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Research paper

Independent Fuzzy Logic Control of Two Five-phase Linear Induction Motors Supplied from a Single Voltage Source Inverter

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Abstract

Background and Objectives: The principal aim of this paper is to show an independent vector control of two five-phase Linear Induction Motors (LIMs) that are supplied from a single VSI.

Methods: The LIMs are running at the same speed but with different load conditions. This concept can be especially beneficial in long trains with distributed power. To achieve excellent control characteristics and to reduce the undesirable tension forces between the train mechanical couplers, Fuzzy Logic Controllers (FLCs) have been utilized.

Results: As a result, the fault occurrence of the train control systems decreases, and the system reliability increases. The results prove the electrical independence in control of a five-phase two-LIM drive supplied with a single VSI. Furthermore, in the presence of the train mechanical couplers and connections, the application of FLC offers excellent control characteristics and reduces the undesirable tension forces. Furthermore, to obtain a more worthwhile validation of the theoretical results, an experimental set up has been constructed and results have also been presented.

Conclusion:
According to the results, the undesirable tension forces imposed on train couplers are reduced. Consequently, it leads to higher system efficiency, lower deterioration of the train couplers and connections, greater system reliability, and higher passenger safety and comfort.

Introduction

Due to the utilization of Voltage Source Inverters (VSIs), multiphase motors (with more than three phases) can be controlled in electrical motor drives. Multiphase motor drives offer significant benefits in comparison with three-phase machines [1]-[2]. The significant advantages of multiphase motors are greater torque density, higher efficiency, less torque pulsation, more fault tolerance, and lower required rating per inverter leg (and consequently simpler and more reliable power conditioning equipment) [3]. Furthermore, in vector control applications, multiphase motors need only two current components. As a result, the extra degrees of freedom could be used for controlling independently other multiphase motor drives [3]-[5]. This can be obtained if stator windings of the multiphase motors are properly transposed and then, connected in series. Accordingly, an independent (Indirect Field Oriented

Control) IFOC of multiple multiphase motors can be performed using only one inverter [3]-[5]. The principal privilege of this idea is decreasing the number of inverter arms.

This idea can be applied for all multiphase ac machine types. But the most work in the field of multiphase ac motors is concentrated on ac rotational motors [1]-[19]. As a result, this work is concentrated on controlling multiphase linear induction motors that have more than three phases. Three-phase LIM drives are utilized in various industries, such as railway transport systems, because of the benefits they offer. Consequently, precise modeling of the LIM, which is appropriate for IFOC applications, is essential. Extracting and analyzing an equivalent circuit model is a less complicated solution for a LIM. But since the end effect phenomena exist, extracting the accurate equivalent circuit model of a LIM is more complex than a rotational induction machine. Duncan proposed a per-phase equivalent circuit model for the LIM [20]. It was a modified version of the per-phase equivalent model of the rotational induction motor. For considering the end effect, the magnetizing inductance was appropriately changed with a coefficient opposite to the speed [20]. In [21], the dynamic model of the three-phase LIM was derived according to Duncan's model. This dynamic model has been utilized in the IFOC of three-phase LIMs [22]-[24]. But in this model, only the end effect has been included only in the direct axis circuit model, and the quadrature axis circuit model was not modified. In [25], the presented model of [21] has been modified, and a new dynamic equivalent circuit model has been proposed for three-phase LIM in which the end effect was taken into account in both direct and quadrature axes. This model was extracted by applying Park's transformation to Duncan's per-phase model. In [26], the dynamic model of the multiphase LIMs was proposed taking into account the end effect.

Additionally, in the field of control strategies of the three-phase LIM, several investigations have been reported in the literature. A well-known control method that has been extensively utilized for three-phase LIM drive applications is the IFOC method [26]. The principal purpose of the IFOC for LIM drive is to decouple the flux and thrust. Accordingly, the secondary flux vector of the LIM is aligned to the d-axis. To achieve this purpose, the d-axis secondary flux must be set to the nominal flux, and the q-axis secondary flux must be considered equal to zero [23]-[26].

According to the above mentioned, the main scope of this paper is the independent IFOC of multiple multiphase LIMs supplied through a single VSI, which could have beneficial advantages especially for transportation applications. For this reason, two five-phase LIMs have been considered, which should run at the same speed but with various load conditions physically imposed on different parts of a long train with distributed power. Fuzzy Logic Controllers (FLCs) have been utilized to achieve excellent control characteristics and to reduce the unwanted forces imposed on the train couplers in practice. The remainder of this paper is organized as follows.

This paper is structured as follows. In the next section, the dynamic model of the n-phase LIM is given with the end effect consideration. Next, the suitable phase transposition is presented by which the multiphase primary windings of a five-phase two-LIM drive can be connected in series. Then, the control scheme based on the mentioned five-phase two-LIM drive is illustrated. After that, the main advantages of the electrical independence in control of multi-phase multi-motor drive for traction applications will be discussed. Then, the designed fuzzy logic controller will be introduced. Some simulation results are provided for a five-phase two-LIM drive in the next section. Finally, the experimental results are provided for two five-phase LIMs with series connection. At the end, the conclusion is presented.

Mathematical Modeling of the Five-Phase LIM

Fig. 1 illustrates a simplified version of Duncan's per-phase model for a LIM. In the traditional model, a resistance was connected in a series with the magnetizing branch that represented the eddy current loss caused by the end effect [28]. For simplicity, this eddy current loss is ignored in this work [25]-[26]. To consider the end effect, a coefficient Q was utilized in Duncan's model [26]-[27]:

$$Q \cong \frac{T_v}{T_r} = \frac{D.R'_r}{L'_r.v_r} \tag{1}$$

In which D and v_r are the LIM length and speed, respectively [20]. In addition, L'_r and R'_r are the self-inductance and resistance of the secondary, respectively [20].

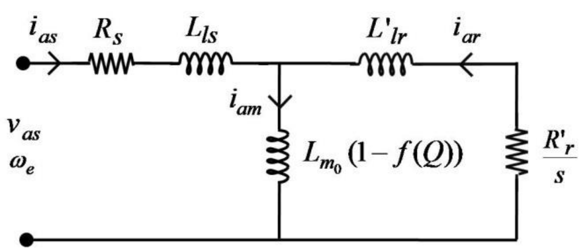

Fig. 1: The per-phase equivalent circuit model of LIM [26].

$T_r = L'_r / R'_r$ represents the secondary time constant. Also, T_v denotes the transmission time of the primary through the secondary. Because the end effect depends on the LIM speed, the magnetizing inductance has been changed to $L_m = L_{m_0}(1 - f(Q))$, in which the coefficient Q can be calculated from (1), and f(Q) can be defined as $f(Q) = \left(1 - e^{-Q}\right)/Q$ [20]. Moreover, when LIM is not moving, $f(Q) = 0$ and the magnetizing inductance will be equal to the traditional magnetizing inductance (L_{m_0}).

By applying Park's transformation to Duncan's model, the dynamic voltage and flux equations of the five-phase LIM can be derived as follows [26]:

Primary voltage equations:

$$
\begin{aligned}
v_{qs} &= R_s i_{qs} + \omega \lambda_{ds} + p\lambda_{qs} \\
v_{ds} &= R_s i_{ds} - \omega \lambda_{qs} + p\lambda_{ds} \\
v_{xs} &= R_s i_{xs} + p\lambda_{xs} \\
v_{ys} &= R_s i_{ys} + p\lambda_{ys} \\
v_{0s} &= R_s i_{0s} + p\lambda_{0s}
\end{aligned} \tag{2}
$$

Secondary voltage equations:

$$
\begin{aligned}
v_{qr} &= R'_r\, i_{qr} + (\omega - \omega_r)\lambda_{dr} + p\lambda_{qr} = 0 \\
v_{dr} &= R'_r\, i_{dr} - (\omega - \omega_r)\lambda_{qr} + p\lambda_{dr} = 0 \\
v_{xr} &= R'_r\, i_{xr} + p\lambda_{xr} = 0 \\
v_{yr} &= R'_r\, i_{yr} + p\lambda_{yr} = 0 \\
v_{0r} &= R'_r\, i_{0r} + p\lambda_{0r} = 0
\end{aligned} \tag{3}
$$

Primary flux linkage equations:

$$
\begin{aligned}
\lambda_{qs} &= L_{ls} i_{qs} + L_m \{1 - f(Q)\}(i_{qs} + i_{qr}) \\
\lambda_{ds} &= L_{ls} i_{ds} + L_m \{1 - f(Q)\}(i_{ds} + i_{dr}) \\
\lambda_{xs} &= L_{ls} i_{xs} \\
\lambda_{ys} &= L_{ls} i_{ys} \\
\lambda_{0s} &= L_{ls} i_{0s}
\end{aligned} \tag{4}
$$

Secondary flux linkage equations:

$$
\begin{aligned}
\lambda_{qr} &= L'_{lr}\, i_{qr} + L_m \{1 - f(Q)\}(i_{qs} + i_{qr}) \\
\lambda_{dr} &= L'_{lr}\, i_{dr} + L_m \{1 - f(Q)\}(i_{ds} + i_{dr}) \\
\lambda_{xr} &= L'_{lr}\, i_{xr} \\
\lambda_{yr} &= L'_{lr}\, i_{yr} \\
\lambda_{0r} &= L'_{lr}\, i_{0r}
\end{aligned} \tag{5}
$$

In which $p \equiv d/dt$. Also, ω_r and ω represent the angular velocity of the LIM and the reference frame. Note that the above equations represent the LIM model in the rotational reference frame.

The five-phase LIM thrust can be written as:

$$
F = \frac{5}{2}\frac{\pi}{\tau}\left(\lambda_{qr} i_{dr} - \lambda_{dr} i_{qr}\right) \tag{6}
$$

where τ represents the motor pole pitch.

Series Connection of Two Five-Phase Primary Windings [4]-[5]

The vector control diagram of a multiphase LIM requires just a pair of primary q-d current components. Therefore, for controlling other multiphase motors, the remaining current components could be utilized. Overall, in an n-phase LIM, with an odd number of phases, $(n-1)/2$ pairs of primary current components exist. Consequently, $(n-1)/2$ multiphase LIMs can be independently controlled. To achieve this purpose, the primary windings of the LIMs must be connected in series, with a proper phase displacement, in a way that the thrust producing current components of each LIM cannot generate thrust in other motors. Consequently, the independent speed control of $(n-1)/2$ LIMs can be performed supplied through a single VSI. In a five-phase drive, two LIMs could be independently controlled. For a five-phase two-LIM drive, the suitable phase transposition utilized for connecting the primary windings in series (called connectivity matrix) is given in Table 1 [4]-[5]. Fig. 2 shows the connection scheme of two five-phase LIMs. The notations A, B, C, D, and E represent the VSI phases. The notations a, b, c, d, and e stand for the LIM primary phases. The notations 1, and 2 represent the machine numbers.

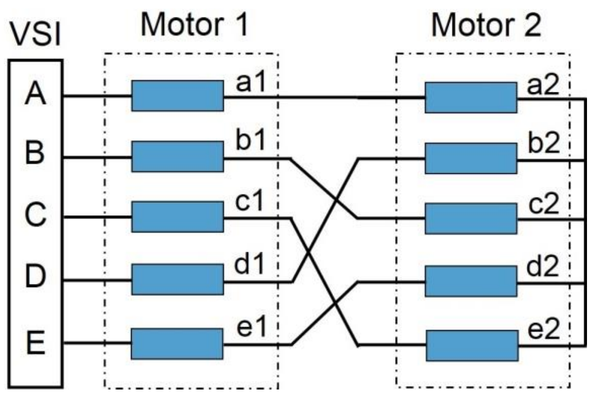

Fig. 2: Connection scheme of a two five-phase LIM system.

Table 1: Connection matrix of a two five-phase LIM system

	A	B	C	D	E
LIM1	a1	b1	c1	d1	e1
LIM2	a2	c2	e2	b2	d2

Control Method

The IFOC of LIM in the synchronous reference frame, the reference frame is aligned to the secondary flux and $\omega=\omega_e$ is considered. For decoupling between the flux and the trust, the secondary linkage flux and the direct axis are aligned with each other. Subsequently [26]:

$$\lambda_{qr}=0 \quad , \quad \frac{d\lambda_{qr}}{dt}=0 \tag{7}$$

Considering $v_{qr}=v_{dr}=0$, the slip frequency ($\omega_{sl}\equiv\omega_e-\omega_r$) is be calculated from (3) and (5) and with the elimination of i_{qr} as:

$$\omega_{sl}=R'_r\left[\frac{1-f(Q)}{\frac{L'_{lr}}{L_m}+(1-f(Q))}\right]\times\frac{i_{qs}}{\lambda_{dr}} \tag{8}$$

From (3) and (5) and after elimination of i_{dr}, the d-axis secondary flux (λ_{dr}) will be written as:

$$\lambda_{dr}=\frac{L_m(1-f(Q))}{1+\left\{\frac{L'_{lr}+L_m(1-f(Q))}{R'_r}\right\}p}\times i_{ds} \tag{9}$$

The motor thrust can be derived and written as [26]:

$$F=\frac{5}{2}\frac{\pi}{\tau}\frac{L_m(1-f(Q))}{L'_{lr}+L_m(1-f(Q))}\lambda_{dr}i_{qs} \tag{10}$$

In Fig. 3, the IFOC diagram of the five-phase LIM drive is depicted. The end effect is considered in the LIM model and the IFOC scheme [26], [28]. In the IFOC diagram, a speed controller and a current controller are utilized.

The speed controller applies the error between the reference and actual speed to a PI controller, and thus, the commend q-axis primary current (i_{qs}^*) is produced. Using (9), the command d-axis primary current (i_{ds}^*) can be computed with respect to the rated d-axis secondary flux (λ_{dr}^*) [28]. The gains K1 and K2 in the IFOC diagram are dependent to f(Q) and LIM speed, and are derived from (8) and (9). After calculating the q-d axis current commands, the phase current commands are produced using inverse Park's transformation [28]. Due to the existence of the current control loop, the LIM actual currents track the command currents, and accordingly, the switching pulses for the inverter will be produced. In the first step, this IFOC diagram is utilized for each of the five-phase LIM drives, and the required command currents for each LIM will be produced. But, in a five-phase two-LIM drive system, the primary windings are connected in series. Therefore, in the next step, the overall command currents must be calculated and utilized in the current control loop.

In a five-phase two-LIM drive, the phase current references of the two motors can be determined according to the connection diagram of Fig. 3 as follows [3]-[4]:

$$\begin{aligned}&i_A^*=i_{a1}^*+i_{a2}^* \ , \ i_B^*=i_{b1}^*+i_{c2}^* \ , \ i_C^*=i_{c1}^*+i_{e2}^*\\&i_D^*=i_{d1}^*+i_{b2}^* \ , \ i_E^*=i_{e1}^*+i_{d2}^*\end{aligned} \tag{11}$$

For simulation, it is supposed that the VSI with current control loop is considered as a current source. Therefore, the current references of (11) are supposed equal to the phase currents of VSI [4].

Inverter phase voltages can be obtained with the proper summation of primary phase voltages of the series connected LIMs [4]. Thus, for the five-phase drive, the inverter phase voltages are as follows [4]-[5]:

$$\begin{aligned}&v_A=v_{a1}+v_{a2} \ , \ v_B=v_{b1}+v_{b2} \ , \ v_C=v_{c1}+v_{c2}\\&v_D=v_{d1}+v_{d2} \ , \ v_E=v_{e1}+v_{e2}\end{aligned} \tag{12}$$

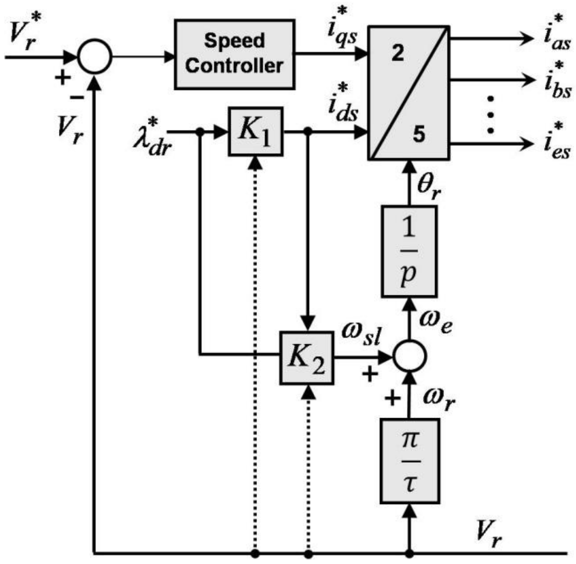

Fig. 3: IFOC scheme of the five-phase LIM.

Electrical Independent Control of Multiphase Multi-machine Drive for Traction Application

As mentioned before, multiphase motors possess extra degrees of freedom, making them suitable for the multimotor independent control applications. Among lots of interesting reported utilizations for multiphase machines, a significant usage that is worthy enough to achieve more considerations and investigations is the application of independent multiphase machines in traction applications, particularly in long trains with distributed power. Significant benefits obtained from the application of multiphase motors in the electrical railway industry are as follows:

1) In railway transportation, distributed power refers to the placing and distributing railway locomotives throughout the length of a train, remotely controlled from the leading locomotive. To achieve this purpose, the locomotives should be equipped with extra radio network equipment and sophisticated control apparatus called locotrol. Independent control of multiple motors and locomotives with a single VSI can be a suitable solution, installed in parallel with the locotrol systems (or as a replacement, if properly developed). It results in the reliability increment of the train control systems, especially when the fault occurrence of radio network equipment has more probability or when the communication network signals are affected by noise and disturbances.

2) The electrical independence in control of multi-machines will decrease the mechanical tension forces of the couplers and connections used to connect rolling stocks in a train. In long trains, this factor becomes considerable because various parts of a long train can be affected by different forces like railroad slope and centrifugal force. Independent control of multi-machines helps to decrease the mechanical stresses of the train couplers and so reduces the couplings destructions. The main resultant is more system reliability and a longer lifetime.

3) A significant benefit of multiphase machines is the reduction of thrust pulsations. In transportation systems, this feature can be of great importance because the reduction of motor thrust pulsations decreases the train thrust pulsations, which itself reduces the force vibrations of the passengers and thus improves passenger safety and comfort.

4) Profiting from all other remarkable advantages offered by multiphase machines, in compare with the three-phase motors. For example, lower current rating per inverter leg and more reliability in the power delivery [5] which will be significant in high power applications.

The main drawback of this concept is the limitation in the number of independent controlled machines. Because the series connection of primary windings, the currents flow through the primary windings of other motors. Thus, the ohmic losses of the primary windings will increase [5]. Therefore, it should be a compromise between the machine numbers and the winding losses.

Based on the previous discussions, the principal goal of this paper is to represent an IFOC of two five-phase linear induction motors that are fed through only one current-controlled VSI. Both LIMs are running with the same reference speed but with different load conditions, which refer to the various external forces imposed on different parts of a long train.

It is worth noting that both five-phase LIMs can be controlled simultaneously and independently from each other if rigid mechanical connections do not exist between the train compartments. Hence, the proposed method only ensures the electrical independence of the machines. However, in practice, because of mechanical couplers and connections used to connect railway rolling stocks in a train, mechanical dependence cannot be avoided. Therefore, the speed response and the produced thrust of each machine are affected by the loading conditions and external forces of the other machine. The mechanical couplings moderate the thrust variations of the tractions and thus, restrict the railway rolling stock parts to run only at the same equivalent speed. The equivalent speed of the train can be calculated using Newton's second law of motion, as follows:

$$F_T = \sum_{i=1}^{\frac{n-1}{2}} F_i = M_T \frac{dV_{eq}}{dt} \tag{13}$$

$$V_{eq} = \frac{1}{M_T} \int_{t_1}^{t_2} F_T \, dt \tag{14}$$

where M_T is the total mass of the train and V_{eq} is the final equivalent speed of the train. F_T is the resultant train force and can be evaluated according to Newton's first law and F_i is the developed thrust of the i-th machine. n is the phase numbers and $(n-1)/2$ is the machine numbers that can be independently controlled. In transient operating conditions of the drive, the undesirable tension forces imposed on the train mechanical couplers reach the maximum. These unwanted tension forces reduce the overall system efficiency and prevents the deterioration of the train couplers and connections with the lapse of time.

As the next step in this work, to modify the dynamic tracking response and decrease the tension forces of the proposed *n*-phase multi-LIM drive, the PI regulators are replaced by fuzzy logic controllers. The result is fewer overshoots and undershoots in the speed response and faster and smoother tracking responses of the five-phase two-LIM drive. Moreover, the force variations of the train, imposed on the train couplers, will be reduced.

Fuzzy Logic Controller (FLC)

The input and output linguistic variables of the FLC will be determined with respect to the LIM model [29]. The present sample of speed error $\Delta V_r(m)$ and the change of speed error $\Delta e(m)$ are considered as the input variables of the FLC [29]. The change of speed error, $\Delta e(m)$, is the difference of the present and the past samples of speed error, where m is the present sample. Also, the command q-axis primary current (i_{qn}^{*}) is defined as the output variable of the FLC [29]. In Fig. 4, the IFOC diagram of a five-phase LIM with FLC is represented. The principal aim of the IFOC system is that LIM speed tracks the reference speed and the required thrust can be provided according to the operating conditions. After determination of the linguistic variables for the FLC, the scaling factors K_{ω}, K_e and K_i should be adjusted in order to produce the command q-axis primary current (i_{qs}^{*}). These scaling factors are essential in proper functionality of the FLC system. The factors K_{ω} and K_e normalize the values of the speed error $\Delta V_r(m)$ and the change of speed error $\Delta e(m)$, respectively. Accordingly, ΔV_n and Δe_n are the normalized values of $\Delta V_r(m)$ and $\Delta e(m)$, respectively, in the limit ± 1. In this paper, the scaling factors K_{ω}, K_e and K_i are tuned by trial and error to obtain the optimal speed response of the five-phase LIM drive. Moreover, Mamdani-type fuzzy inference and the center of gravity method for defuzzification are used in this work. The rules utilized for the FLC algorithm are as follows [30][29][30]:

If ΔV_n is PH (Positive High), then i_{qn}^{*} is PH.

If ΔV_n is PL (Positive Low), then i_{qn}^{*} is PM (Positive Medium).

If ΔV_n is ZE (Zero) and Δe_n is PO (Positive), then i_{qn}^{*} is PL.

If ΔV_n is ZE and Δe_n is NE (Negative), then i_{qn}^{*} is NC (No Change).

If ΔV_n is ZE and Δe_n is ZE, then i_{qn}^{*} is NC.

If ΔV_n is NL (Negative Low), then i_{qn}^{*} is NL.

If ΔV_n is NH (Negative High), then i_{qn}^{*} is NH.

With respect to the mentioned fuzzy rules, in Table 2, the FLC rule base matrix is represented. Furthermore, in Fig. 5, the membership functions of the FLC are depicted [30].

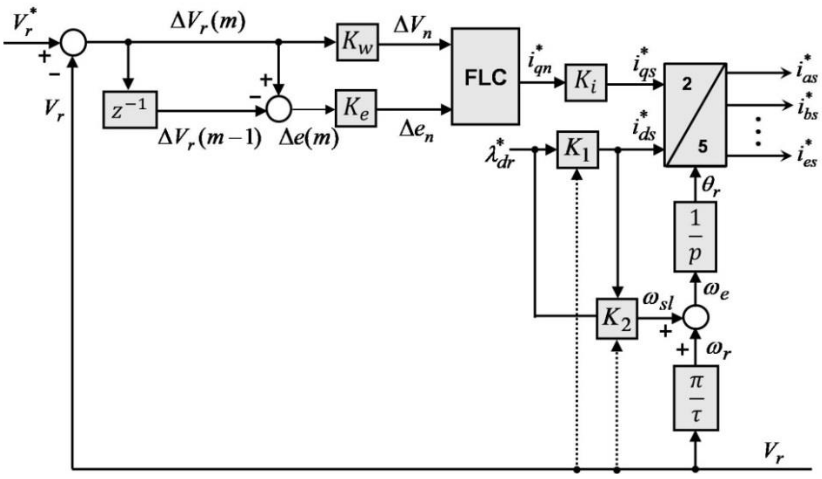

Fig. 4: IFOC scheme based FLC for one five-phase LIM.

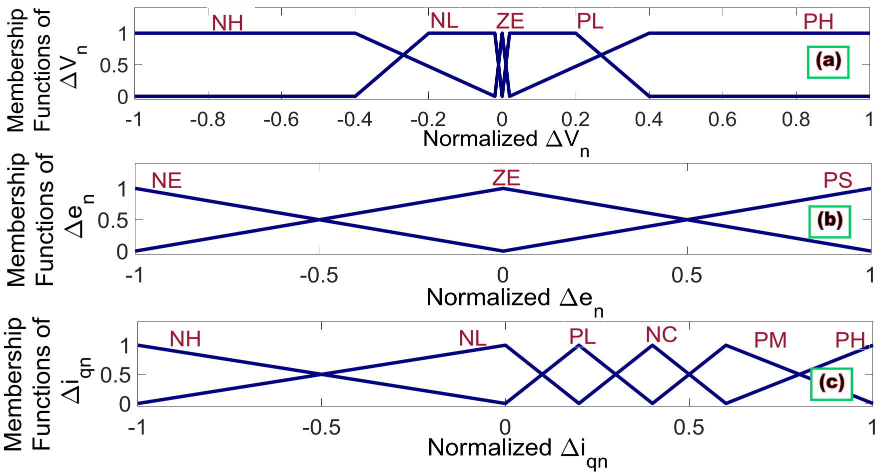

Fig. 5: FLC membership functions: a) speed error ΔV_n, b) speed error change Δe_n, c) command q-axis current i_{qn}^{*} [29].

Table 2 : FLC Rule Base Matrix [30]

ΔV_n / Δe_n	NH	NL	ZE	PL	PH
NE	NH	NL	NC	PM	PH
ZE	NH	NL	NC	PM	PH
PO	NH	NL	PL	PM	PH

Results and Discussion

The validity of the independent control of multiple multiphase machines is investigated by simulation of a five-phase two-LIM drive supplied through one current-controlled VSI. The end effect has been considered in the five-phase LIM model and the IFOC scheme. Both LIMs are running with the same reference speed but with different loading conditions, which refer to the various external forces imposed on different parts of a long train. To examine the effectiveness of the mentioned drive, different tests have been performed at various operating conditions.

The speed and current waveforms are monitored under various operational conditions. Simulation of the five-phase two-LIM drive is implemented utilizing Matlab/Simulink. Simulation parameters are represented in Table 3. The FLC gains are K_w =0.01, K_e=0.1, K_i =4500. The PI controller are K_i =625, K_p=250. It is supposed that both LIMs have the same parameters and ratings.

For simulation, the current controlled VSI is considered as a current source; therefore, the current references of (11) are supposed equal to the phase currents of VSI [4]-[5]. Some of the results are represented in the following parts.

Table 3: Five-Phase LIM Drive Parameters

Phase voltage	220 V	Secondary length	0.413 m	Lm	3 mH
Rated current	93.65 A	R_s	0.049 Ω	λ^*_{dr}	0.145 Wb
Power factor	0.4884	R'_r	0.803 Ω	M	29.34 kg
Pole pairs	2	L_{ls}	1.5 mH	slip	0.5
Pole pitch	0.1024 m	L'_{lr}	≈ 0	Rated external force	1913 N

At the first stage, the electrical independence of the LIMs from each other is investigated. To achieve this purpose, the mechanical interactions are disregarded. In other words, it is assumed that the train compartments are not connected together. In practice, these mechanical interactions, affect the electrical performance of the multi-machine drive. Figs. 6 (a)-(b) illustrate the dynamic speed responses and the reference speeds of the LIMs, when PI controllers are utilized for speed regulation in the IFOC scheme of two LIM drives.

The secondary flux command is fixed at the nominal value for both machines. The reference speeds are considered the same for the LIMs. The reference speed is changed from 12 m/s to 20 m/s at t=8 sec and from 20 m/s to 8 m/s at t=16 sec. LIM1 always runs at full load (i.e., 1366 N). LIM2 starts at no-load, then its external load is increased to half load (i.e., 683 N) at t=4 sec and from half load to full load at t=12 sec. Here, the external forces refer to the natural forces that might be imposed on a long train in practice, such as track gradient force and curve resistance force according to the railroad topology.

As shown in Figs. 6 (a)-(b), the LIMs are electrically independently controlled. In each of the LIMs, the motor speed tracks its related reference speed under different loading conditions. Accordingly, the changes in the loading conditions of each LIM do not affect the dynamic behavior of the other one. Moreover, due to the different loading conditions of the LIMs, the speed of each machine is different at the transient conditions. This is because of the mechanical independence assumption of the machines. It becomes obvious when PI controllers are used as speed regulators in the IFOC drive since PI controllers are sensitive to the loading conditions. Figs. 6 (c)-(d) show the dynamic speed responses and the reference speeds of the LIMs when FLCs are utilized for speed regulation in the IFOC scheme of two LIM drives. However, in practice, mechanical dependence cannot be avoided. Consequently, the complete electrical independence of the five-phase two-LIM drive cannot be provided. Therefore, as the next step of this work, the mechanical dependence of the train rigid connections will be considered that affects the electrical performance of the drive. It becomes more significant at transient conditions in which the speed variations and the tension forces imposed on the LIMs connections are always high.

Figs. 7 (a) represents the equivalent speed of the five-phase two-LIM drive with mechanical interactions and dependence. In This figure, the equivalent speed of the two LIMs is depicted when running at the same speed and with a rigid mechanical connection. As can be seen from this figure, due to the rigid mechanical connection, the equivalent speed of the drive is influenced by the dynamic performance of both machines like the loading conditions and changes of external forces.

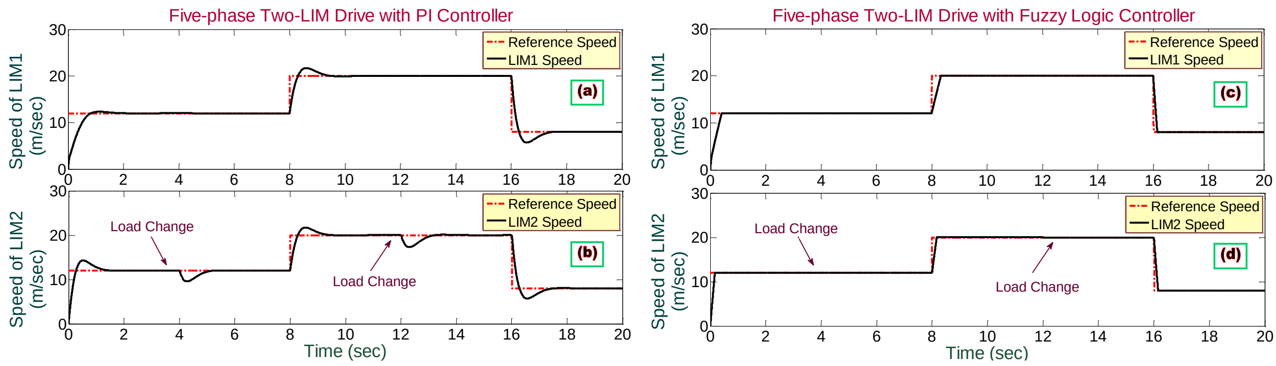

Fig. 6: Dynamic speed responses of the five-phase two-LIM drive with no mechanical connections (with speed step at t=8 sec and t=16 sec, external force increase of LIM2 at t=4 sec and t=12 sec); a) speed response of LIM1 with PI controller, b) speed response of LIM2 with PI controller, c) speed response of LIM1 with FLC, d) speed response of LIM2 with FLC.

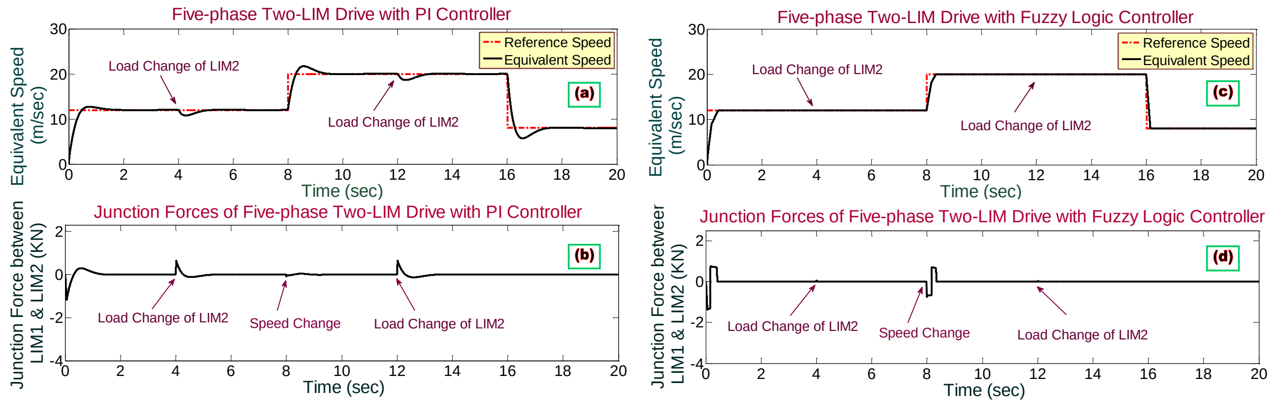

Fig. 7: The equivalent speed responses and tension forces of the five-phase two-LIM drive with mechanical connections (with speed step at t=8 sec and t=16 sec, external force increase of LIM2 at t=4 sec and t=12 sec); a) Equivalent speed with PI controller, b) Tension force between LIM1 and LIM2 with PI controller, c) Equivalent speed with FLC, d) Tension force between LIM1 and LIM2 with FLC as a function of applied field.

Figs. 7 (b) represents the tension force between LIM1 and LIM2 connection. Because of the different loading conditions of the LIMs, the speed of each machine varies from the other one at transient conditions. In case that PI controllers are utilized for speed regulation of the five-phase drive, more overshoots and undershoots appear in the transient conditions of the drive. High-speed variations of the LIMs are proportional to the train acceleration and therefore proportional to the forces. The result is higher tension forces in the connection of the LIM compartments.

Note that in transient operating conditions of the drive, the undesirable tension forces imposed on the train coupler reach the maximum. In this work, to evaluate the dynamic behavior of the two-LIM drive correctly, the reference speeds were selected to have a stepwise manner.

This will result in high accelerations, and thus, high transient forces will be imposed on the train coupler. The better the tracking characteristics are, the higher the transient tension forces will be. On the other hand, the better the tracking characteristics are, the shorter the transient period of tension forces will last. In practice, to guarantee passenger safety and comfort, the reference speeds of the trains are selected in a way not to exceed the maximum acceleration and deceleration according to the related standards.

In this research, to improve the dynamic response of the five-phase two-LIM drive and to reduce the tension force, FLCs are utilized as speed regulators in the IFOC scheme of the two-LIM drive. The result is given in Figs. 7 (c), where the equivalent speed of five-phase two-LIM drive with FLC application is represented, and the mechanical considerations are also presented. The reference speeds and the external loads applied to the LIMs remain the same as in Figs. 1 (a). As can be seen by comparing Figs. 7 (a)-(c), even though the PI controllers are adjusted to have their appropriate response, the fuzzy logic controllers yield preferable tracking responses such as faster speed response with no overshoot and are also adaptive to external force changes.

Figs. 7 (d) represents the tension force between LIM1 and LIM2 connection if FLCs are utilized as speed regulators. As can be seen, in transient operating conditions of the drive, the undesirable tension force imposed on the train connection lasts relatively shorter in comparison with Fig. 7 (b).

It should be noted that although FLCs may sometimes have higher pick values in the tension force (as in Fig. 7 (d)) due to the stepwise speed references, the transient periods of these forces last relatively shorter than that of PI controllers. This is because of the excellent tracking characteristics that FLCs have.

In case that the mechanical couplings are disregarded, the phase current references of the LIMs (i_{a1}^{*} and i_{a2}^{*}) and the inverter phase current (i_{A}^{*}), for the series-connected primaries of the LIMs, are shown in Fig. 8 (a)-(c), respectively. The effect of speed and load changes of each LIM is obvious in the phase current references. According to (11), the inverter phase current waveform is composed of two current references. In other words, the overall inverter phase current waveform is the aggregation of two sinusoidal waveforms that might have various frequencies and phases.

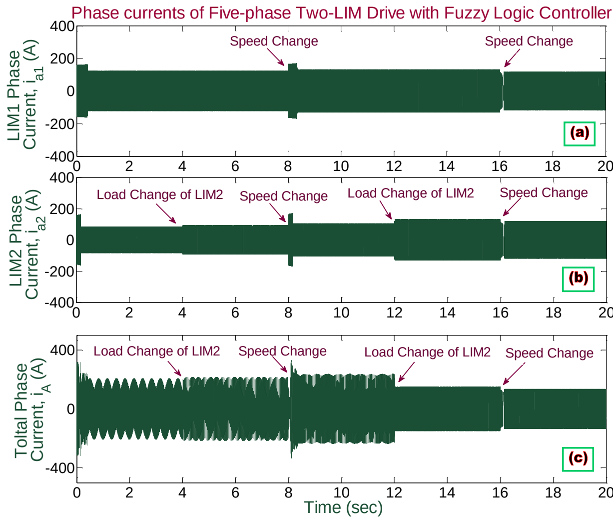

Fig. 8: The phase current references of the five-phase two-LIM drive (with speed step at t=8 sec and t=16 sec, external force increase of LIM2 at t=4 sec and t=12 sec); a) The phase current reference of LIM1 (i_{a1}^{*}), b) The phase current reference of LIM2 (i_{a2}^{*}), c) The total phase current of the LIMs (i_{A}^{*}).

The total inverter phase current (i_{A}^{*}) and its related harmonic spectrums are represented in Figs. 9 (a)-(b), respectively. To analyze the harmonic spectrums of the inverter phase current, five time regions (A-E) are considered according to different loading conditions of the machines.

The inverter phase current (i_{A}^{*}) and its related harmonic spectrums are represented in Figs. 9 (a)-(b), respectively. To analyze the harmonic spectrums of the inverter phase current, five time regions (A-E) are considered according to different loading conditions of the machines.

For harmonic analysis, the simulation time of each time region has been increased, and a time window equal to 10 sec has been utilized in the steady-state operating conditions of the drive. Thus, the frequency resolution of 0.1 Hz has been obtained. The Fast Fourier Transform (FFT) has been applied on time-domain waveforms obtained from the simulations. The harmonic components (amplitude and frequency) of the phase current are illustrated in Table 4.

Note that although both LIMs run at equal speeds, due to the different loading conditions, the slip frequencies and the synchronous frequencies (the frequency of the primary current references of the LIMs, shown in Fig. 9 (b) might be different.

In the 'A' region, which is in accordance with the first time window, two different frequency components (i.e., 114.6 Hz and 58.8 Hz) are evident in the harmonic spectrum of the inverter phase current, which are related to the full-load and no-load operating conditions of LIM1 and LIM2, respectively. Also, the magnitudes of the obtained frequency components are in accordance with that of Figs. 8 (a)-(b) (i.e., 119.9 A and 84.2, respectively).

In the 'B' region, LIM2 will run at half-load, and thus, its frequency component is shifted up (i.e., 84.8 Hz and 91.45 A) to reach the previous reference speed. Moreover, LIM1 continues running at full-load, and therefore, its related frequency component does not change in magnitude and frequency (i.e., 119.9 A and 114.6 Hz).

The spectrum of the 'C' region contains two frequency components due to the unchanged loading conditions of the LIMs (Figs. 6 (a-b)). However, since the reference speeds are increased in comparison with the 'B' region, both frequency components are shifted up (i.e., 152.4 Hz for LIM1 and 122.4 Hz for LIM2). The related magnitudes are equal to 130.29 A for LIM1 and 105.18 A for LIM2.

In the 'D' region, both LIMs run at full-load, and thus, only one frequency component is evident in the spectrum. The overall magnitude depends on the phase difference of the components, which is in accordance with that of Fig. 8 (c). Therefore, two 152.4 Hz frequency components related to LIM1 and LIM2 are added together, and the overall component has a magnitude of 148.2 A.

The spectrum of the 'E' region contains one frequency component due to the unchanged loading conditions of the LIMs (Figs. 6 (a-b)). However, since the reference speeds are reduced in comparison with the 'D' region, the frequency component is shifted down (i.e., 95.4 Hz and 132.1 A).

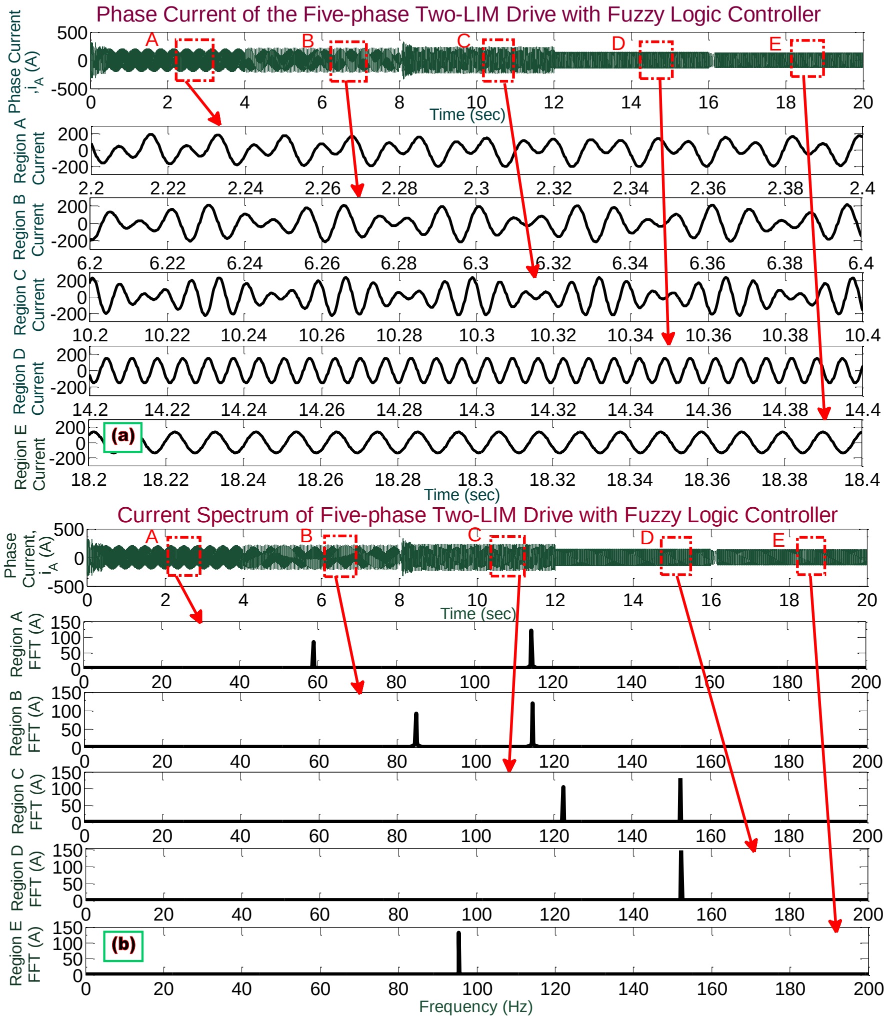

Fig. 9: a) The total phase current waveform of the two series LIMs (iA*) in different time regions (regions A-E), b) The harmonic spectrums of the phase current waveform in different time regions.

Table 4: Harmonic components of the phase current in different time regions

Time Region	First harmonic component		Second harmonic component	
	Frequency	Amplitude	Frequency	Amplitude
Region A	f_1=114.6 Hz	a_1=119.9 A	f_2=58.8 Hz	a_2=84.2 A
Region B	f_1=114.6 Hz	a_1=119.9 A	f_2=84.8 Hz	a_2=91.4 A
Region C	f_1=152.4 Hz	a_1=130.3 A	f_2=122.4 Hz	a_2=105.2 A
Region D	f_1=152.4 Hz	a_1=148.2 A	-	-
Region E	f_1=95.4 Hz	a_1=132.1 A	-	-

As can be seen from the results, the loading conditions of each LIM do not affect the performance of the other LIM, which validates that the LIMs are electrically independently controlled.

According to the results, the LIMs are electrically independently controlled. Moreover, it is clear that the five-phase two-LIM drive with IFOC based FLC offers perfect dynamic characteristics in terms of fast and accurate speed response, which is also adaptive to the imposed external forces.

Experimental Results

To validate the theoretical concepts, a five-phase and a five-phase LIM with a 10 meter secondary have been constructed. A photograph of the five-phase LIM is shown in Fig. 10. Moreover, a seven-phase VSI was build utilizing three PM50CTJ060 600V/50A Mitsubishi IPMs supplied through a six-pulse diode rectifier with a DC-link capacitor. For firing of the IGBT switches, a gate driver board has been designed. 74HCT244N buffer IC has been utilized for amplifying the current values, and TLP521 photo-couplers have been used for isolating the power circuit and the DSP board. Also, a protection circuit has been added to the gate driver board, which prevents simultaneous conduction of up and down switches by controlling the enable pin of the buffer IC using 74ALS08 NAND and 74HC4078 OR ICs. The PWM switching techniques are programmed with Code Composed Studio (CCS). They are implemented utilizing a TMS320F2812 Digital Signal Processor (DSP) board, which is connected to a PC through an XDS100 emulator to compile and load the programs. A photograph of the implemented seven-phase VSI is represented in Fig. 11.

Fig. 10: Photograph of the primary of the five-phase LIM.

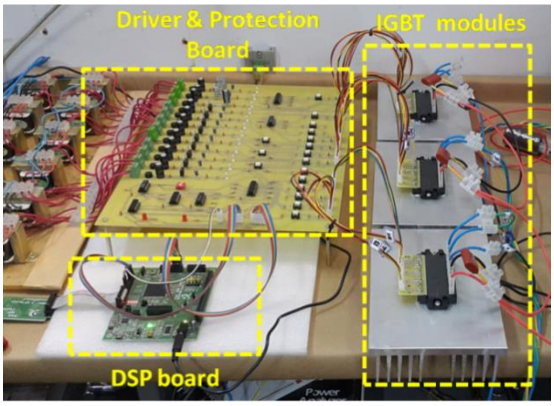

Fig. 11: Photograph of the seven-phase VSI experimental setup.

To investigate the theoretical concept of the independent control of multiphase machines through a single VSI, different tests have been carried out.

At the first step, the five-phase and seven-phase LIMs have been supplied individually through the multiphase VSI with a proper phase transposition, according to Table 1 and [3]. In Fig. 12, the experimental phase current i_a, and the line voltage v_{ad} of the seven-phase inverter are illustrated for M=0.8, f_s=525Hz, and f_1=15Hz. The DC-link voltage has been considered 90V. Due to the proper phase transposition, although the input voltage is applied and the primary currents flow through the LIM windings, the thrust will not be produced, and motors will not move.

In the next step, to investigate the theoretical concept of independent control of multiphase machines through a single VSI, the seven-phase LIM has been used as a five-phase LIM, and thus, the independent operation of two five-phase LIMs has been validated. To achieve this purpose, the primary phases of the LIMs have been connected in series and with a phase transposition, according to Table 1. So, the thrust producing current of “LIM 1” does not impact the thrust producing current of “LIM 2” and vice versa. Photograph of the two series-connected five-phase LIMs with proper phase transposition is shown in Fig. 13.

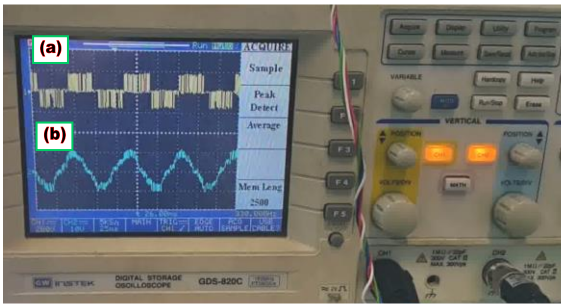

Fig. 12: Experimental results of the seven-phase LIM with phase transposition: a) phase current i_a, b) line voltage v_{ad} with M=0.8, f_s=525Hz, and f_1=15Hz: (10A/div and 100V/div).

According to the experimental results, although the LIMs are connected in series, and the currents flow through both primary windings, the operation of the LIMs are independent of each other. This is clear when only one of the LIMs is decided to move while the other one remains static.

Fig. 13: Photograph of the LIMs with series-connection.

Conclusion

Due to the lack of adequate researches on multiphase linear machines, this paper concentrates on independent vector control of two five-phase LIMs fed with one current-controlled VSI. This can be especially helpful in long trains with distributed power and can be a proper replacement for the locotrols. As a result, it leads to reliability increment and reduces the fault occurrence of the train control systems. The LIMs are running at the same reference speed but with different load conditions, which refer to the various external forces physically imposed on different parts of a long train. The principal advantages of the proposed concept are provided and discussed in this work. Also, fuzzy logic controllers were successfully utilized to achieve a more satisfactory dynamic tracking response of the proposed five-phase two-LIM drive and to reduce the undesirable tension forces. The results affirm the accuracy of the proposed fuzzy logic controlling scheme for the suggested five-phase two-LIM drive system, which guarantees perfect tracking characteristics and dynamic responses. Moreover, the undesirable tension forces imposed on train couplers are reduced. Consequently, it leads to higher system efficiency, lower deterioration of the train couplers and connections, greater system reliability, and higher passenger safety and comfort. To validate the theoretical concepts, some experimental results have been provided.

Author Contributions

P. Hamedani carried out the simulation results and designed the experimental set up. S. Sadr interpreted the results and wrote the manuscript. A. Shoulaei supervised this work and provided the experimental facilities.

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Conflict of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy have been completely observed by the authors.

Abbreviations

M	Primary weight
v_r	LIM speed
L'_r	Self-inductance of the secondary
R'_r	Resistance of the secondary
L'_{lr}	Leakage inductance of the secondary
R_s	Resistance of the primary
L_{ls}	Leakage inductance of the primary
$L_{m0}\,(1\text{-}f(Q))$	Magnetizing inductance of LIM
ω_r	Secondary angular speed
ω	Synchronous angular speed
ω_{sl}	Slip angular frequency
F	LIM thrust
τ	Motor pole pitch
n	Number of phases
$i_A^*, i_B^*,..., i_E^*$	Primary currents of series LIMs
$V_A^*, V_B^*,..., V_E^*$	Phase voltages of series LIMs
i_{qs}^*	Command q-axis primary current
i_{ds}^*	Command d-axis primary current
λ_{qr}	q-axis secondary flux
λ_{dr}	d-axis secondary flux
F_T	Resultant train force
V_{eq}	Equivalent speed of the train
M_T	Total mass of the train
$\Delta V_r(m)$	Speed error
$\Delta e(m)$	Change of speed error
m	Present sample
K_ω, K_e, K_i	Fuzzy Logic controller gains
K_i, K_p	PI controller gains

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