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Novel Force Ripple Reduction Method for a Moving-Magnet Linear Synchronous Motor with a Segmented Stator

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Abstract—This paper concerns the analysis of and force ripple reduction method for a moving-magnet linear motor with a segmented stator. The system consists of multiple individually excited three-phase stator segments with an iron core and coils with concentrated windings and one translator with permanent magnets. Because of the segmentation of the stator, the translator experiences force ripples when it moves from one stator segment to the next. A segment of the structure, consisting of one stator segment and one translator, has been analyzed using 2D and 3D FEM and the sources of the force ripples have been identified. A novel commutational algorithm, which calculates the three-phase currents based on the EMF waveforms, to compensate the force ripples has been implemented, experimentally verified, and compared to a traditional (dq0-based) commutational algorithm.

I. INTRODUCTION

In traditional permanent magnet linear synchronous motors (PMLSMs), the moving part is the armature and the stator part consists of permanent magnets (PMs). The consequence of a moving-coil machine is that the moving part needs to be connected by cables to a power supply to energize the coils, which introduces a cable slab and limits the length of the stroke. This is a disadvantage when the machine is used as a transportation system. When the structure is inverted, the moving part is the magnet plate and, therefore, does not need any wired connection to a power supply. The track can consist of a segmented-stator structure, i.e., it comprises several stator segments at a certain distance apart. A schematic representation of the system with one translator and n stator segments at a distance d1 apart is shown in Fig. 1. The advantages of a segmented stator structure are that the number of coils and power amplifiers is reduced with respect to a structure in which the track is a continuous array of coils and that it allows for the use of multiple translators. A disadvantage is that the translator is switching between subsequent stators as it moves over the track, resulting in force ripples which need to be compensated.

Examples of a moving-magnet linear synchronous motor with a segmented-stator are presented in [1], however, these do not offer force ripple reduction. For moving-coil machines, force ripple reduction is presented in e.g. [2] (by control) and [3] (by design). Force ripple reduction for moving-magnet machines is presented in e.g. [4] (by design), however, they do not consider the thrust force ripple due to the segmented stator structure.

This paper presents an electromagnetic analysis of the force production mechanisms using the finite element method (FEM) of a segment of the moving-magnet linear synchronous motor structure. In order to improve the positioning accuracy of a system comprising several stator segments and one translator, two commutation algorithms are investigated: a traditional (dq0-based) commutation algorithm and a novel commutation algorithm which compensates for the force ripples based on the instantaneous values of the EMF. An optimal distance is determined which minimizes the force ripple during the switching interval between subsequent stator segments and the performance of both algorithms is experimentally verified and compared for a certain nonoptimal distance.

II. SYSTEM DESCRIPTION

The positioning system under study is constructed of Tecno TL-6 motors. The system consists of multiple individually excited three-phase star-connected stator segments with an iron core and coils with concentrated windings and one translator with permanent magnets. A drawing of the machine is shown in Fig. 2 and the dimensions of the structure are shown in Tab I. The magnets are skewed at a 4° angle to decrease the cogging force.

The force acting on the translator can be split into three components. First, the thrust force, denoted by \( F_k \), which is the force due to the currents in the coils. Second, the reluctance force, denoted by \( F_r \), due to a change in inductance of the coils due to the presence of the back iron in the translator. Third, a cogging force component due to the interactions between the magnets and the back iron in the stator segments, which can be split up into the components as shown in Figs. 3 and 4. In Fig. 3, \( F_{\text{sloc}} \) is the cogging force due to slotting and \( F_{\text{end,s}} \) is the end-effect due to infinite stator length (as discussed in [5]). In Fig. 4, \( F_{\text{end,t}} \) is the end-effect due to the fact that the translator has a finite length and is partially overlapping two stator segments when switching between subsequent stator segments.

III. ELECTROMAGNETIC ANALYSIS

To analyze the behaviour of the PMLSM, a segment comprising one stator and one translator has been analyzed with a magnetostatic FEM simulation (using Cedrat FLUX 2D).
Electromotive force

The electromotive force (EMF) is the voltage induced in the coils due to movement of the magnets. The EMF can be used to calculate the force which is exerted on the translator due to the current in the coils. For one phase $U$ of the synchronous PMLSM with surface mounted PMs, this force is equal to:

$$F_U(x) = e_U(x) \cdot \left( \frac{dx}{dt} \right)^{-1} \cdot i_U(x) = k_U(x) \cdot i_U(x), \quad (1)$$

where $e_U(x)$ is the electromotive force (EMF) induced in phase $U$, $\frac{dx}{dt}$ is the speed at which the EMF is induced, $i_U(x)$ is the current in phase $U$ and $k_U$ is a force function for phase $U$ linking the force acting on the translator to the current in phase $U$. Using FEM, the induced EMF for a speed of 1.0 m/s is determined and the result of this is shown in Fig. 5. This shows that, for positions $-0.1 \text{ m} < x < 0.1 \text{ m}$, the balanced three-phase voltage has an amplitude of approximately 13.6 V. As the translator moves away from the stator segment, positions $x < -0.1 \text{ m}$ and $x > 0.1 \text{ m}$, the three-phase EMF is no longer balanced. The results obtained from simulations have been verified by measurements.

Reluctance force

The reluctance force, denoted by $F_r$, is the force caused by a change in inductance of the coils when the translator partly overlaps the stator segment, as shown in Figure 4. This force component is estimated to be smaller than 1% of the thrust force and, therefore, is neglected in the further analysis.

Cogging force and end-effects

The profile of the cogging force and end-effects is obtained from FEM (both 2D and 3D, to verify the effect of skewing of the magnets) and the result is shown in Fig. 6. For verification, the cogging force is also measured with a load cell. The negligible difference between the 2D and 3D simulations and
which allows for the simple controller structure as shown in Fig. 7. The desired thrust force $F_k(x)$ is equal to the force $F_c(x)$ calculated by the controller subsystem (consisting of a feedback and a feedforward for mass and damping) minus the value of the cogging force $F_{cog}(x)$ (determined by the cogging feedforward, or cogging FF, subsystem):

$$F_k(x) = F_c(x) - F_{cog}(x) = \frac{3}{2}\hat{k}i_{q1}, \quad (3)$$

The thrust force acting on the translator for $i_q = 1$ A is depicted in Fig. 8, which shows that, as long as a stator segment is completely under the translator, approximately for positions $-0.1 \text{ m} < x < 0.1 \text{ m}$, the thrust force ($F_k$) is constant and equal to $\frac{3}{2}\hat{k}$. Beyond these positions, $x < -0.1 \text{ m}$ and $x > 0.1 \text{ m}$, the $dq0$-decomposition is not valid (since the three-phase EMF is not balanced) and the thrust force decreases nonlinearly.

To investigate the effect of commutating between subsequent stator segments, a situation with two stator segment segments, $S_1$ and $S_2$, at a distance $d$ apart, and one translator is considered. For a given $i_q$, the currents in the $(U, V, W)$-frame are equal to [6]:

$$\begin{bmatrix} i_{S_1U}(x) \\
i_{S_1V}(x) \\
i_{S_1W}(x) \\
i_{S_2U}(x) \\
i_{S_2V}(x) \\
i_{S_2W}(x) \end{bmatrix} = i_q \begin{bmatrix} \sin \left( \frac{\pi x}{r} \right) \\
\sin \left( \frac{\pi x + \frac{\pi}{3}}{r} \right) \\
\sin \left( \frac{\pi x + \frac{\pi}{3}}{r} \right) \\
\sin \left( \frac{\pi(x-d)}{r} \right) \\
\sin \left( \frac{\pi(x-d) + \frac{\pi}{3}}{r} \right) \\
\sin \left( \frac{\pi(x-d) + \frac{\pi}{3}}{r} \right) \end{bmatrix} \quad (4)$$

IV. COMMUTATION USING $dq0$-BASED ALGORITHM

The $dq0$-transformation is used to transform the stator quantities onto a moving reference frame fixed to the translator. Using the $dq0$-transformation, the armature quantities are split into two orthogonal components, namely the direct-axis ($d$-axis) component and the quadrature-axis ($q$-axis) component. The thrust force $F_k$ equals (for surface mounted PM machines) [6]:

$$F_k = \frac{3}{2}\hat{k}i_{q1}, \quad (2)$$

where $\hat{k}$ is the amplitude of the force function and $i_{q1}$ is the current in an equivalent $q$-axis circuit. Hence, the total thrust force is equal to a constant times the current in the $q$-axis.

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where \( i_{SN}(x) \) is the current in phase \( N \) of stator segment \( S_M \). The total force acting on the translator during the transition from one stator segment to the next is dependent on the distance \( d \) between the two segments. To find the optimal distance between the two stator segments, i.e. the distance which minimizes the force ripple, the RMS ripple of the force as function of the distance between subsequent stator segments is determined and shown in Fig. 9, where \( F_k \), \( F_{cog} \) and \( F_{tot} \) represent the RMS ripple of the thrust, cogging and total force profile, respectively. Fig. 9 shows that the minima of the RMS ripple of the three force profiles coincide, and that the optimal distance between subsequent stator segments is equal to 312.6 mm. Using this distance, the force has the shape as shown in Fig. 10. The result is shown with and with cogging force compensation and it shows that feedforward of the cogging force does not completely remove the force ripple, being approximately 5% of the thrust force in case cogging feedforward is implemented. This is due to the fact that the \( dq0 \)-based algorithm is invalid during commutation between subsequent stator segments.

V. DIRECT FORCE-CURRENT DECOUPLING COMMUTATION ALGORITHM

As shown in the previous section, the system under study is not a balanced three-phase system for the entire stroke of the translator. Consequently, the \( dq0 \)-transformation to calculate the three-phase current is incorrect and using a \( dq0 \)-based commutation algorithm results in force ripples. Instead, the current per phase is calculated with a novel direct force-current decoupling algorithm, which is based on the instantaneous values of the EMF per phase.

Consider again the situation with two stator segments, \( S_1 \) and \( S_2 \) and one translator. The thrust force, \( F_k(x) \), is then equal to:

\[
F_k(x) = \vec{k}(x)\vec{\tau}(x),
\]

where \( \vec{\tau}(x) \) is given in (4) and \( \vec{\tau}(x) \) is equal to:

\[
\vec{k}(x) = \begin{pmatrix} k_{S1u}(x) \\ k_{S1v}(x) \\ k_{S1w}(x) \\ k_{S2u}(x) \\ k_{S2v}(x) \\ k_{S2w}(x) \end{pmatrix}.
\] (6)

An objective is to find an expression for the current so that the total force acting on the translator is equal to a desired thrust force \( F_k(x) \) being equal to the force \( F_c(x) \) calculated by the controller subsystem minus the value of the cogging force \( F_{cog}(x) \):

\[
F_k(x) = F_c(x) - F_{cog}(x) = \vec{k}(x)\vec{\tau}(x).
\] (7)

Since a three-phase amplifier is used and a connection to the neutral point is not available, the sum of the currents through each of the stators has to be equal to zero. To include this last requirement in the equations, (7) is written as shown in (8). The currents \( \vec{\tau}(x) \) which obtain the desired reference force \( F_c \) can then be found analogous to [7], resulting in:

\[
\vec{\tau}(x) = k^{-1}(x)\vec{F}_e(x),
\] (9)

where \( k^{-1}(x) \) is the Moore-Penrose pseudoinverse [8] of \( k(x) \), which is equal to:

\[
k^{-1}(x) = k^T(x)(k(x)k^T(x))^{-1}.
\] (10)

The system then has a control structure as shown in Fig. 11, and it can be demonstrated that for a balanced three-phase system, the current waveforms have a shape similar to (4).

To test this disturbance compensation, the algorithm has been simulated and compared to the \( dq0 \)-based commutation algorithm. During the simulation, the distance between subsequent stator segments is equal to the (non-optimal) value of \( d = 0.33 \) m. The force acting on the translator during the commutation between two stators is shown in Fig. 12 (without cogging feedforward) and Fig. 13 (with cogging feedforward).
\[
\left( \begin{array}{c}
F_1(x) \\
0 \\
0
\end{array} \right) = \left( \begin{array}{cccc}
k_{s1u}(x) & k_{s1v}(x) & k_{s1w}(x) & k_{s2u}(x) \\
1 & 1 & 1 & 0 \\
0 & 0 & 0 & 1
\end{array} \right) \left( \begin{array}{c}
k_{s2u}(x) \\
k_{s2v}(x) \\
k_{s2w}(x) \\
0
\end{array} \right)
\]

\[\bar{F}(x) = k(x)\vec{r}(x).\]

for both commutation algorithms. During the switching interval from \(S_1\) to \(S_2\), the force exerted on the translator decreases significantly when using the \(dq0\)-based commutation algorithm (indicated by \(F_{tot, dq0}\)) whereas the translator only experiences force ripples due to the cogging force components when the direct force-current decoupling commutation algorithm (indicated by \(F_{tot, EMF}\)) is used. The cogging force feedback does not significantly improve performance for the \(dq0\)-based commutation algorithm, however, it completely removes the force ripple when using it in combination with the direct force-current decoupling commutation algorithm. The currents as calculated by the direct force-current decoupling commutation algorithm (with cogging feedforward) are shown in Fig. 14. The currents are non-sinusoidal for positions (approximately) 0.09 m < \(x\) < 0.24 m, which is to compensate the fact that the three-phase EMF is not balanced.

VI. EXPERIMENTAL VERIFICATION

For implementation, a test track is available which has three stator segments and one translator. A photo of the system is shown in Fig. 15.

The system is controlled using a dSpace CP1103 PPC controller board. The position of the translator is determined with a Heidenhain LIDA 47 linear encoder, with a resolution of 2 \(\mu m\), and the coils are powered by ELMO FLU-3/100 amplifiers. The maximum voltage is 75 V, limiting the velocity and acceleration to 0.5 m/s and 3 m/s\(^2\), respectively. A PD-controller with feedforward for damping, mass and cogging force with a bandwidth of 10 Hz (which is lower than the
The main frequency of the disturbances has been used during the experiments. The positions of the midpoints (of the stator segments) are shown in Table II. The results from the 2D PEM simulations are used for values of the cogging force and EMF (to calculate the current vector in case of the direct force-current decoupling commutation algorithm).

For comparison, both the dq0-based commutation algorithm as well as the direct force-current decoupling commutation algorithm were implemented. The position error as a function of time is shown in Fig. 16. During the measurement, the translator moves from position $x = -0.23$ m to $x = 0.26$ m with a maximum velocity of $0.5$ m/s, a maximum acceleration of $2$ m/s$^2$ and a jerk equal to $1000$ m/s$^3$. From these results, it is clear that the direct force-current decoupling commutation algorithm performs especially well, compared to the dq0-based commutation algorithm, during the switching time from stator segment $S_1$ to stator segment $S_2$. Apart from this interval, the performance between the two commutation algorithms is similar. This clearly indicates that the direct force-current decoupling commutation algorithm makes the position error less dependent on the distance between subsequent stator segments.

VII. CONCLUSIONS AND RECOMMENDATIONS

In this paper, a segmented-stator moving-magnet linear motor system has been researched. The electromagnetic behaviour of the machine has been analyzed in detail and, using a dq0-based commutation algorithm, the switching between subsequent stators has been investigated. The disturbances acting on the translator during its motion over the track have been identified. The dq0-decomposition is not valid for the entire stroke of the machine and this results in force ripples when using a dq0-based commutation algorithm. It has been shown that, in the case of the dq0-based commutation algorithm, an optimal distance between subsequent stators which decreases the force ripple exists. However, this force ripple is still significant.

To compensate these force ripples, a novel commutation algorithm called the direct force-current decoupling commutation algorithm, which calculates the three-phase currents based on the instantaneous values of the EMF per phase, has been implemented. This new commutation algorithm also minimizes ohmic losses in the system.

To verify the functioning of the direct force-current decoupling commutation algorithm, both the commutation algorithms have been simulated and implemented in a track comprising three stator segments and one translator. Compared to the dq0-based commutation algorithm, the performance of the direct force-current decoupling commutation algorithm is less dependent on the distance between subsequent stators. Overall, the novel direct force-current decoupling commutation algorithm has a better performance than the dq0-based commutation algorithm and could be recommended for a wider class of linear motion positioning systems with segmented stator.

REFERENCES