

ENHANCED DYNAMIC PERFORMANCE OF MATRIX CONVERTER CAGE DRIVE WITH NEURO-FUZZY APPROACH

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ABSTRACT

This paper proposes a new control algorithm for a matrix converter (MC) induction motor drive system. First, a new switching strategy, which applies a back-propagation neural network to adjust a pseudo dc bus voltage, is proposed to reduce the current harmonics of the induction motor. Next, a two-degree-of-freedom controller is proposed to improve the system performance. The controller design algorithm can be applied in an adjustable speed control system and a position control system to obtain good transient responses and good load disturbance rejection abilities. The implementation of this kind of controller is only possible by using a high-speed digital signal processor. In this paper, all the control loops, including current-loop, speed-loop, and position-loop, are implemented by TMS320C6711 digital signal processor. Several experimental results are shown to validate the theoretical analysis.

Index Terms— Matrix converter, Adjustable speed control system, controller design algorithm, control loops, load disturbance rejection.

NOMENCLATURE

K_T	Torque constant
I^*	Ideal current command
T_e^*	Ideal torque command
I_{ref}^C	Required compensating current
$\Delta w_r(k)$	Speed error of motor at sampling interval k
$\alpha(k)$	Change of speed error at sampling interval k
$G_c(z)$	Transfer function of PI controller
$G_p(z)$	Transfer function of simplified plant
$N(I^*)$	Describing function of the current limiter
μ_n	Grade of the membership function
w_{ik}, v_{kj}	Parameters of the neural
θ_{hk}	network obtained from and
θ_{oi}	the off-line learning

I. INTRODUCTION

The matrix converter (MC) has received considerable attention in recent years. The ac/ac matrix converter has many advantages. For example, it uses only nine bi-directional switches and does not require any dc links. In addition, it has a high-power-factor, sinusoidal input current, bi-directional power flow, and low switching frequency on each power device. Different switching schemes for an ac/ac matrix converter have been proposed to achieve sinusoidal input and output current waveforms. For example, the space vector modulating method and input power factor

correction were applied in a matrix converter [1] and [2]. Several methods have been proposed to improve the performance of the matrix converter.

For instance, an optimum-amplitude matrix converter was implemented to increase its output voltage and a switching strategy to reduce the harmonic content of the input current under unbalanced conditions was proposed [3] and [4]. Several different commutation techniques have been proposed to safely commute the power devices of the matrix



converter. For instance, a dead time technique and an overlap-time commutation method were used to improve the commutating performance [5] and [6].

Many researchers have studied the matrix converters that drive AC motors. For example, a matrix converter was developed to drive an induction motor [7] and [8]. These studies focused on the new type of matrix converter and the field-oriented control in adjustable-speed induction drive systems. In addition, a 30-hp matrix converter was applied in an induction motor to adjust its speed. The current harmonics, however, were large because only the high bus voltage was selected [9]. Some researchers investigated the clamp (snubber) circuit design for a matrix converter based on an induction drive system [10]. This research, however, only focused on clamp circuit design. Recently, in [11], combining the principle of sliding mode, DTC (Direct torque control), and SVM (Space vector modulation) in high performance sensorless AC drive has been investigated. Efforts towards applying intelligent techniques in resolving MC problems are scarce in the literature.

The matrix converter is superior to the traditional PWM (Pulse width modulation) drives because of regeneration ability and sinusoidal input current. Therefore it meets the stringent energy-efficiency and power quality requirements of the new century. Matrix converter can be considered to be a direct converter, in this respect similar to a cycloconverter, because, first, it doesn't employ a dc link and, secondly the output waveforms are composed of switched segments of the input waveforms. The matrix converter therefore possesses the advantages of both the cycloconverter and the PWM drive, as summarized below :

1. It can operate in all four quadrants of the torque-speed plane because of its regeneration capability.
2. Its input current waveform is sinusoidal and the input power factor is unity
3. The input power factor may be controlled across the whole speed range.
4. There is no dc link and therefore no requirement for energy storage devices
5. The output voltage and input current waveforms can be controlled such that they are near sinusoidal in form.
6. The harmonic distortion that is incurred is at high frequencies

7. It may be used as direct frequency changer, converting a fixed ac or dc source into a variable ac or dc supply.
8. Compact converter design.
9. No dc-link components.

Most of the previous publications on matrix converters have dealt with modulation strategies [1]–[6], or with aspects of adjustable speed control [7]–[11]. Very few publications have considered the controller design for the matrix converter based ac drive system [11], and only some simulated results have been provided. In addition, the previous publications did not discuss the position control for the matrix converter based ac drive system. The position control includes an inner speed control loop. If the speed cannot be adjusted from a very low speed to a high speed with precise control, the inner speed loop of the position control system becomes nonlinear. Then, the performance of the position control is seriously deteriorated. As a result, the position control is more challenging than the speed control system for other ac motors.

In this paper, a back-propagation neural network is used to adjust the pseudo dc-bus voltage of the matrix converter according to the motor speed and the output current deviation of the matrix converter. As a result, the switching pattern of the matrix converter is new. In addition, a matrix converter based induction motor drive system is developed. A two-degree-of-freedom controller is used for the drive system. The implementation of this kind of controller is only possible by using a high speed digital signal processor. In this paper, all the current, speed, and position-loops are implemented by a digital signal processor, TMS320C6711. This system has several improvements over previously published papers, which selected the highest pseudo dc-bus voltage and focused on the implementation of the matrix converter and its applications in speed-control drive systems only [7]–[11].

In this paper, first, a new switching strategy for an ac/ac matrix converter is presented. The current harmonics of the matrix converter induction motor drive system have been effectively reduced. Second, a two-degree-of-freedom optimal control algorithm is applied. By using this optimization algorithm, a satisfactory Servo drive can be achieved. The forward controller determines the transient response. On the other hand, the load compensator determines the load disturbance response. The forward controller and the load

compensator can be individually designed. As a result, a two-degree-of-freedom controller can be obtained. For speed control, the adjustable speed range is from 1 r/min to rated speed. The system can also perform precise position control. The steady-state error is ± 1 b, which is caused by the truncation error or round off error of the digital signal processor. The system can track a triangular time-varying position command well. As a result, the system has satisfactory performance as a servo drive system. It has a fast response and a good load disturbance rejection capability.

To the author's best knowledge, this is the first time that a two-degree-of-freedom controller with parameter optimization has been applied in matrix converter induction motor drive system. Implementation of a high performance induction motor position-control system driven by a matrix converter is also an original idea. The proposed method has several advantages. The design procedures of the control law require only algebraic computation. In addition, the implementation of the control law is relatively simple using a high-speed digital signal processor TMS320C6711.

This paper is structured as follows. In section II, neural network based switching strategy is discussed. In section III, fuzzy controller design with torque pulsation improvement is described. In section IV, DSP based implementation is described. Section V and VI provide experimental results and conclusions respectively, followed by references.

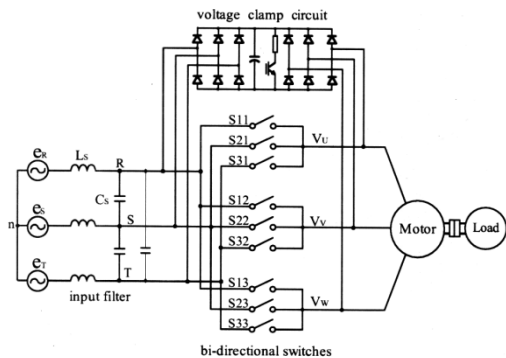
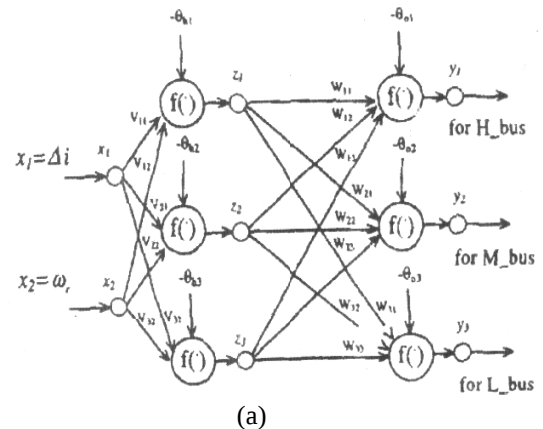


Fig.1. Basic Matrix converter topology
II. NEURAL NETWORK BASED SWITCHING STRATEGY

A multilayer neural network is used here to determine the bus voltage of the matrix converter. It is possible to compute the required voltage vector of the motor, and then determine

the optimal selection of the bus voltage. This method, however, requires a lot of computations and is difficult to implement. An off-line learning neural network is therefore proposed. Fig. 2(a) shows the structure of the proposed neural network which includes an input layer, a hidden layer, and an output layer. The parameters of the synaptic weights are off-line trained. The input state variables are the motor speed and current deviation because they are related to the bus voltage. For example, a higher speed range requires a high bus voltage to produce the required current regulation. In addition, the current deviations during transient response and steady-state conditions appear different and thus require different bus voltages to reduce the deviations.

The parameters of the neural network, w_{ik} , v_{kj} , θ_{hk} , and θ_{oi} are obtained from the off-line learning processes. The off-line learning algorithm is shown in Fig. 2 (b). First, we obtain some desired training data from experimental results. Then, we can execute the training process to obtain the required parameters w_{ik} , v_{kj} , θ_{hk} , and θ_{oi} . In the application of the back-propagation algorithm, two passes are required: the forward pass and the backward pass. In the forward pass, the synaptic weights remain unaltered throughout the network. The forward pass input state variables are the motor speed and the maximum absolute value of the three-phase current deviations. The backward pass, on the other hand, starts at the output layer by passing the error signals leftward through the network, layer by layer, and recursively computing the relative weight corrections and then adjusting the synaptic weights.



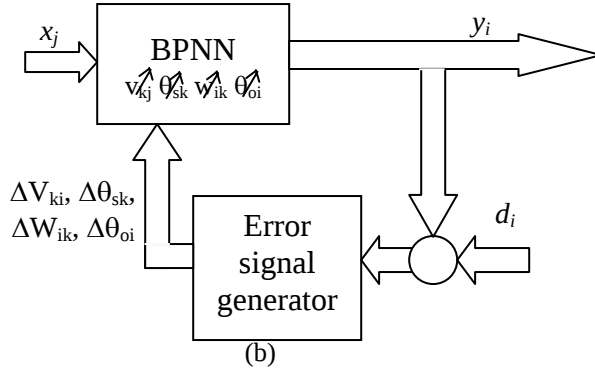


Fig. 2. Neural network (a) On-line NN (b) Off-line parameter tuning

III. TORQUE PULSATION IMPROVEMENT AND FUZZY CONTROLLER

Unfortunately, in the real world, the torque pulsation can be produced in many different ways. First, the rotor magnetic flux flows through a minimum reluctance path to the stator, which produces cogging torque. Second, the analog-to-digital (A/D) converter and Hall-effect current sensors have offset biases and thus produce torque pulsation. Finally, the phase currents and motor back emf are affected by the undesired high-order harmonics. In order to describe the real torque, a simple mathematical model, which is related to the rotor position of the motor and the current command, is used as [9]

$T_e(\theta_r, I^*) = a_0(\theta_r) + K_T I^* (1 + a_1(\theta_r))$ (1)
where a_0 and a_1 are the parameters relative to torque pulsation, K_T is the torque constant which is equal to $L_{md} I_{fd}$ and I^* is the ideal current command. The parameter $a_0(\theta_r)$ includes the torque pulsation due to the cogging torque and the current offset in the drives. It can be measured by setting the I^* to zero, and then measuring the relative torque in different shaft angles. The parameter $a_1(\theta_r)$ includes the torque pulsation related to the harmonic contents, and the phase misalignment of the current and the back emf profiles. It can be calculated by using the following equation :

$$a_1(\theta_r) = \frac{T_e(\theta_r, I^*) - a_0(\theta_r) - K_T I^*}{K_T I^*} \quad (2)$$

A compensation current command is designed to produce an ideal torque. The relationship between the compensation command and the ideal torque is shown as follows

$$T_e^* = K_T I^* = a_0(\theta_r) + K_T I_{ref}^e (1 + a_1(\theta_r)) \quad (3)$$

where T_e^* is the ideal torque command, and I_{ref}^e is the required compensating current command. Now, it is easy to obtain the compensation current command as

$$I_{ref}^e = \frac{I^*}{1 + a_1(\theta_r)} - \frac{a_0(\theta_r)}{K_T (1 + a_1(\theta_r))} \quad (4)$$

The proportional - integral (PI) controller has been widely used in industry for a long time due to its simplicity and reliability. Unfortunately, by using a fixed PI controller, it is difficult to obtain both a good transient response and a good load disturbance rejection. It is possible to tune the PI controller by using a self-tuning algorithm. However, this method is very complicated and is difficult to implement. A fuzzy algorithm is therefore proposed to adjust the parameters of the PI controller. Both a good transient response and a good load disturbance rejection capability can be achieved by using this method. First, the state variables of this system are defined as

$$\Delta \omega_r(k) = \omega_r^* - \omega_r(k) \\ \alpha(k) = [\Delta \omega_r(k) - \Delta \omega_r(k-1)]/T \quad (5)$$

where $\Delta \omega_r(k)$ is the speed error of the motor at sampling interval k , $\alpha(k)$ is the change of the speed error at sampling interval k , and T is the sampling interval of the drive system.

Then, the PI controller is tuned according to the proposed fuzzy algorithm. The acceptable tuning range of the PI controller can be determined as follows. A saturation-type current limiter exists in the forward loop. The reason is that the matrix converter has its allowable maximum current to avoid damage to the solid-state power devices. The current limiter is a nonlinear element which may cause limit cycles of the speed response. In order to avoid producing limit cycles, the parameters of the PI controller should be limited within a reasonable range. The describing function technique is used here to determine the range of the parameters of the PI controller. In the discrete-time domain, the transfer function in the forward-loop is

$$Gf(z) = Gc(z) Gp(z) = \frac{K_r T}{J_m} \frac{K_p(z-1) + K_i z}{(z-1)^2} \quad (6)$$

where $G_c(z)$ is the transfer function of the PI controller, $G_p(z)$ is the transfer function of the simplified plant, and J_m is the equivalent inertia of the system. Then, we can use the bilinear transformation, $z = (1 + \omega)/(1 - \omega)$, to obtain

$$G_f(\omega) = \frac{K_T T [-(K_I + 2K_p) \omega^2 + 2K_p \omega + K_I]}{4J_m \omega^2} \quad (7)$$

The $G_f(\omega)$ can be transformed into the frequency domain. The current limiter can be approximated by its describing function

$$N(I^*) = \frac{2}{\pi} \left[\frac{I^*_{\max}}{I^*} \cos \left(\sin^{-1} \frac{I^*_{\max}}{I^*} \right) + \sin^{-1} \frac{I^*_{\max}}{I^*} \right] \quad (8)$$

where $N(I^*)$ is the describing function of the current limiter, $I^*_{\max}$ is the maximum allowable current of the inverter. The closed-loop system exhibits limit cycles if $G_f(j\omega)$ and $-1/N$ intersect. It is easy to observe that the magnitude of $N(I^*)$ is always positive and varies from 0 to 1. As a result, the phase of $-1/N$ is always -180 degrees and the magnitude of $-1/N$ varies from 1 to infinity. Assume ω_c is the phase crossover frequency for $G_f(j\omega)$. Then, the $G_f(j\omega_c)$ is approximated by

$$|G_f(j\omega_c)| \cong K_T T (2K_p + K_I) / (4J_m) \quad (9)$$

The condition for the closed-loop system to be stable, is one in which $G_f(j\omega_c)$ cannot intersect with $-1/N$. This, then implies that the $|G_f(j\omega_c)|$ satisfies the following inequality

$$0 < |G_f(j\omega_c)| < 1 \quad (10)$$

Finally, the tuning range of the PI controller can be obtained as

$$0 < K_T T (2K_p + K_I) < 4J_m \quad (11)$$

A. Membership Functions and Fuzzy Control Law :

The membership functions are used to describe the compatibility or degree of truth. The speed error is divided into three categories: the large error, the small error, and the zero error and is shown in Fig. 3(a). Then, any $\Delta \omega_r(k)$ may have different membership functions which are related to the three different categories. In Fig. 3(b), the change of the speed error is $\alpha(k)$, which can be divided into three categories as well. The maximum value of the change of the speed error is set as 400 rad/s^2 due to the current limitation and inertia of the induction motor drive system.

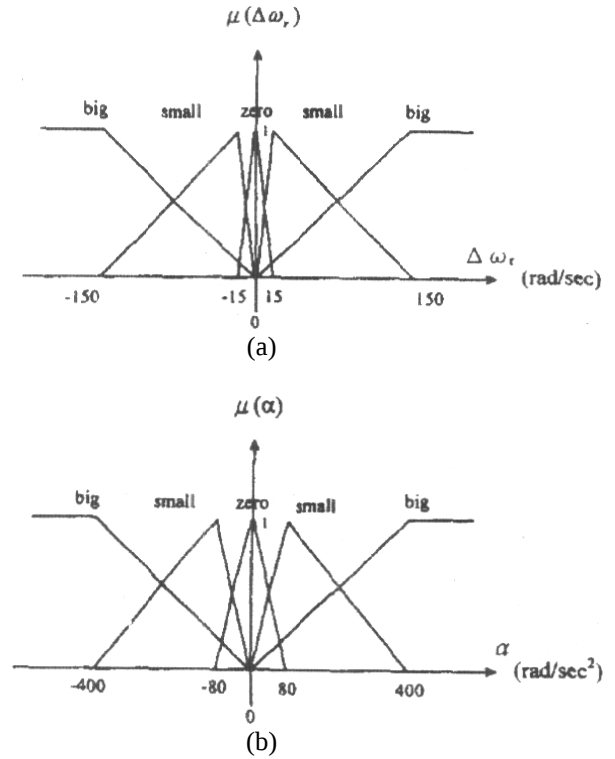


Fig. 3. Membership functions. (a) Speed error.

(b) Change of speed error

The fuzzy-reasoning algorithm is based on the characteristics of the induction motor drive system and the designer's experience. For example, when the motor is starting, the PI controller is adjusted to achieve a fast response. However, when the motor is in a close to steady-state condition, the PI controller is tuned to avoid oscillations of the speed response. The details are as follows :

IF $|\Delta \omega_r(k)|$ is big THEN $K_p = K_{p1}$, $K_I = K_{I1}$.

IF $|\Delta \omega_r(k)|$ is small and $|\alpha(k)|$ is big THEN $K_p = K_{p2}$, $K_I = K_{I2}$.

IF $|\Delta \omega_r(k)|$ is small and $|\alpha(k)|$ is zero THEN $K_p = K_{p4}$, $K_I = K_{I4}$.

IF $|\Delta \omega_r(k)|$ is zero THEN $K_p = K_{p5}$, $K_I = K_{I5}$.

The parameters $K_{p1} - K_{p5}$ and $K_{I1} - K_{I5}$ should satisfy tuning range of PI controller, keeping in mind, these parameters are determined by the designer's experience.

B. Defuzzification:

The center of area (COA) method is used to obtain the PI parameters. In order to consider the effect of both the state variables, $\Delta \omega_r$ and α the intersection of the grade of the membership function with $\Delta \omega_r$ and α is calculated as

$$\mu_n = \mu_{\Delta \omega_r} \Delta_a = \min ((\mu(\Delta \omega_r), \mu(\alpha)))$$

$$K_p = \sum_{n=1}^5 \mu_n K_{pn} / \sum_{n=1}^5 \mu_n \quad (12)$$

$$K_I = \sum_{n=1}^5 \mu_n K_{In} / \sum_{n=1}^5 \mu_n \quad (13)$$

where μ_n is the grade of the membership function in the different categories. Finally the control input u is set as

$$u = K_p \Delta \omega_r(k) + K_I \sum_{i=0}^k \Delta \omega_r(i) \quad (14)$$

IV. DSP BASED IMPLEMENTATION

A TMS320C6711 digital signal processor was used for on-line calculation of the switch timings. The DSP is mounted on a PC-compatible card, the Evaluation Module (EVM) to facilitate the development process. An additional interface card was used for outputting the calculated switch timings. This comprises of programmable timers, clock, a EPROM, I/O port and a few logic gates. Both DSP and interface card are plugged in a PC which provides a convenient means for data communication and user interface. Any control algorithm for a matrix converter must be synchronized with the input voltage cycle so that the calculation of switch timings can be correctly performed. This is achieved by using the software phase-lock-loop (PLL) which detects the zero-crossing of the input phase voltage. An interrupt pulse generated at each zero-crossing will cause the DSP to initialize appropriate variables for calculation. The general requirements for generating the switch control signals for a matrix converter on-line in real-time are listed as follows :

- Computation of the switch duty cycles must be completed within one switching period.
- Accurate timing of the pulse-pattern output should be achieved, and
- The computational process must be synchronized with the input-voltage sinusoidal cycle.

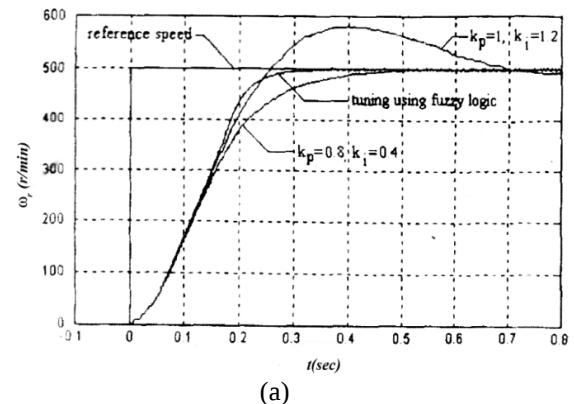
V. EXPERIMENTAL RESULTS

An experimental prototype matrix converter drive system based on the proposed control method has been constructed. The motor

line currents are measured by two Hall-effect current sensors. The other feedback quantities are the absolute rotor shaft angle and motor speed, which can be obtained by the resolver mounted on the motor shaft. The parameters of the induction motor are shown as follows. The stator resistance is 0.40Ω /phase, the d-axis inductance is 6.7 mH , the q-axis inductance is 6.7 mH , the inertia of the motor and dynamometer is $0.0233 \text{ N}\cdot\text{m}\cdot\text{s}^2/\text{rad}$, and the torque constant is $0.643 \text{ N}\cdot\text{m}/\text{A}$. The current limitation of the matrix converter is $\pm 14 \text{ A}$.

Fig. 4 shows the measured speed responses of the matrix converter drive system with different control methods. Fig. 4(a) is the transient responses with a speed command of 500 r/min . Fig. 4(b) is the load disturbance responses when a $2 \text{ N}\cdot\text{m}$ external load is added at a speed of 500 r/min . According to Fig. 4(a) and Fig. 4(b), the proposed control algorithm, which uses fuzzy logic to adjust the PI controller parameters, performs better than the fixed PI controllers.

The traditional PWM drive system employ either a traditional rectifier or a PWM rectifier to convert the source voltage in the required dc voltage. A PWM inverter is normally used to convert the dc voltage to the required ac output voltage and frequency. Smaller power converters may employ PWM converter and inverters using IGBT devices. Larger PWM drives, often favours diode Rectifier Bridge, thereby overcoming the reverse voltage limitation of the IGBT devices. The matrix converter is superior to the traditional PWM drives because of regeneration ability and sinusoidal input current. Therefore it meets the stringent energy-efficiency and power quality requirements of the new century.



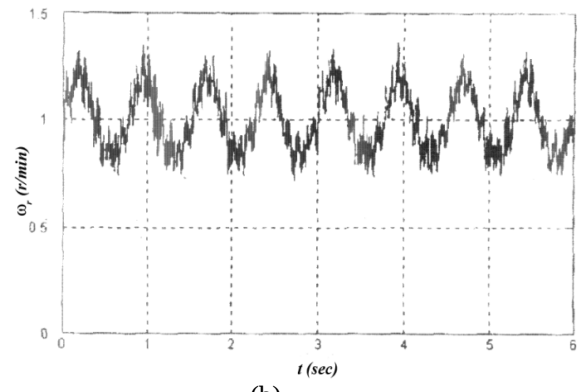
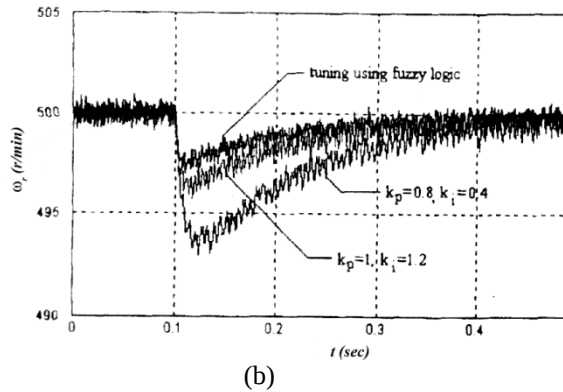
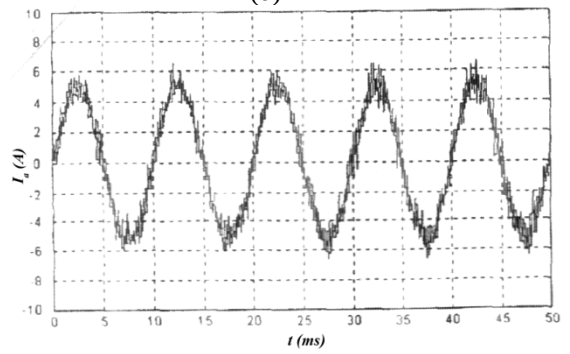
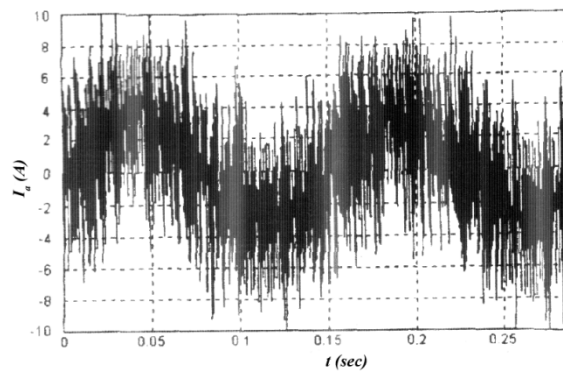
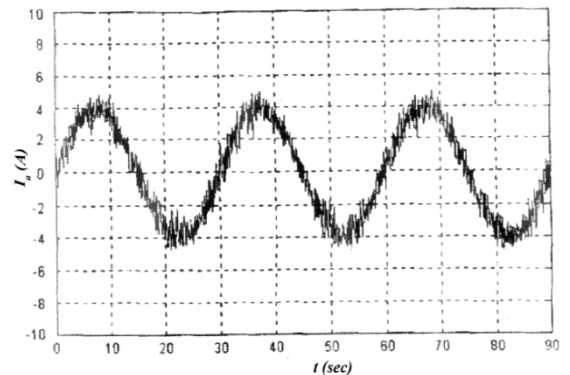
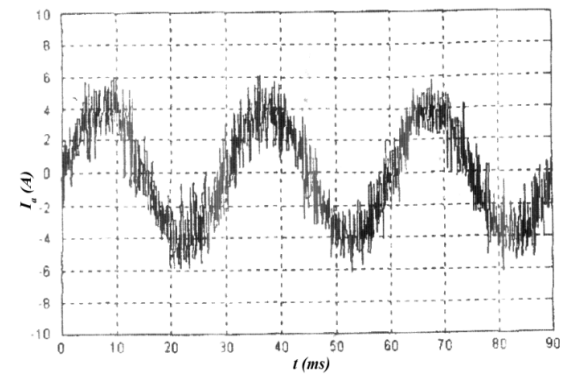


Fig. 4. Measured speed response at 500 r/min
(a) transient (b) load disturbance

Fig. 5 shows the measured a-phase currents in steady-state. Fig. 5(a) shows the a-phase current at 100 r/min and 2 N*m by using the traditional method. Fig. 5(b) shows the a-phase current in the same condition by using the proposed method. The proposed method performs better. Fig. 5(c) shows the a-phase current at 500 r/min and 2 N*m by using the traditional method proposed in reference paper [5]. Fig. 5(d) shows the a-phase current in the same situation by using the proposed method. The proposed method performs better again. Fig. 5(e) shows the a-phase current at 1500 r/min and 2 N*m by using the traditional method. Fig. 5(f) shows the a-phase current in the same condition by using the proposed method. The proposed method has similar performance to the traditional one when the motor is operated at a rated speed. The major reason for this is that almost the highest bus voltage switching patterns are selected as the motor is operated at a rated speed. According to Fig. 5, we can observe that the proposed method can effectively reduce the current deviations in a low or middle speed range.



(a)

(e)

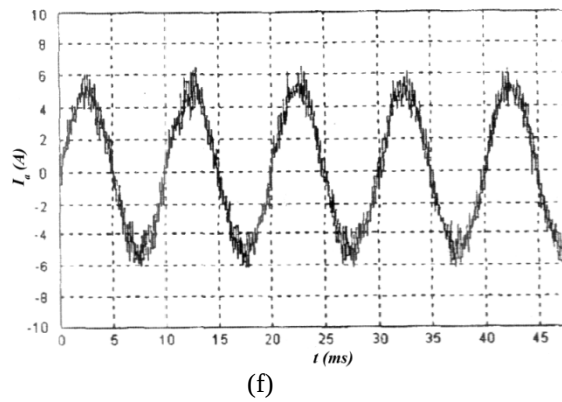


Fig. 5. Measured steady-state stator currents. (a) Traditional at 100 r/min. (b) Proposed at 100 r/min. (c) Traditional at 500 r/min. (d) Proposed at 500 r/min. (e) Traditional at 1500 r/min. (f) Proposed at 1500 r/min..

Fig. 6 shows the low speed responses of 1 r / min. Fig. 6(a) is the speed response of the traditional method proposed in [5]. Fig. 6(b) is the speed response obtained by using the neural-network learning technique without using torque compensation. Fig. 6(c) is the speed response when using the neural network learning technique and torque compensation. This method can obtain a smooth speed with small ripples.

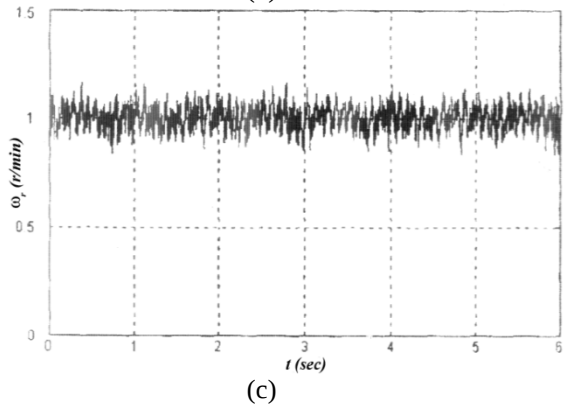
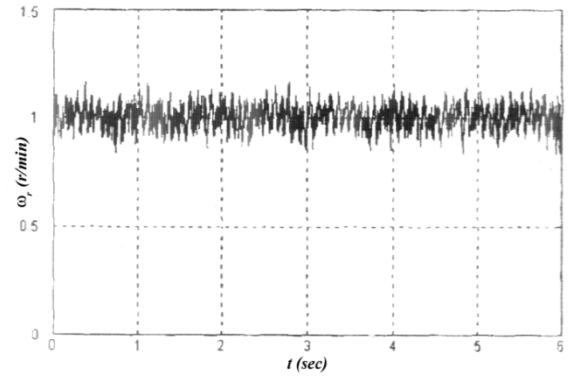
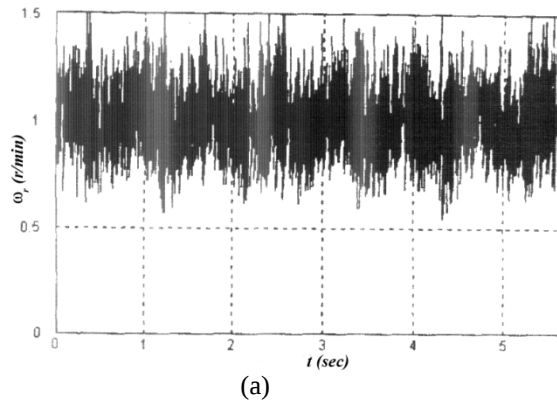


Fig. 6. Low speed responses. (a) Traditional method. (b) Proposed method without torque compensation. (c) Proposed method with torque compensation

VI. CONCLUSIONS

In this paper, design and implementation of a novel matrix converter induction motor system has been investigated. All the control algorithms, which include the switching strategy, the coordinate transformation, the speed control, and the position control, are executed by a digital signal processor TMS320C6711. This paper has provided a systematic and analytic approach for designing a high performance matrix converter induction motor drive system. The proposed design approach has been validated by actual implementation. Moreover, this design approach can be applied in both the speed and the position control system with an added advantage that the implemented system is flexible.

These research results concerning intelligent control scheme and robustness of the bidirectional switch commutation have led to innovative solutions and from technical point of view industrial use seem to be reasonable now. The impact of these results on the future work

in IM control is in speeding-up process of the matrix converter technology in real industrial applications. As a result, it is likely to play major role in future converter designs both as a motor drive at low and high powers and as a power converter linking two electrical power systems having different voltages and frequencies.

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