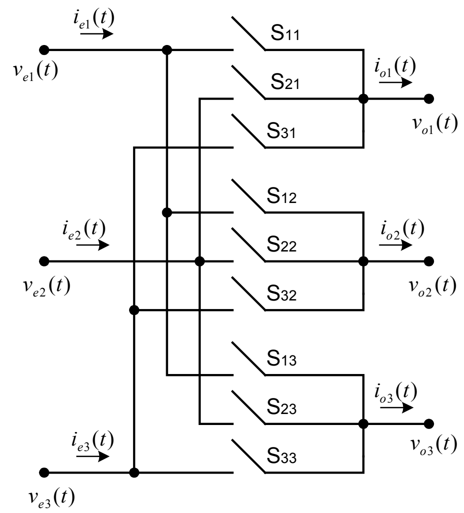

Fig. 1. Three-phase to three-phase MPEC.

Consider S_{ij} a bidirectional switch in the (*i,j*) position, where *i* is related with the input and *j* is related with the output of the MPEC. The operating states of the switches are:

$$S_{ij} = \begin{cases} 1, \ if\ the\ switch\ is\ closed \\ 0, \ if\ the\ switch\ is\ open \end{cases} \quad (3)$$

Proper current commutation in the MPEC requires that:

$$\sum_{i=1}^{3} S_{ij} = 1 \quad for\ any\ j \quad (4)$$

The MPEC bidirectional switch must be capable of blocking voltage and conducting current in both directions. However, there is no such device avaliable in the market. The pratical bidirectional switch may be constructed using insulated gate bipolar transistors (IGBT) in a configuration as shown in figure 2.

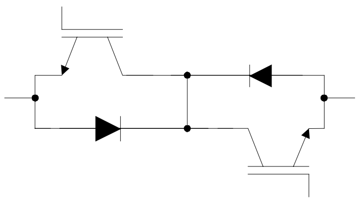

Fig. 2. Bidirectional switch using IGBT.

III. VENTURINI MODULATION METHOD

In this paper, the Venturini modulation method [1] to control the MPEC feeding a three-phase induction motor will be used due to its simplicity and because it is widely used in this type of converter. In the Venturini method the switches that form each column of the converter must be closed sequentially and cyclically during each time interval *Ta* called sampling time, complying with equation (4). If *1/Ta* is much higher then the input voltage frequency and the output voltage frequency, the input voltages $v_{e1}(t)$, $v_{e2}(t)$ and $v_{e3}(t)$ may be considered constant during the sampling time *Ta*. With this approach, the desirable average output voltages which come close to output voltage given by equation (2) can be describe as:

$$\begin{bmatrix} \bar{v}_{o1}(t) \\ \bar{v}_{o2}(t) \\ \bar{v}_{o3}(t) \end{bmatrix} = \frac{1}{T_a} \begin{bmatrix} v_{e1}(t) & v_{e2}(t) & v_{e3}(t) \\ v_{e2}(t) & v_{e3}(t) & v_{e1}(t) \\ v_{e3}(t) & v_{e1}(t) & v_{e2}(t) \end{bmatrix} \begin{bmatrix} t_{1,k} \\ t_{2,k} \\ t_{3,k} \end{bmatrix} \quad (5a)$$

$$\vec{v}_o = \frac{1}{T_a} V_e \vec{t}_k \quad (5b)$$

Where $t_{1,k}$, $t_{2,k}$ and $t_{3,k}$ are the switching time intervals during any k^{th} sampling interval *Ta* so that:

$$T_a = t_{1,k} + t_{2,k} + t_{3,k} \quad (6)$$

Since that $det[V_e]=0$, an infinite number of solutions for $\vec{t}_k$ exists. But with the constraint given by equation (6) a unique solution for the time vector $\vec{t}_k$ can be evaluated [1,2], as shown in equation (7):

$$\begin{aligned} t_{1,k} &= T_a\left[\frac{1}{3} + \frac{2}{3} q \cos(\omega_o - \omega_i)t\right] \\ t_{2,k} &= T_a\left[\frac{1}{3} + \frac{2}{3} q \cos((\omega_o - \omega_i)t - \frac{2\pi}{3})\right] \\ t_{3,k} &= T_a\left[\frac{1}{3} + \frac{2}{3} q \cos((\omega_o - \omega_i)t + \frac{2\pi}{3}\right] \end{aligned} \quad (7)$$

Where q is the output/input voltage ratio:

$$q = \frac{V_o}{V_i} \le 0{,}5 \quad (8)$$

The voltage ratio q is limited to 0.5 since $t_{1,k}$, $t_{2,k}$ and $t_{3,k}$ are $\ge$ 0. The solution shown in equation (7) results in the rotation of the output voltage vector in the same direction of the input voltage vector so that $\phi_I=\phi_o$. This mode of operation of the MPEC is called symmetric mode.

The output voltage vector can also rotate in a reverse direction if the average output voltages are described as:

$$\begin{bmatrix} \bar{v}_{o1}(t) \\ \bar{v}_{o2}(t) \\ \bar{v}_{o3}(t) \end{bmatrix} = \frac{1}{T_a} \begin{bmatrix} v_{e1}(t) & v_{e2}(t) & v_{e3}(t) \\ v_{e2}(t) & v_{e1}(t) & v_{e3}(t) \\ v_{e3}(t) & v_{e2}(t) & v_{e1}(t) \end{bmatrix} \begin{bmatrix} t_{1,k} \\ t_{2,k} \\ t_{3,k} \end{bmatrix} \quad (9)$$

The solution of $\vec{t}_k$ with equation (9) will be:

$$\begin{aligned} t_{1,k} &= T_a\left[\frac{1}{3} + \frac{2}{3} q \cos(\omega_o + \omega_i)t\right] \\ t_{2,k} &= T_a\left[\frac{1}{3} + \frac{2}{3} q \cos((\omega_o + \omega_i)t - \frac{2\pi}{3})\right] \\ t_{3,k} &= T_a\left[\frac{1}{3} + \frac{2}{3} q \cos((\omega_o + \omega_i)t + \frac{2\pi}{3}\right] \end{aligned} \quad (10)$$

This solution yields $\phi_I=-\phi_o$. This mode of operation is known as antisymmetric mode. When both modes are used together they may be used to control the input phase displacement. For the unity power factor operation, the MPEC must operate in the symmetric and antisymmetric modes in the same proportion during the sampling time Ta [2]. Let m_{ij} be the duty cycle of switch S_{ij}, because $1/Ta>>\omega_I$ and ω_o, the desirable average output voltages can also be described as:

$$\begin{bmatrix} \bar{v}_{o1}(t) \\ \bar{v}_{o2}(t) \\ \bar{v}_{o3}(t) \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} v_{e1}(t) \\ v_{e2}(t) \\ v_{e3}(t) \end{bmatrix} \quad (11)$$

Using the solution shown in equations (7) and (10), for unity power factor operation, m_{ij} will be:

$$\begin{bmatrix} m_{11} \\ m_{12} \\ m_{13} \end{bmatrix} = \begin{bmatrix} \frac{1}{6}[1+2q\cos(\omega_o-\omega_i)t] + \frac{1}{6}[1+2q\cos(\omega_o+\omega_i)t] \\ \frac{1}{6}[1+2q\cos((\omega_o-\omega_i)t+\frac{2\pi}{3})] + \frac{1}{6}[1+2q\cos((\omega_o+\omega_i)t-\frac{2\pi}{3})] \\ \frac{1}{6}[1+2q\cos((\omega_o-\omega_i)t-\frac{2\pi}{3})] + \frac{1}{6}[1+2q\cos((\omega_o+\omega_i)t+\frac{2\pi}{3})] \end{bmatrix}$$

$$\begin{bmatrix} m_{21} \\ m_{22} \\ m_{23} \end{bmatrix} = \begin{bmatrix} \frac{1}{6}[1+2q\cos((\omega_o-\omega_i)t-\frac{2\pi}{3})] + \frac{1}{6}[1+2q\cos((\omega_o+\omega_i)t-\frac{2\pi}{3}) \\ \frac{1}{6}[1+2q\cos(\omega_o-\omega_i)t] + \frac{1}{6}[1+2q\cos((\omega_o+\omega_i)t+\frac{2\pi}{3})] \\ \frac{1}{6}[1+2q\cos((\omega_o-\omega_i)t+\frac{2\pi}{3})] + \frac{1}{6}[1+2q\cos(\omega_o+\omega_i)t] \end{bmatrix}$$

$$\begin{bmatrix} m_{31} \\ m_{32} \\ m_{33} \end{bmatrix} = \begin{bmatrix} \frac{1}{6}[1+2q\cos((\omega_o-\omega_i)t+\frac{2\pi}{3})] + \frac{1}{6}[1+2q\cos((\omega_o+\omega_i)t+\frac{2\pi}{3})] \\ \frac{1}{6}[1+2q\cos((\omega_o-\omega_i)t-\frac{2\pi}{3})] + \frac{1}{6}[1+2q\cos(\omega_o+\omega_i)t] \\ \frac{1}{6}[1+2q\cos(\omega_o-\omega_i)t] + \frac{1}{6}[1+2q\cos((\omega_o+\omega_i)t-\frac{2\pi}{3}) \end{bmatrix} \quad (12)$$

This solution shows that unity input power factor can be achieved without the need of input current sensing but is a computational burden. In order to reduce the computational effort for a future microprocessor implementation, equation (12) is conveniently directly expressed in terms of the input voltages and the desired output voltages in the form shown in equation (13):

$$m_{ij} = \frac{1}{3}\left(1 + \frac{2v_{ei}v_{oj}}{V_n^2}\right) \qquad \text{for i, j=1, 2, 3.} \tag{13}$$

Where V_n^2 is the magnitude of the input voltages.

The MPEC output voltages controlled by Venturini method consist of several input voltage chops assembled sequentially during each interval *Ta*.

In [3] the authors proved that for a three-phase to three-phase MPEC the upper limit on the voltage ratio is 0.866 for any modulation method. They also proposed improvements concerning this control method, which increase the voltage ratio to 0.866.

Because the MPEC acts as a current source converter for the mains, an input filter is necessary to filter the high frequency ripple of the input currents. The greater the frequency of operation of the MPEC, the smaller will be the filter.

IV. A STATOR FLUX ORIENTED THREE-PHASE INDUCTION MOTOR VOLTAGE CONTROL USING MPEC

The field-oriented control (FOC) is based on the idea of the decoupling torque and flux through coordinate transformation, which can be implemented in different ways [7]. A suitable form of implementation with MPEC is the stator flux oriented three-phase induction motor voltage control [8] shown in figure 3:

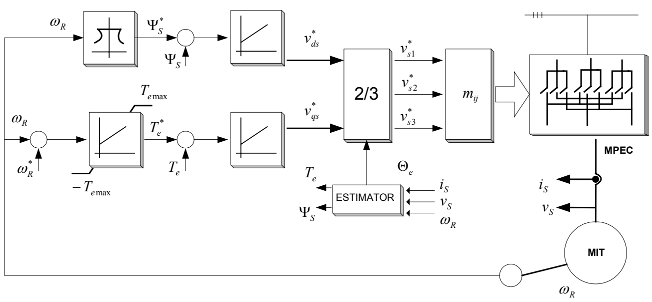

Fig. 3. A stator flux oriented three-phase induction motor voltage control scheme.

In this scheme two PI regulators are used to regulate the average value of the torque and the flux magnitudes. The outputs of the PI regulators provide the voltage reference in a synchronous d-q reference frame. An additional torque loop has been added within the speed loop to make its response faster.

Since that the estimation of the stator flux directly by a pure integrator has the integration drift problem [9], the stator flux components $\psi_{\alpha s}$ and $\psi_{\beta s}$ estimation is done using a low pass filter with the transfer function:

$$F(s) = \frac{1}{s + 0.1} \tag{14}$$

The stator flux magnitude and the sine and cosine angle θ are calculated by:

$$\left|\hat{\Psi}_s\right| = \sqrt{\hat{\Psi}_{\alpha s}^2 + \hat{\Psi}_{\beta s}^2} \tag{15}$$

$$\cos\hat{\theta} = \frac{\hat{\Psi}_{\alpha s}}{\left|\hat{\Psi}_s\right|} \tag{16}$$

$$\mathrm{sen}\,\hat{\theta} = \frac{\hat{\Psi}_{\beta s}}{\left|\Psi_s\right|} \tag{17}$$

The electromagnetic torque can be expressed in terms of the stator flux and the stator current as seen below:

$$\hat{T}_e = \frac{3P}{4}\left(\hat{\Psi}_{\alpha s} i_{\beta s} - \hat{\Psi}_{\beta s} i_{\alpha s}\right) \tag{18}$$

The synchronous reference frame voltage v_{ds}^* and v_{qs}^* is transformed into the $v_{s1}^*, v_{s2}^*\, and\, v_{s3}^*$ desired reference voltages using the stator flux angle information, applying the equations (19) and (20):

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \begin{bmatrix} sin(\theta) & \cos(\theta) \\ \cos(\theta) & -sin(\theta) \end{bmatrix} \begin{bmatrix} v_{ds}^* \\ v_{qs}^* \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} v_{s1}^* \\ v_{s2}^* \\ v_{s3}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -0.5 & -0.866 \\ -0.5 & 0.866 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{20}$$

The Venturini algorithm described before is used to calculate the switching duty ratios m_{ij} using equation (13) where v_{oj} will be $v_{s1}^*, v_{s2}^*\, and\, v_{s3}^*$.

V. SIMULATION RESULTS

The MPEC and the described vector control strategy mentioned before were simulated using the Simulink/Power System Blockset™. The motor characteristics and parameters are [10]: Pn=3hp, Vn=220V, f=60Hz, four poles, r_s=0.435Ω Ls=2mH, r'_r=0.816Ω, L'_r=2mH, Lm=69.31mH, J=0.089kgm^2 and the converter rms input voltage is 440V at 60Hz. A low-pass filter with 1.5khz cut-off frequency was used to filter the input current. The switching frequency was 5kHz. The simulated results are shown in the following figures.

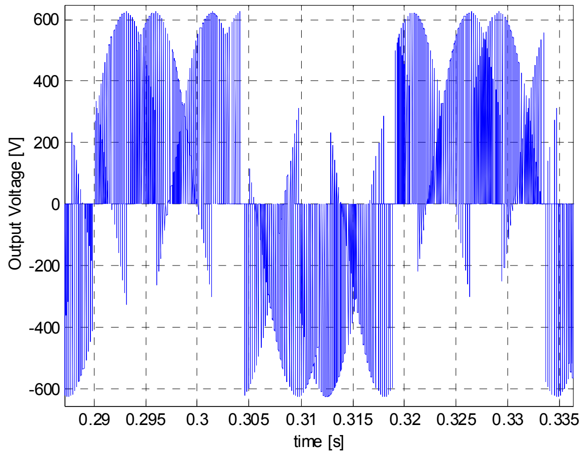

Fig. 4. Output line voltage.

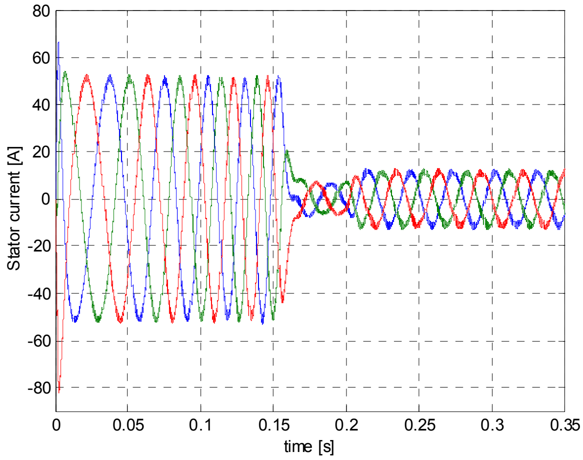

Fig. 5. Motor stator currents.

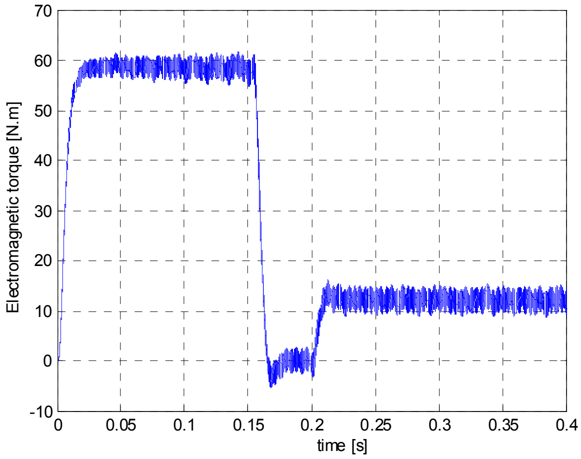

Fig. 6. Motor electromagnetic torque.

Figure 4 shows the output line voltage of the MPEC applied to the motor stator. Figures 5 and 6 show the stator current and torque response respectively when the motor starts with no load and when a load step of 12N.m is applied to the motor at the instant 0.2s. The reference rotor speed was set at 100 rad/s. Figures 7 and 8 show that the input current filtered by a low-pass filter is sinusoidal and the power factor is almost unitary both at motor starting and at steady state.

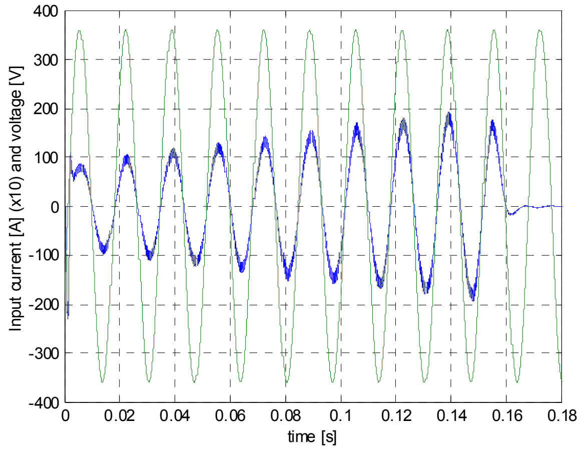

Fig. 7. Input current of one phase at motor starting.

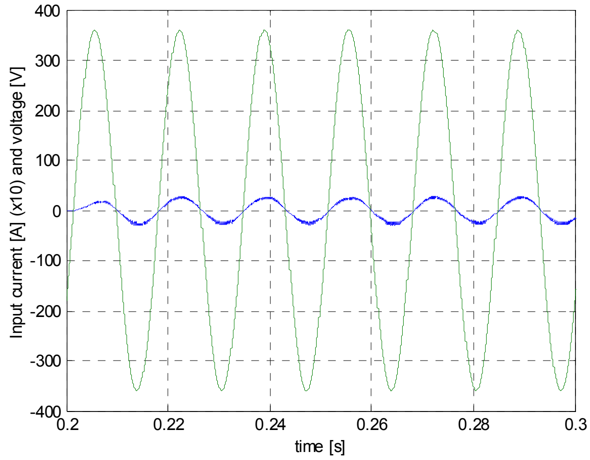

Fig. 8. Input current of one phase at steady state.

Figures 9 and 10 show respectively the stator current and the torque response when the reference rotor speed changes from 100rad/s to –100rad/s (figure 11).

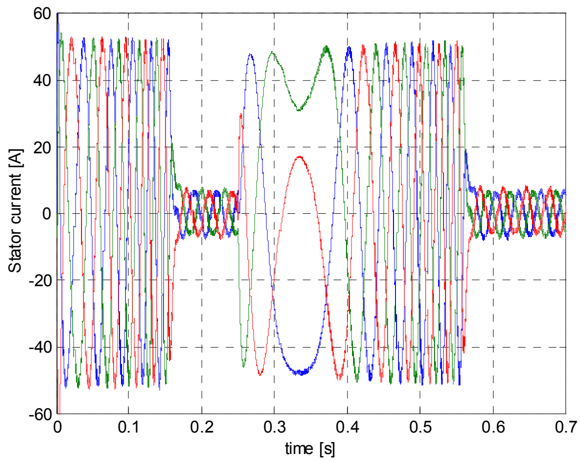

Fig. 9. Motor stator currents.

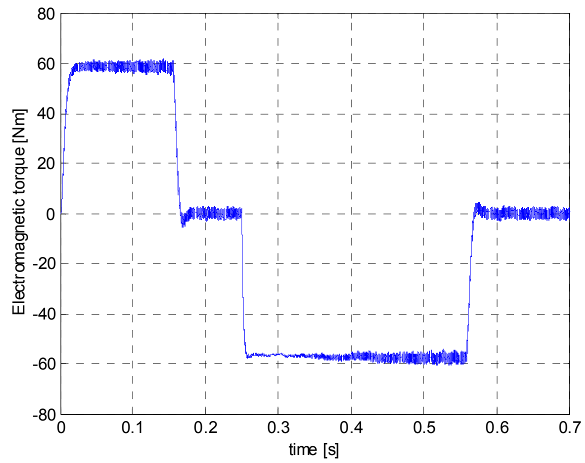

Fig. 10. Electromagnetic torque.

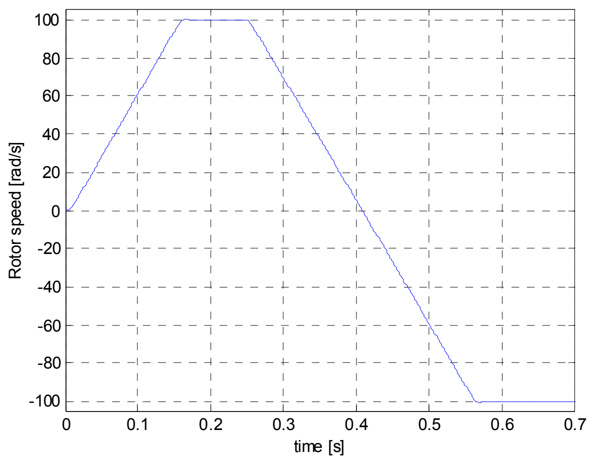

Fig. 11. Rotor speed.

The stator flux is kept constant during the operation of the motor as seen in figure 12.

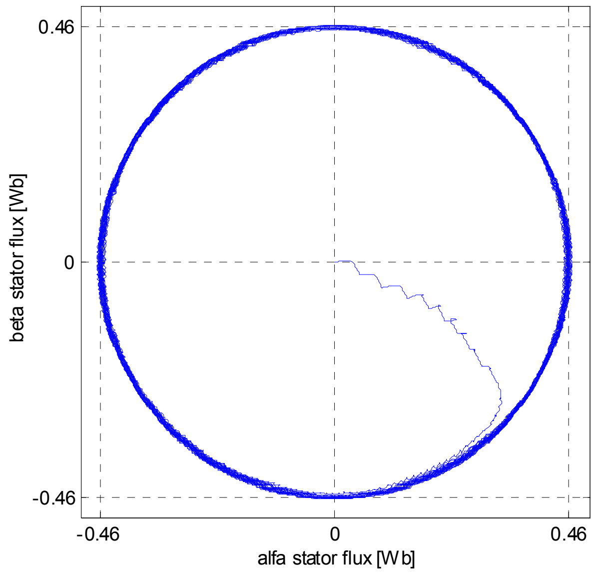

Fig. 12. Stator flux locus.

The results show that the dynamic response and tracking capability are very adequate.

VI. CONCLUSION

A MPEC driving a three-phase induction motor in closed loop control has been simulated. Simulation results show that the MPEC is feasible to be used on electric drive applications. Future researches will include studies using other types of modulation strategies like the space vector modulation [6] and the implementation of the MPEC driving an AC motor under closed-loop control.

VII ACKNOWLEDGMENT

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