

Contouring Control for a CNC Milling Machine Driven by Direct thrust Controlled Linear Induction Motors

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Abstract: According to various advantages of linear induction motor (LIM), such as high starting thrust force, high speed operation and reduction of mechanical losses, more applications have utilized this type of motors. Direct Thrust Control (DTC) technique is considered as one of the most efficient techniques that can be used for LIM. DTC is preferable to give a fast and good dynamic thrust response. So, to improve the accuracy and robustness of contouring control for CNC machine tools, linear induction motors with a direct thrust control technique are introduced for driving these machines. An industry standard motion control system is applied for reducing the tracking error and improving the desired accuracy. Different loading conditions are simulated to validate the reliability and robustness of the introduced system to match the application field. The proposed system is simulated using the MATLAB/SIMULINK Package; simulation results validated both tracking accuracy and robustness of the proposed motion control system for contouring control for a CNC (Computer Numerical Control) milling machine.

Keywords: Linear Induction Motor (LIM), Direct Thrust Control (DTC), Modified-Industry Standard Digital Motion Control System (MISDMCS), Contouring control, CNC-Milling Machine.

I. INTRODUCTION

Linear electric motors (LEMs) belong to the group of special electrical machines. LEMs convert electrical energy directly into mechanical energy of linear motion. Thus, there is no need for wheel, gear or any type of mechanical rotary-to-linear converters. The linear electric motors are classified into several types such as a single-sided linear induction motors (LIMs), double-sided LIMs, permanent magnet linear synchronous motor, permanent magnet brushless DC motor, and linear stepping motors. Among these, the LIM has many advantages such as high-starting thrust force, alleviation of gear between motor and the motion devices, reduction of mechanical losses and the size of motion devices, high-speed operation, no backlash and less friction. LIM's are now widely used, in many industrial applications including transportation, conveyor systems, actuators, material handling, pumping of liquid metal, and sliding door closers [1-4].

The driving principle of LIM is similar to traditional rotary induction motor (RIM), but its control characteristics are more complicated than the RIM, and the motor parameters are time varying due to change of operating conditions such as

changing of mover speed, temperature, and configuration of the rail.

Several control techniques have been used to control the speed and/or position of LIM drives. Among these control techniques, the method of Direct Thrust Control (DTC) is considered as one of the most efficient techniques that can be used for induction motors. DTC is preferable to give a fast and good dynamic thrust response in the small and medium power range applications. DTC technology has simple algorithms, fast dynamic response, robustness against parameter variations, and is ideal for controlling traction motor [5, 6]. DTC does not require either the rotor position detection or the current controller in the rotating coordinate system. The basic principle of DTC is to directly select voltage vectors according to the difference between reference and actual value of thrust and flux linkage. The typical DTC includes two hysteresis controllers; the first is for thrust error correction while the second is for flux linkage error correction [5-8].

In this paper the speed control and position tracking control of a linear induction motor using DTC are proposed. First, the DTC is proposed to control both the thrust and flux of the LIM, and then the position and speed controllers are used to achieve the reference speed and position trajectories. The output of the each controller is considered as a reference input to the following controller to maintain the actual motor speed and position close to the reference trajectories. In CNC contouring control, a fast and good dynamic response is considered an important requirement, so an industry standard digital motion control system driven by direct thrust controlled linear induction motors has been proposed. The dynamic model of LIM is presented in section (2). The DTC of LIM is presented in section (3). Simulation results of DTC and discussions are presented in section (4). Proposed motion control system of DTC-LIM for a CNC milling machine are presented in section (5). Simulation results of the proposed motion control system of DTC-LIM are presented in section (6). Fuzzy Logic Control system of DTC-LIM for a CNC milling machine presented in section (7). Conclusions are presented in section (8).

II. DYNAMIC MODELLING OF LINEAR INDUCTION MOTOR (LIM)

The dynamic model of the LIM is modified from the traditional model of a three phase, Y-connected induction motor in stationary reference frame, and it can be described by the following differential equations [1-5].

$$\frac{d(i_{\alpha s})}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right)i_{\alpha s} + \frac{L_m}{\sigma L_s L_r T_r}\lambda_{\alpha r} + \frac{n_p L_m \pi}{\sigma L_s L_r h}v\lambda_{\beta r} + \frac{1}{\sigma L_s} \quad (1)$$

$$\frac{d(i_{\beta s})}{dt} = -\left(\frac{R_s}{\sigma L_s} + \frac{1-\sigma}{\sigma T_r}\right)i_{\beta s} - \frac{n_p L_m \pi}{\sigma L_s L_r h}v\lambda_{\alpha r} + \frac{L_m}{\sigma L_s L_r T_r}\lambda_{\beta r} + \frac{1}{\sigma L_s}V_{\beta s} \quad (2)$$

$$\frac{d(\lambda_{\alpha r})}{dt} = \frac{L_m}{T_r}i_{\alpha s} - \frac{1}{T_r} - \frac{n_p \pi}{h}v\lambda_{\beta r} \quad (3)$$

$$\frac{d(\lambda_{\beta r})}{dt} = \frac{L_m}{T_r}i_{\beta s} + \frac{n_p \pi}{h}v\lambda_{\alpha r} - \frac{1}{T_r}\lambda_{\beta r} \quad (4)$$

$$\frac{d(v)}{dt} = \frac{1}{M}F_e - \frac{D}{M}v - \frac{1}{M}F_L \quad (5)$$

Where $T_r = \frac{L_r}{R_r}$, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$ and where:

D : viscous friction and iron-loss coefficient.

F_e : electromagnetic force.

F_L : external force disturbance.

h : pole pitch.

L_s : primary inductance per phase.

L_r : secondary inductance per phase.

L_m : magnetizing inductance per phase.

n_p : number of pole pairs.

R_s : primary winding resistance per phase.

R_r : secondary winding resistance per phase.

T_r : secondary time constant.

v : mover linear velocity.

$\lambda_{\alpha r}, \lambda_{\beta r}$: α - β secondary flux components.

$i_{\alpha s}, i_{\beta s}$: α - β primary current components.

$V_{\alpha s}, V_{\beta s}$: α - β primary voltage components.

σ : leakage coefficient.

The electromagnetic force can be described in the fixed frame as: α - β fixed frame as:

$$F_e = k_f(\lambda_{\alpha r} i_{\beta s} - \lambda_{\beta r} i_{\alpha s}) \quad (6)$$

Where k_f is the force constant which is equal to:

$$k_f = \frac{3n_p L_m \pi}{2L_r h} \quad (7)$$

III. DIRECT THRUST CONTROL (DTC)

The basic block diagram of DTC is shown in fig. (1). The basic principle of DTC is to directly select voltage vectors according to the difference between reference and actual value of primary thrust and flux. The voltage vectors include eight vectors, six of them are considered to be active states, and the remaining two vectors are considered to be zero states. The typical DTC includes two hysteresis controllers; the first is for

thrust error correction while the second is for flux error correction. The hysteresis controllers keep the controlled variable within a certain band. The voltage vector selection block is responsible for generating the voltage pattern of the inverter to be fed to the motor terminals. The voltage vector is selected from a look up table based on the output of hysteresis controllers and the sector of the primary flux vector [7].

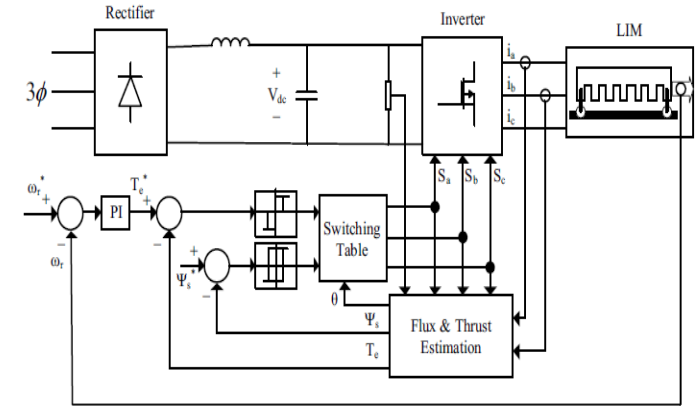


Figure (1): Basic D-Thrust Control scheme for LIM

To determine the proper voltage vectors, information from the thrust and flux hysteresis outputs, as well as primary flux vector position are required. The DTC technique selects the new voltage vector that maximizes the flux and thrust error correction, and minimizes the number of commutations required to change from the old to the new inverter output. The switching table is shown in table (1).

Table (1) switching table for DTC inverter.

Flux error pos	Thr error pos	Sector					
		sector 1	sector 2	sector 3	sector 4	sector 5	sector 6
1	1	V ₂ (110)	V ₃ (010)	V ₄ (001)	V ₅ (110)	V ₆ (110)	V ₇ (110)
	0	V ₇ (111)	V ₀ (000)	V ₇ (111)	V ₀ (000)	V ₇ (111)	V ₀ (000)
	-1	V ₆ (101)	V ₁ (100)	V ₂ (010)	V ₃ (011)	V ₄ (110)	V ₅ (110)
0	1	V ₃ (010)	V ₄ (011)	V ₅ (101)	V ₆ (100)	V ₁ (110)	V ₂ (110)
	0	V ₀ (000)	V ₇ (111)	V ₀ (000)	V ₇ (111)	V ₀ (000)	V ₇ (111)
	-1	V ₅ (001)	V ₆ (101)	V ₁ (110)	V ₂ (010)	V ₃ (110)	V ₃ (110)

The estimated values of the primary thrust and flux are calculated in the stationary frame as follows [8, 9]:

$$\lambda_{ds} = \int (V_{ds} - R_s i_{ds}) dt \quad (8)$$

$$\lambda_{qs} = \int (V_{qs} - R_s i_{qs}) dt \quad (9)$$

$$\lambda = \sqrt{(\lambda_{ds}^2 + \lambda_{qs}^2)} \quad (10)$$

$$\theta = \tan^{-1} \frac{\lambda_{qs}}{\lambda_{ds}} \quad (11)$$

TABLE 2.Parameters of the simulated LIM.

$R_s(\Omega)$	1.3
$R_r(\Omega)$	2.66
Motor time constant (Sec.)	0.066
Rated frequency (Hertz)	50
Number of poles	4
$L_s(H)$	0.06
$L_m(H)$	0.0376
$L_r(H)$	0.0451

The voltage vector in the stationary frame is calculated from the voltage in abc reference frame from the following equation:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (12)$$

The primary phase voltages are obtained from the switches states by:

$$V_a = \frac{V_{dc}}{3} (2S_a - S_b - S_c) \quad (13)$$

$$V_b = \frac{V_{dc}}{3} (-S_a + 2S_b - S_c) \quad (14)$$

$$V_c = \frac{V_{dc}}{3} (-S_a - S_b + 2S_c) \quad (15)$$

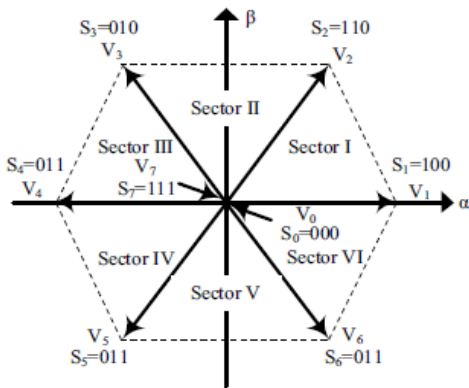


Figure (2): VSI voltage vectors.

The Simulink block diagram shows the DTC of LIM is shown in figure (3).

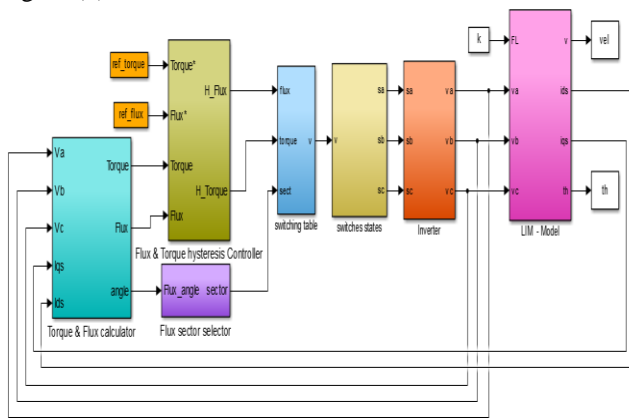


Figure 3: Proposed direct thrust controlled linear induction motor motion control system.

IV.SIMULATION RESULTS OF DTC AND DISCUSSIONS

Computer simulations have been carried out in order to validate the proposed scheme. The Matlab/Simulink software package has been used. Different operating conditions including load changing have been tested. The parameters of the simulated LIM are listed in Table 2.

Figure (4) shows the actual flux of the motor with reference value of 0.5Wb. Figure (5) shows the flux trajectory (relation between direct and quadrature axis components) at the same state. The figure shows a circular trajectory between these components with radius corresponding to the reference value (0.5Wb). Figure (6) shows the direct and quadrature current components. Figure (7) shows the reference and actual thrust trajectory for change from 5N.m to 3N.m at time t=2.5sec., then from 3 N.m 4 N.m at time t=5sec.from 4 N.m to 6 N.m at time t=7.5sec.

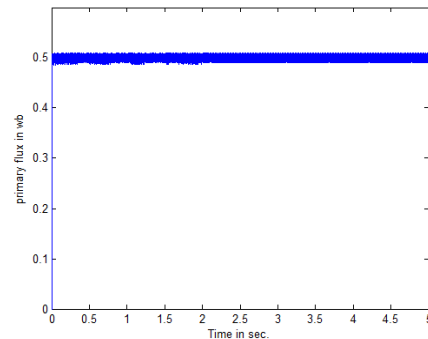


Figure (4): Actual flux of the motor with reference value of 0.5

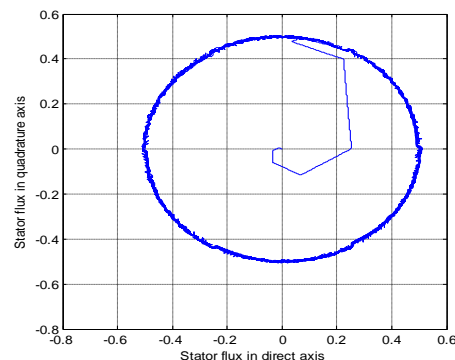


Figure (5): Flux trajectory

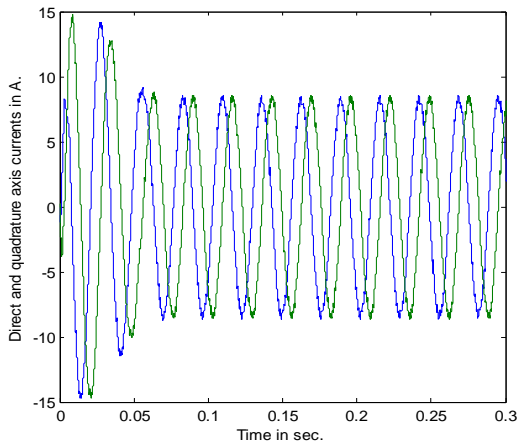


Figure (6): Currents in direct and quadrature axes.

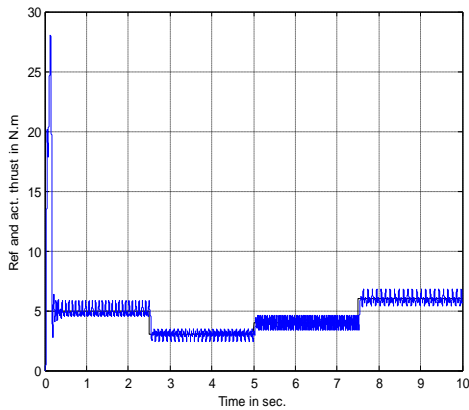


Figure (7): Ref. and actual Thrust trajectories at (5-3-4-6) N.m.

V.PROPOSED MOTION CONTROL SYSTEM OF DTC-LIM FOR A CNC MILLING MACHINE

This part investigates the application of feed-forward controller in order to control the speed and/or position of the LIM drive. The main goal of this controller is to provide the optimal 3-phase primary voltages necessary for tracking a certain position and speed reference trajectories. Moreover, constraints over the flux and current could be imposed to keep them within permissible values. There are two cascaded controllers. The first control loop is the speed controller. The inputs are the reference and actual speed trajectories, while the output is the reference thrust signal for DTC to drive the LIM. The second controller is the position controller. The inputs are the reference and actual position trajectories, while the output is the reference speed signal for the following speed controller. The Simulink block diagram showing the proposed position control system is shown in figure (8).

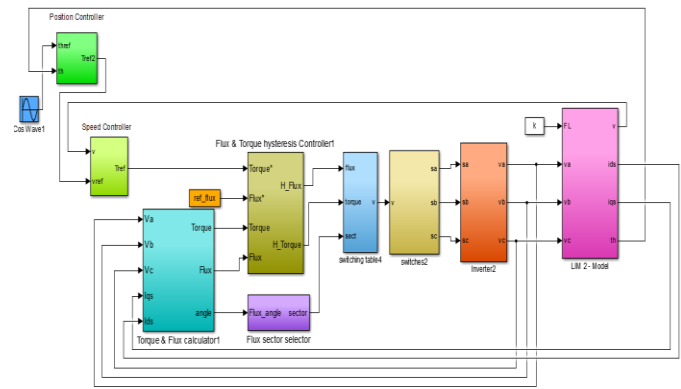


Figure (8) Proposed digital motion control system of DTC-LIM.

VI.SIMULATION RESULTS OF THE PROPOSED MOTION CONTROL SYSTEM OF DTC-LIM

Figure (9) shows the reference and actual position trajectories. The reference position is introduced as in equation (16). Figure (10) shows the reference and actual speed trajectories for the same reference position trajectory.

$$ref.pos. = \left(1 - \frac{2}{3} * \frac{t}{T_r}\right) * \left(\frac{t}{T_r}\right)^2 \quad (16)$$

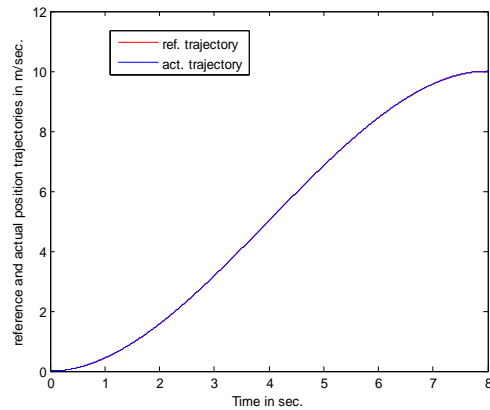


Figure (9): reference and actual position trajectories

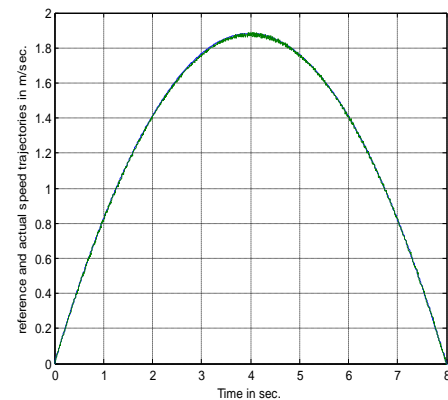


Figure (10): reference and actual speed trajectories.

VII. FUZZY LOGIC CONTROL SYSTEM OF DTC-LIM FOR A CNC MILLING MACHINE

In computer numerical control (CNC) machines, in a multi-axis motion control system that has a task of following a desired path, contouring errors arise. These errors are usually in the acceptable range in low speed applications, however they become significant in high speeds, high accuracy applications. The contouring errors have poor effect on the dimensional accuracy of the machined part, and hence the need for implementation of proper contouring controller arises [9]. So, a modified proposed an industry standard motion control system has been introduced. As in the outer loop of position, the controller has been modified and enhanced by using fuzzy logic controller (FLC) instead of a constant gain. The proposed FLC deals with the error in position trajectory, for tracking accuracy assurance. The proposed position controller is shown in figure (11). The output and input membership functions of the proposed FLC are shown in figure(12-a), figure(12-b)

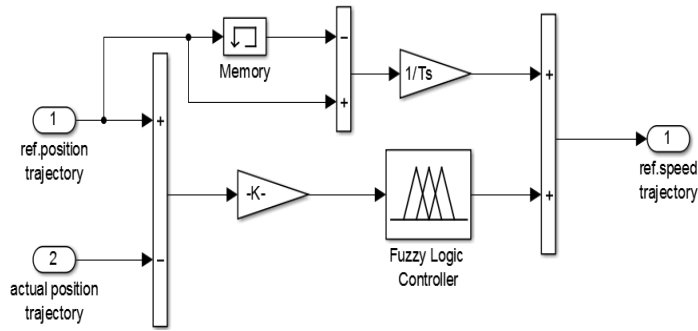


Figure (11): Proposed Fuzzy logic Position Controller.

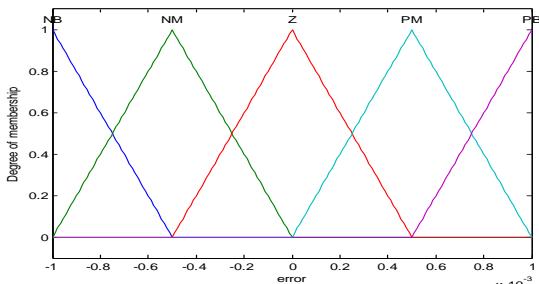


Figure (12-a): membership function for input variable.

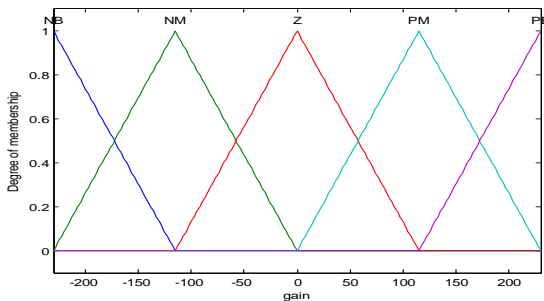


Figure (12-b): membership function for output variable.

Figure (13) shows the reference and actual position and speed trajectories for sinusoidal reference position input. Figure (14)

shows the error in the position trajectory. It is shown that the maximum tracking error is in about 15 micro-meters.

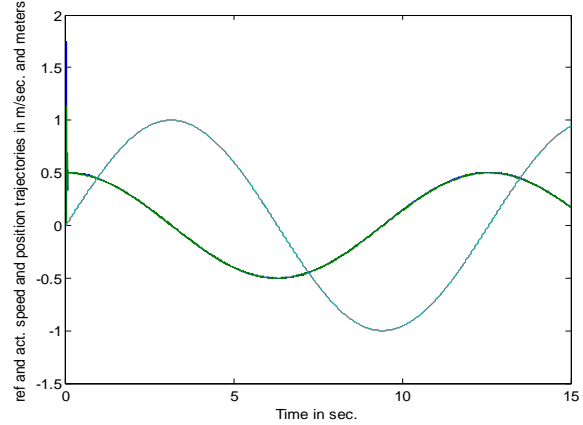


Figure (13): reference and actual position and linear velocity trajectories.

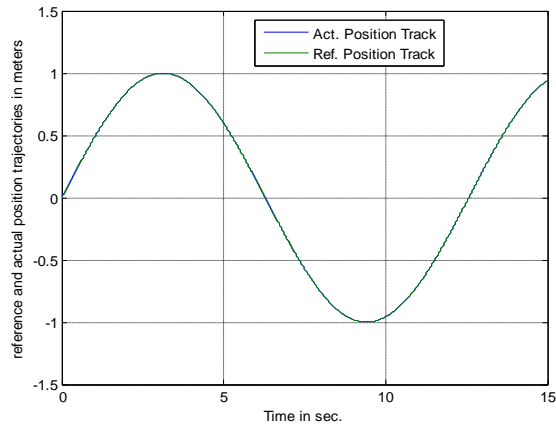


Figure (14): error in the position trajectory

A feed forward motion controller was applied to improve both the tracking accuracy and the contouring accuracy for multi-axis motion control systems as shown in figure (15). In CNC contouring control, a fast and good dynamic response is considered an important requirement, so a modified industry standard for digital motion control system driven by direct thrust controlled linear induction motors has been examined.

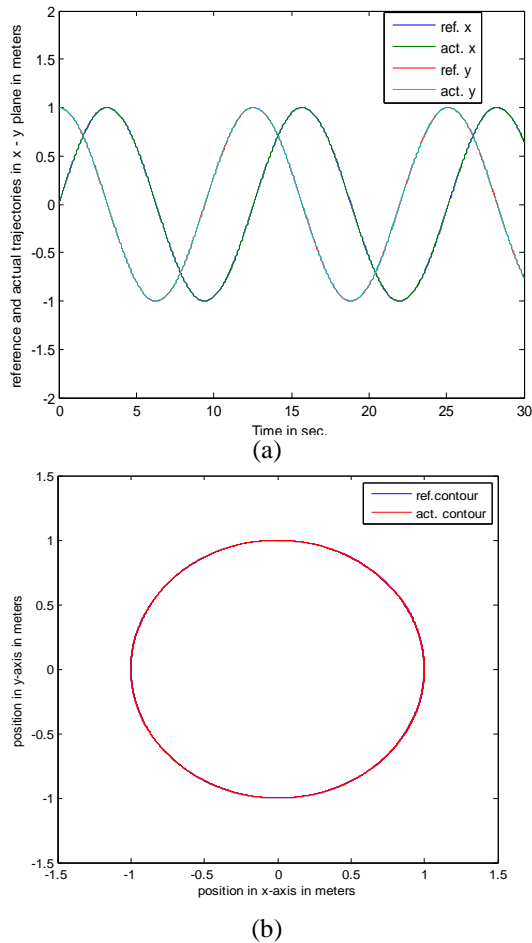


Figure 15) (a): reference and actual trajectories in x-y plane in meters, (b): ref. and actual generated contour.

CONCLUSIONS

A proposed motion control system using direct thrust controlled (DTC) linear induction motor has been introduced. The outer position loop of industry standard motion control system has been enhanced by using fuzzy logic controller instead of using fixed gain based position error. The proposed system is not only error based, but also it includes the rate of change for the error. The introduced system has been simulated, and the results proved that, the proposed system has a good tracking accuracy at different trajectories under different loading conditions, so the system can be applied in contouring control for the CNC milling machines.

REFERENCES

- i. M. Ali Usta, Omur Akyazi, A. Sefa Akpinar, 'Simulation of Direct Thrust Control for Linear Induction Motor Including End Effect', 2012 IEEE, International Symposium on Innovations in Intelligent Systems and Applications (INISTA), Trabzon, 2-4 July 2012, pp. 1-5
- ii. Emre Ozkop, A. Sefa Akpinar, Halil I. Okumus, 'Direct Torque Control for Linear Induction Motor', 12th International Middle-East Power System Conference, MEPCON, 2008, pp. 373 – 376.
- iii. A.A. Hassan, and J. Thomas, : 'Model Predictive Control of Linear Induction Motor Drive', Proceedings of the 17th World Congress, The International Federation of Automatic Control, Seoul, Korea, July 6-11, 2008, pp.10904-10909.
- iv. K. Bousserhane, A. Hazzab, M. Rahli, B. Mazari, M. Kamli, 'Position Control of Linear Induction Motor using an Adaptive Fuzzy Integral – Backstepping Controller', Serbian Journal Of Electrical Engineering Vol. 3, No. 1, June 2006, pp. 1 – 17.
- v. Cai-Xia Tao, Dan Zhang, Xiao Li, 'Thrust Control of Traction Linear Induction Motors in Switch Areas', WSEAS TRANSACTIONS on SYSTEMS and CONTROL, Volume 10, 2015, pp.16-21.
- vi. Jean Thomas and Anders Hansson, 'Speed Tracking of a Linear Induction Motor- Enumerative Nonlinear Model Predictive Control', 2013, IEEE Transactions on Control Systems Technology, (21), 5, 1956-1962.
- vii. Hala Shaban Mohamed, 'MODELING AND SIMULATION OF HYBRID ELECTRIC VEHICLE SYSTEM', PHD thesis, Cairo University, faculty of Engineering, January 2012, Cairo-Egypt.
- viii. H. Shadabi, A. Rahnama Sadat, A. Pashaei, M.B.B. Sharifian, 'Speed Control Of Linear Induction Motor Using Dtc Method Considering End-Effect Phenomenon', International Journal on Technical and Physical Problems of Engineering, December 2014 Issue 21, Volume 6, Number 4, Pages 75-81.
- ix. Edin Golubovic, Eray A. Baran, Asif Sabanovic, 'Contouring Controller for Precise Motion Control Systems', ATKAF 54(1), 19–27(2013).
- x. F. Korkmaz, I. Topaloglu, R. Gurbuz, ' Simulink Model of Vector Controlled Linear Induction Motor with End Effect for Electromagnetic Launcher System', ELEKTRONIKA IR ELEKTROTEHNIKA, ISSN 1392-1215, VOL. 20, NO. 1, 2014.
- xi. Syh-Shiuh Yeh and Jin-Tsu Sun, ' Feedforward Motion Control Design for Improving Contouring Accuracy of CNC Machine Tools', Proceedings of the International MultiConference of Engineers and Computer Scientists 2013 Vol I, IMECS 2013, March 13 - 15, 2013, Hong Kong.