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Direct electromagnetic force control of linear induction motor with end effects using fuzzy controller

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Abstract. In this article is a present dynamic model of a linen induction motor with end effects, occurs when the electromagnetic system of the motor is open. Instead of the angular speed and electromagnetic torque as a rotation motor, in the linear induction motor we have linear speed and linear electromagnetic force, which are sufficiently influenced by the open electromagnetic system of the primary and secondary elements of the linear motor. The choice of an appropriate control system for a linear induction motor is of particular importance considering the use of this type of motor in manufacturing. There are different types of control schemes for standard rotary motors that have their own advantages and disadvantages. When choosing a motor control scheme, we strive to achieve the following parameters, such as smoothness of regulation, ability to regulate in all four quadrants, accuracy of regulation, range of regulation and last but not least, simplicity of regulation. One such method that meets these criteria for rotary motors is the direct torque control method with space vector modulation. The control system of the linear induction motor proposed in this paper is based on this method, taking into account the open electromagnetic system and the occurrence of the end effects of the linear induction motor. Instead of the angular reference velocity as a rotary motor, in this case we have a linear reference velocity to the input, which is compared to the current linear velocity of the motor. The present paper also uses the vector modulation method by analogy with direct torque control with space vector modulation of the rotary motor. For the conversion of a linear velocity to a linear electromagnetic force, instead of a standard PI controller, it is using a fuzzy controller to convert a linear velocity to a reference electromagnetic force.

1 Introduction

Linear induction motors (LIM) are used in several industrial and domestic applications such as high voltage circuit breakers, mechanical pushers, and control of automatic doors, in agricultural machinery such as vibratory conveyors. They are also used in rocket construction and naval equipment. The reason for the small application of LIM is the open

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electromagnetic system that these types of motors work with which requires more precise control. When choosing a LIM control, the following requirements should be considered: wide adjustment range, accurate and fast response to the electromagnetic force and speed of the secondary element, good smoothness, and possibility for four-quadrant control of the motor [1]. The method responding to these criteria at rotary machines is known as direct torque control. This method was first proposed for standard rotary motors in [2, 3] for low and medium-power electric drives and was further introduced in [3] for high-power electric drives.

The basis of the DTC control method is the presence of two comparators. One comparator is for comparing the reference electromagnetic torque with the current electromagnetic torque, and the second comparator compares the reference flux linkage with the current value of the flux linkage obtained from the current values of the voltages and currents of the stator. The resulting differences from the electromagnetic torque, and the flux linkage are input values to the optimal switching table, which forms the control signals for the power switches of the inverter. The main advantage of DTC is the quick response of the motor to the reference torque and flux linkage. Among the disadvantages of this type of control is the difficulty in maintaining the reference values of electromagnetic torque and stator flux linkage at low motor speeds, as well as torque distortions when changing the sector in the d, q coordinate system. Electromagnetic torque ripples, on the other hand, generate noise and vibration and cause errors in sensorless electric drives [4, 9]. To reduce electromagnetic torque ripples, has a many methods to increase vectors for controlling a stator voltage. One such method is Space Vector Modulation-Direct Torque Control (SVM-DTC) [4]. There are various SVM techniques which are Direct-Reverse SVM, Direct-Direct SVM, Direct-Direct with $Vnull$=[000], and Direct-Direct with $Vnull$=[111] at industrial applications [3,5]. The choice of the SVM method depends on the reference criteria, and whether is taken into account switching losses in the inverter [8].

The purpose of this article is to investigate the SVM-DTC method for controlling a linear induction motor with end effects. For transformation, linear speed to electromagnetic force is using a fuzzy controller.

2 Materials and methods

In [7], was the purpose of a dynamic model of a linear induction motor with end effects.

The end effects of the linear motor are calculated if the add function. The following calculated as follows:

$$f(Q)=\frac{1-e^{-Q}}{Q}, \tag{1}$$

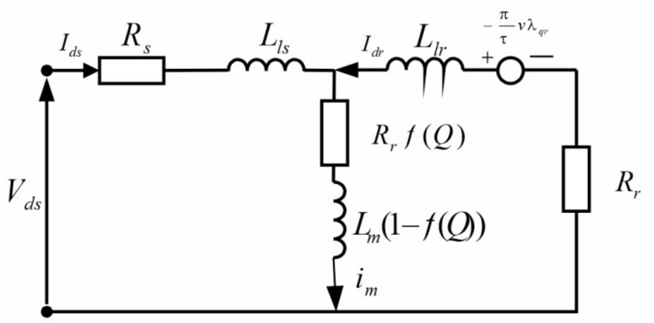
where:

$$Q=\frac{DR_r}{L_r v}, \tag{2}$$

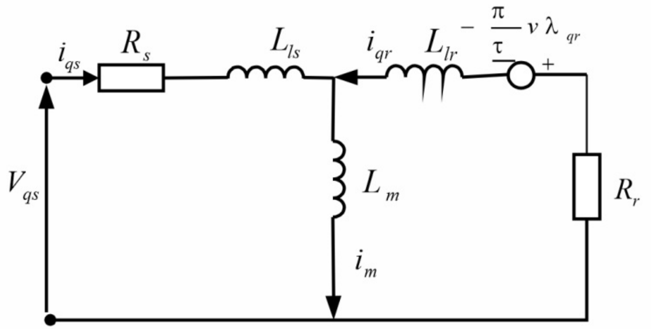
where:

D is the length of the inductor of the linear induction motor, [m];
R_r is the active resistance of the secondary elements, [Ω];
L_r is theinductive resistance of the secondary element, $[H]$;
v is the linear speed of movement of the secondary element, $[m/s]$.

The linear induction motor with end effects can be shown in the stationary frame equivalent circuit in Figure 1.



a) equivalent circuit of the *d* axes



b) equivalent circuit of the *q* axes

Fig. 1. Equivalent circuit in the stationary reference frame of the linear induction motor with the end effects.

The equations describing dynamical model in an equivalent circuit of the linear induction motor with end effects in the stationary frame have the following form [7]:

It is noticed:

$$\mathrm{L}'_{\mathrm{m}}=\mathrm{L}_{\mathrm{m}}(1-\mathrm{f}(\mathrm{Q})). \tag{3}$$

The flux linkage equations have the following form:

$$\frac{\mathrm{d}\lambda_{\mathrm{sd}}}{\mathrm{dt}}=\mathrm{V}_{\mathrm{sd}}-\mathrm{R}_{\mathrm{s}}\mathrm{I}_{\mathrm{sd}}-\mathrm{R}_{\mathrm{s}}\mathrm{f}(\mathrm{Q}).(\mathrm{I}_{\mathrm{sd}}+\mathrm{I}_{\mathrm{rd}}); \tag{4}$$

$$\frac{\mathrm{d}\lambda_{\mathrm{dr}}}{\mathrm{dt}}=-\mathrm{R}_{\mathrm{r}}\mathrm{I}_{\mathrm{dr}}-\mathrm{R}_{\mathrm{r}}\mathrm{f}(\mathrm{Q})(\mathrm{I}_{\mathrm{ds}}+\mathrm{I}_{\mathrm{dr}})-\frac{\pi}{\tau}\mathrm{v}\lambda_{\mathrm{qr}}; \tag{5}$$

$$\frac{\mathrm{d}\lambda_{\mathrm{qr}}}{\mathrm{dt}}=-\mathrm{R}_{\mathrm{r}}\mathrm{I}_{\mathrm{qr}}+\frac{\pi}{\tau}\mathrm{v}\lambda_{\mathrm{dr}}. \tag{6}$$

The flux linkage of linear induction motor can be represented by:

$$\lambda_{\mathrm{ds}}=\mathrm{L}_{\mathrm{ls}}\mathrm{I}_{\mathrm{ds}}+\mathrm{L}'_{\mathrm{m}}(\mathrm{I}_{\mathrm{ds}}+\mathrm{I}_{\mathrm{dr}}); \tag{7}$$

$$\lambda_{\mathrm{qs}}=\mathrm{L}_{\mathrm{ls}}\mathrm{I}_{\mathrm{qs}}+\mathrm{L}_{\mathrm{m}}\left(\mathrm{I}_{\mathrm{qs}}+\mathrm{I}_{\mathrm{qr}}\right); \tag{8}$$

$$\lambda_{\mathrm{dr}}=\mathrm{L}_{\mathrm{lr}}\mathrm{I}_{\mathrm{dr}}+\mathrm{L}'_{\mathrm{m}}(\mathrm{I}_{\mathrm{ds}}+\mathrm{I}_{\mathrm{dr}}); \tag{9}$$

$$\lambda_{\mathrm{qr}}=\mathrm{L}_{\mathrm{lr}}\mathrm{I}_{\mathrm{qr}}+\mathrm{L}_{\mathrm{m}}\left(\mathrm{I}_{\mathrm{qs}}+\mathrm{I}_{\mathrm{qr}}\right). \tag{10}$$

The electromagnetic force calculated by the following formula:

$$\mathrm{F}_{\mathrm{e}}=\frac{3}{2}\frac{\pi}{\tau}\frac{\mathrm{p}}{2}\left(\lambda_{\mathrm{ds}}\mathrm{I}_{\mathrm{qs}}-\lambda_{\mathrm{qs}}\mathrm{I}_{\mathrm{ds}}\right). \tag{11}$$

The current I_{ds} is express from equation (7), the current I_{dr} is express from equation (9), I_{qs} is express from (8), and I_{qr} is express from (10) respectively:

$$\mathrm{I_{ds}} = \frac{\lambda_{\mathrm{ds}} - \mathrm{L'_m I_{dr}}}{\mathrm{L_{lr}} + \mathrm{L'_m}}; \tag{12}$$

$$\mathrm{I_{dr}} = \frac{\lambda_{\mathrm{dr}} - \mathrm{L'_m I_{ds}}}{\mathrm{L_{lr}} + \mathrm{L'_m}}; \tag{13}$$

$$\mathrm{I_{qs}} = \frac{\lambda_{\mathrm{qs}} - \mathrm{L_m I_{qr}}}{\mathrm{L_s}}; \tag{14}$$

$$\mathrm{I_{qr}} = \frac{\lambda_{\mathrm{qr}} - \mathrm{L_m I_{qs}}}{\mathrm{L_r}}. \tag{15}$$

If we substitute (13) into (12), and after conversion we receive:

$$\lambda_{\mathrm{ds}} = \frac{(\mathrm{L_r} - \mathrm{L_m f((Q))}\lambda_{\mathrm{ds}} - \mathrm{L_m}(1 - \mathrm{f(Q)})\lambda_{\mathrm{dr}}}{\big(\mathrm{L_s} - \mathrm{L_m f(Q)}\big)\big(\mathrm{L_r} - \mathrm{L_m f(Q)}\big) - \mathrm{L_m^2}(1 - \mathrm{f(Q)})^2}. \tag{16}$$

If we substitute (12) into (13), and after conversion we receive:

$$\lambda_{\mathrm{dr}} = \frac{(\mathrm{L_s} - \mathrm{L_m f((Q))}\lambda_{\mathrm{dr}} - \mathrm{L_m}(1 - \mathrm{f(Q)})\lambda_{\mathrm{ds}}}{\big(\mathrm{L_s} - \mathrm{L_m f(Q)}\big)\big(\mathrm{L_r} - \mathrm{L_m f(Q)}\big) - \mathrm{L_m^2}(1 - \mathrm{f(Q)})^2}. \tag{17}$$

Analogously we receive the following expressions for λ_{qs} and λ_{qr}

$$\lambda_{\mathrm{qs}} = \frac{\mathrm{L_r}\lambda_{\mathrm{ds}} - \mathrm{L_m}\lambda_{\mathrm{dr}}}{\mathrm{L_s L_r} - \mathrm{L_m^2}}; \tag{18}$$

$$\lambda_{\mathrm{qs}} = \frac{\mathrm{L_r}\lambda_{\mathrm{qs}} - \mathrm{L_m}\lambda_{\mathrm{qr}}}{\mathrm{L_s L_r} - \mathrm{L_m^2}}. \tag{19}$$

The equations for motion can be expressed by formula:

$$\frac{\mathrm{dv}}{\mathrm{dt}} = \frac{1}{\mathrm{m}}(\mathrm{F_e} - \mathrm{F_{load}}). \tag{20}$$

The system of equations (1-20) described a dynamical model of a linear induction motor with end effects.

The direct torque control method is a strategy quite different in comparison of Field Oriented Control and does not need additional coordinate transformations [3, 4]. On Figure 2 is presented the schematic diagram of DTC-SVM.

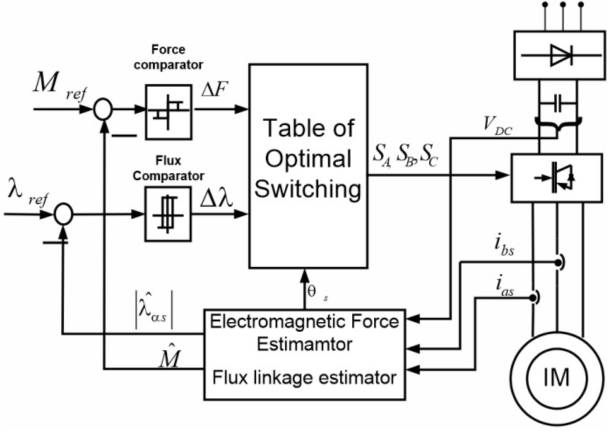


Fig. 2. Principal schematic for control of induction motor by method DTC-SVM.

On the base of the schematic diagram shown in Figure 2 in the present paper can construct a similar control scheme for a linear induction motor with end effects consideration with a fuzzy logic controller, which is shown in Figure 3.

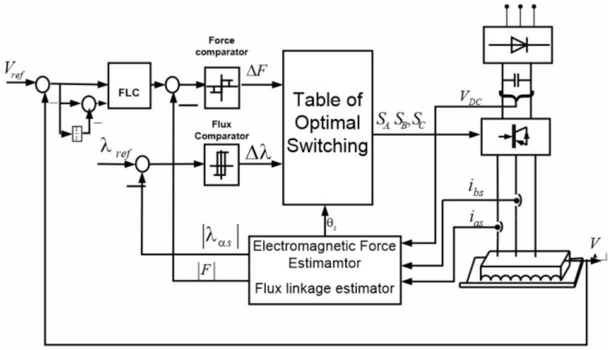


Fig. 3. Principal schematic of DTC of linear induction motor

The formulas for calculating the blocks shown in Figure 3 are:
The stator voltages and currents are calculated as:

$$\mathrm{V_{sd}} = \frac{2}{3}\mathrm{V_{dc}}\left(\mathrm{S_A} - \frac{\mathrm{S_B}+\mathrm{S_C}}{2}\right); \quad (21)$$

$$\mathrm{V_{sq}} = \frac{1}{\sqrt{3}}\mathrm{V_{dc}}(\mathrm{S_A} - \mathrm{S_C}); \quad (22)$$

$$\mathrm{I_{sd}} = \mathrm{I_{SA}}; \quad (23)$$

$$\mathrm{I_{sq}} = \frac{\mathrm{I_{SA}}+2.\mathrm{I_{SB}}}{\sqrt{3}}. \quad (24)$$

The flux linkage and electromagnetic force estimator can be calculated as:

$$\lambda_{\mathrm{sd}} = \int(\mathrm{V_{sd}} - \mathrm{R_s}\mathrm{I_{sd}})\mathrm{dt}; \quad (25)$$

$$\lambda_{\mathrm{sq}} = \int(\mathrm{V_{sq}} - \mathrm{R_s}\mathrm{I_{sq}})\mathrm{dt}. \quad (26)$$

With the following equation can be calculated the angle between the stator flux linkage:

$$\theta = \mathrm{arctg}\left(\frac{\lambda_{\mathrm{sq}}}{\lambda_{\mathrm{sd}}}\right), \quad (27)$$

where the magnitude is:

$$|\lambda_{\mathrm{s}}| = \sqrt{\lambda_{\mathrm{sd}}^2 + \lambda_{\mathrm{sq}}^2}, \quad (28)$$

where:
$\mathrm{V_{sd}}, \mathrm{V_{sq,}}, \mathrm{I_{sd}}, \mathrm{I_{sq}}$ is the projection of the main vectors of currents and tensions of the inductor in the stationary reference frame;
$\mathrm{V_{dc}}$ is the value of the DC voltages of the invertor;
$\mathrm{I_{sA}}, \mathrm{I_{sB}}, \mathrm{I_{sC}}$ are phases currents of the three phases inductor of linear induction motor;
$|\lambda_{\mathrm{s}}|$ is the module of the main vector of the flux linkage of inductor;
$\lambda_{\mathrm{sd}}, \lambda_{\mathrm{sq}}$ are the projection of the vector the main flux linkage of the inductor;
θ is the phase angle of the vector the main flux linkage of the inductor;
$\mathrm{R_s}$ is the active resistance of inductor;
$\mathrm{S_A}, \mathrm{S_B}, \mathrm{S_C}$ are the switching state of voltage source invertor;

Table 1 shown below is named the table for optimal switches. This table forms the control signals of the inverter power switches (Figure 4).

Table1. Table of optimal switches.

Times	**Force error position**	**Sectors**					
		I	**II**	**III**	**IV**	**V**	**VI**
ΔF	− 1	V_2	V_3	V_4	V_5	V_6	V_1
	0	V_7	V_0	V_7	V_0	V_7	V_0
	1	V_6	V_1	V_2	V_3	V_4	V_5
$\Delta\lambda$	− 1	V_3	V_4	V_5	V_6	V_1	V_2
	0	V_0	V_7	V_0	V_7	V_0	V_7
	1	V_5	V_6	V_1	V_2	V_3	V_4

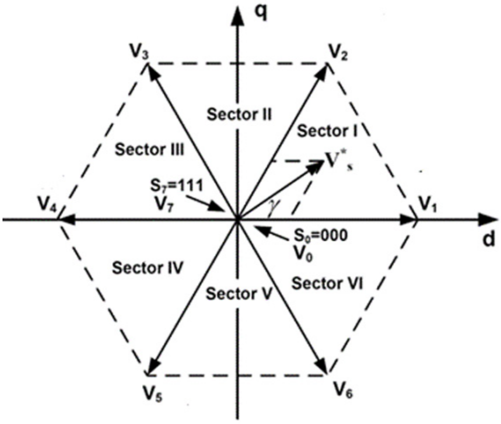
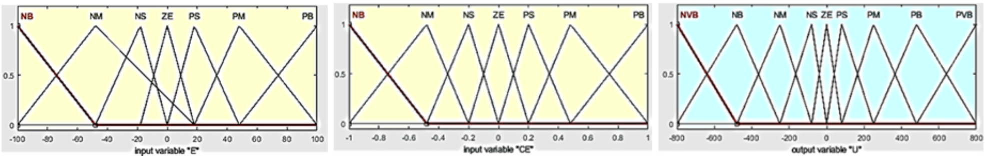


Fig. 4. Voltage space vector position.

The functions defining the fuzzy controller [1, 5] have the following linguistic definitions: PVB is positive very large; PB is positive big; PM is positive medium; PS is positive small; Z is zero; NS is negative small; NM is negative medium; NB is negative big and NVB is negative very big (Table 2 and Figure 5).

Table 2. Fuzzy control rules of the speed of LIM.

E / **CE**	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
N	NV	NV	NV	N	N	NS	Z
N	NV	NV	N	N	NS	Z	S
NS	NV	N	N	NS	Z	S	
Z	N	N	NS	Z	S		B
S	N	NS	Z	S			V
	NS	Z	S			V	V
	Z	S			V	V	V



a) b) c)

Fig. 5. Fuzzy membership functions for tuning (a) Error, (b) Error variation, (c) Control of the output signal.

3 Results

The following model is verified by simulation program Sim Power System. The data of linear induction motor are:
$P_H = 8\,kW; U_H = 400\,V; R_s = 1.25\,\Omega; R_r = 2{,}7; L_s = 40{,}1\,e-3\,H;\ L_r = 33{,}1\,e-3\,H;\ L_m = 32{,}6\,e-3\,H\ ;\ tau = 0{,}066\,m;\ p = 4;\ D = 0{,}286\,m;\ m = 8\,kg.$

Figure 6 shows the speed reference value that is set to the electric drive shown in the figure with the blue colour and has the following values from:

- 0 to 0.15 s-0 m/s;
- 0.15 to 1.40 with steady acceleration up to 5 m/s;
- 1.40 s to 2.5 with a steady state speed of 5 m/s;
- 2.5s to 3.35 with steady deceleration to a speed of 1.8m/s;
- 3.35 s to 4 with a steady linear speed of 1.7 m/s;

The actual resulting speed of the linear induction motor is shown in orange (Figure 6).

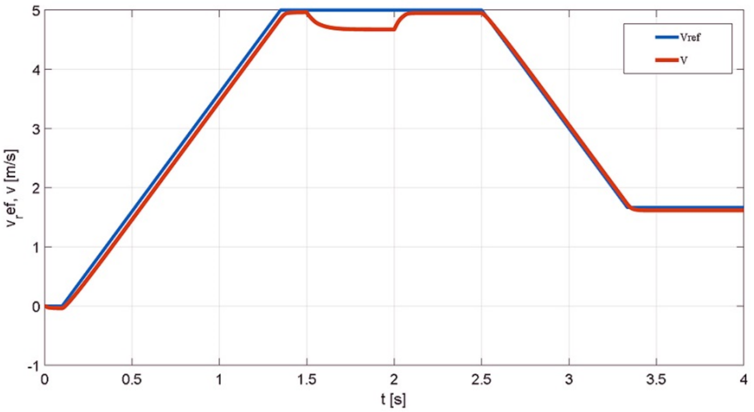


Fig. 6. Linear speed of the LIM.

From the results obtained in LIM linear speed results, it can be seen that the speed of the secondary element follows the reference value of the electric drive (Figure 7). A deviation from the reference value occurs when there is a sudden change in the load on the system, and the maximum deviation is up to 4.68 m/s, and it is due to the sudden change in the load on the linear motor.

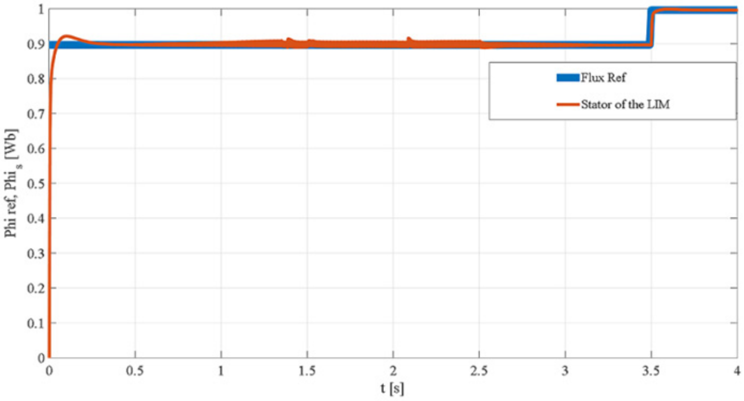
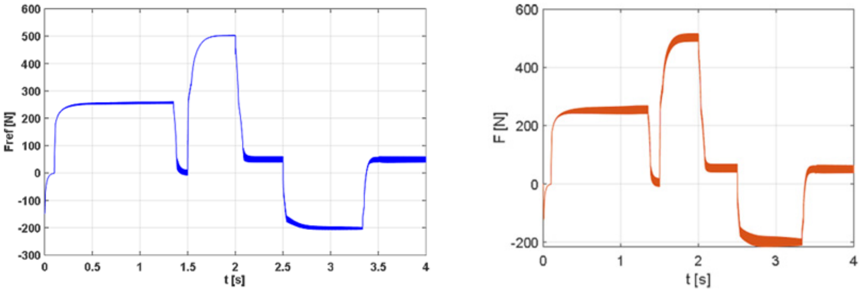


Fig. 7. Reference inductor flux linkage, and flux linkage of the LIM.

Figure 8 shows the reference inductor flux shown in blue and the resulting flux shown in orange. of the inductor of the linear motor. It can be seen from the graph that the current flux follows the set value without deviation.



(a) (b)

Fig 8. Electromagnetic force reference (a), and electromagnetic force (b) of the LIM.

4 Discussions

From the results obtained in LIM linear speed results on the fig. 6, it can be seen that the speed of the secondary element follows the reference value of the electric drive. A deviation from the reference value occurs when there is a sudden change in the load on the system, and the maximum deviation is up to 4.68 m/s, and it is due to the sudden change in the load on the linear motor.

Figure 7 shows the reference inductor flux shown in blue and the resulting flux shown in orange of the inductor of the linear motor. It can be seen from the graph that the current flux follows the set value without deviation.

Figure 8 shows in blue shows the load of linear induction motor, and orange the linear electromagnetic force of the motor.

From the obtained results, can be summarized that the electromagnetic linear force of the linear induction motor follows the resistance with which the linear asynchronous motor is loaded. The electromagnetic force follows the load (deviation is less than ±15 N), and ripples of the electromagnetic force is very small.

The verification by the proposed method SVM-DTC with fuzzy regulator for Linear induction motor with end effects shows that:

1. The speed of the secondary element follows the reference value of the electric drive. A deviation from the reference value occurs when there is a sudden change in the load on the system, and the maximum deviation is up to 4.68 m/s, and it is due to the sudden change in the load on the linear motor.
2. The inductor flux linkage of the linear induction motor follows the reference flux linkage without deviation.
3. The ripples of the electromagnetic force are negligible and relatively smaller compared to the standard DTC-SVM methods with a conventional PI regulator. The deviation between the load of the linear induction drive and the electromagnetic force of the drive is not greater than ±15 N.

5 Conclusion

The simulation results confirm that the proposed method achieves the reduction of flow waves and electromagnetic force with a minimum and gives a fast linear velocity response.

This method minimizes the end effects of the linear induction motor, hence the electromagnetic losses. This is evident from the electromagnetic flux linkage of the secondary element and the small ripples $\pm 15\ N$ of the electromagnetic force.

The speed of the secondary element follows without deviation the reference speed to the control system. Small deviations in the assignment are only noticeable with a sudden change in load (deviation is less $4{,}68\ m/s$).

Fuzzy DTC-SVM with stator flux estimation control algorithm gives an excellent solution for linear induction motor drives.

A future research task is to study the behaviour of the current linear induction motor control system when using a flexible load or a specific drive system.

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