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Optimization of Permanent Magnet Skew in Permanent Magnet Linear Synchronous Motors Using Finite Element and Statistical Method

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Abstract

The permanent magnet skew is one of the techniques mostly used on the Permanent Magnet Linear Synchronous Motors (PMLSMs) to reduce the thrust ripple; even though there is a reduction in the amplitude of ripple and at the same time a significantly decrease of the motor's thrust. This article proposes a combined technique between the Finite Elements Method (FEM) and statistical regression, to obtain an objective function that will allow the achievement of the optimal Permanent Magnet (PM) skew angle, so that there is a greater reduction of ripple with the minimum thrust diminishment.

Keywords: FEM-Statistical Regression Method, Optimization, PM Skew, PMLSM, Ripple, Thrust

1. Introduction

The PMLSMs are widely used for their excellent characteristics such as high force density, fast dynamic response, low thermal losses, and simple structure. However, the thrust ripple, which is the main disadvantage of PMLSM, results in a periodic force oscillation. Consequently, the periodic force oscillation causes mechanical vibration, acoustic noise, and speed oscillation, which will deteriorate the performance of PMLSMs [1].

It is then necessary to look for a way of reducing the thrust's ripple. To achieve the latter, a diversity of techniques are used and one of them is the skew of PM [1,2]. However, the skew also provokes a reduction in the thrust [3,4]; for which it will be necessary to implement a method to obtain the optimum skew angle so that there is a reduction in ripple without diminishing too much the motor's thrust.

The existing Literature [5-14], considers diverse methods of optimization, but none establishes as objectives the maximization of thrust and the minimization of ripple. In addition, techniques that suppose certain degree of complexity like the genetic algorithms are used [6,11]. It is for that reason that this work considers a simpler technique that consists of using the data of thrust and ripple of the simulation by FEM, to obtain by means of quadratic regression the equations that follow the tendency of the data.

The equations are of second order, one for thrust (T) and another one for ripple (R), they are then combined to obtain an only objective function that is maximized and of which the optimal PMs skew is obtained.

The procedure is applied to two types of PMLSMs, the first one has a short pitch winding (PMLSM-1) and the second one has diametrical pitch winding (PMLSM-2). **Figures 1** and **2**, shows the structures of both motor.

Table 1 shows the most relevant dimensions of the two PMLSMs.

2. Fem Simulation

The simulations were made in a 3D FEM software for a displacement of the translator of a polar step and with 10 angles (θ) of skew of the PMs. The angles are measured in fractions of slot step (τ_s) and the chosen values of θ are: $1/4\tau_s$, $1/3\tau_s$, $1/2\tau_s$, $2/3\tau_s$, $3/4\tau_s$, $1\tau_s$, $5/4\tau_s$, $4/3\tau_s$ y $3/2\tau_s$. For each PMLSM, ten simulations were made; consequently the total of simulations for each PMLSM was 20.

The thrust for each skew angle is a mean value of the data obtained for simulation, with a displacement of a polar step and rated current.

The thrust is expressed in P.U. values, taking as base

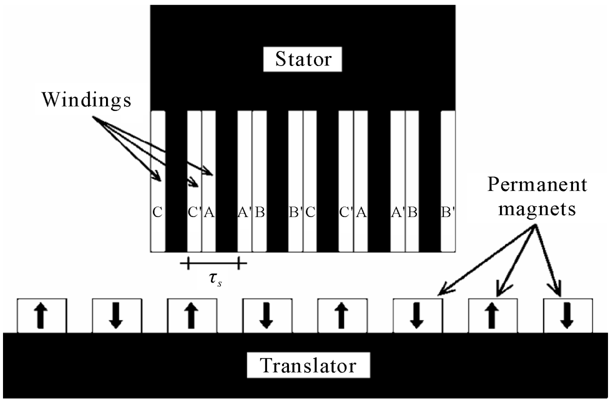
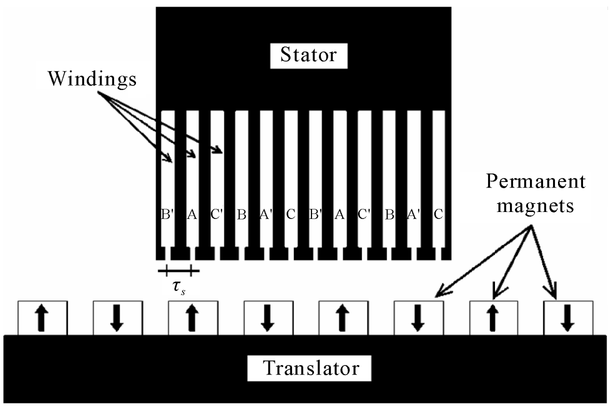


Figure 1. Structure of PMLSM-1.



Figutr 2. Structure of PMLSM-2.

Table 1. PMLSMs dimensions.

Description	PMLSM-1	PMLSM-2
Stator:		
Length	162	162
Depth	100	100
Yoke´s Height	15	15
Slot's Width	15	7,5
Slot Step	27	13,5
Translator:		
Length	324	324
Depth	100	100
Height of Magnets	5	5
Width of Magnets	27	27
Polar Step	40,5	40,5
Air-Gap	1	1

All dimensions are in mm.

value the thrust at $\theta = 0$.

Ripple is analyzed taking as reference its amplitude; subtracting from the maximum value of thrust its minimum.

The relative permeability of iron is 2500, the relative permeability of the permanent magnets is 1.05, the current density is 8.33 A/mm^2 and the speed of translator is 4.05 m/s.

The simulation was done in 51 steps of 0.2ms that correspond to displacements of 0.81 mm each and the meshing of the models has the following characteristics:

Number of nodes: 13736

Number of line elements: 3658

Number of surface elements: 21340

Number of volume elements: 76273

3. Data Processing

The resulting data of thrust and ripple obtained from the simulation by FEM is summarized in **Table 2**.

Quadratic regression by minimum squares is applied to the data of thrust and ripple using the function *polyfit* of Matlab, which gives the coefficients of an equation of second order that comes near to the data generated by the FEM.

The equations obtained for the PMLSM-1 are:

$$\max\{T_1\} = -0.1487\theta_1^2 - 0.0030\theta_1 + 1 \quad (1)$$

$$\min\{R_1\} = 0.1896\theta_1^2 - 0.5190\theta_1 + 0.5846 \quad (2)$$

$$\text{For } \theta_2 \text{ from } \langle 0,\ 1.5\tau_{s2} \rangle$$

Table 2. Thrust and ripple data.

Skew angle $\theta(\tau_{s1}, \tau_{s2})$	PMLSM-1		PMLSM-2	
	Thrust	Ripple	Thrust	Ripple
0	460.7	281.9	362.5	185.4
1/4	458.4	197.1	358.0	147.7
1/3	454.3	200.2	355.6	148.2
1/2	439.9	171.2	355.0	142.7
2/3	426.2	136.8	351.9	146.9
3/4	422.8	147.8	346.6	138.7
1	397.0	121.9	343.7	119.0
5/4	351.5	129.4	333.4	98.4
4/3	334.1	96.6	328.3	94.2
3/2	306.3	97.5	322.9	85.1

All dimensions are in N; Rated thrust at $\theta = 0$.

where:

T_1: PMLSM-1 thrust in P.U.

R_1: PMLSM-1 ripple in P.U.

θ_i: PM skew angle (τ_{s1}) in PMLSM-1.

As you can see, two functions exist to optimize and these are opposed.

Figure 3 shows the data of thrust and ripple in P.U. units, obtained by FEM and the curves of the equations obtained with the function *polyfit* of Matlab.

We can see the closeness of the data with the drawn up curve, with which the optimization can be validated later.

The same procedure is applied to PMLSM-2, which represents the thrust and ripple equations:

$$\max\{T_2\} = -0.0316\theta_2^2 - 0.0235\theta_2 + 1 \quad (3)$$

$$\min\{R_2\} = -0.01\theta_2^2 - 0.1494\theta_2 + 0.4817 \quad (4)$$

$$\text{For } \theta_2 \text{ from } \langle 0,\ 1.5\tau_{s2} \rangle$$

Figure 4 shows data and curves obtained in P.U.

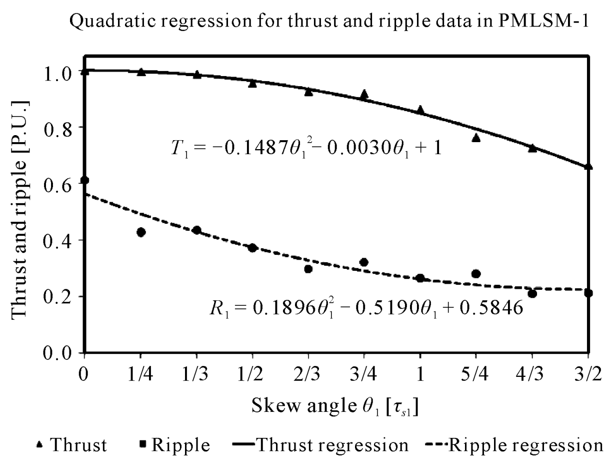


Figure 3. Thrust-Ripple data and equation in PMLSM-1.

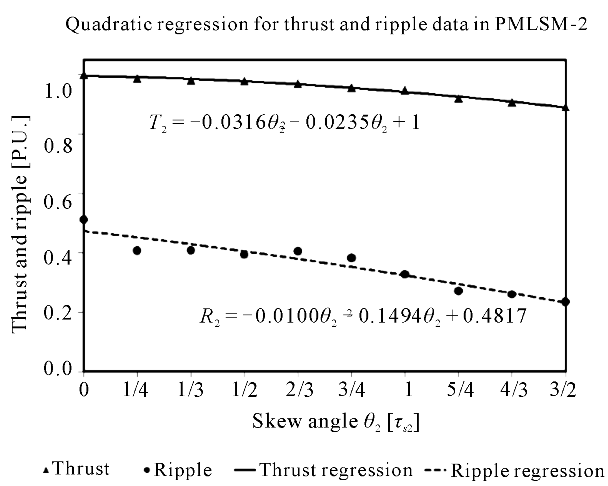


Figure 4. Thrust-Ripple data and equation in PMLSM-2.

units.

4. Optimization

The established problem is of a multi objective optimization and to solve it the weighted-sum approach technique is applied [18], in order to find a unique objective function. This technique consists of giving a specific weight to each function and then they are added or subtracted. In (5) the general expression to apply is indicated.

$$O = k_1 T \pm k_2 R \quad (5)$$

where O is the objective function to optimize and k_1, k_2 are the weights given to the functions of thrust (T) and ripple (R).

In the studied case, an equal weight of 1 is given to both functions [18], since maximization of ripple is as important as thrust diminishing.

$$k_1 = k_2 = 1 \quad (6)$$

To obtain the unique objective function, the function of ripple is subtracted from the function of thrust. This operation can be made because the two functions are of 2nd order and they also have the same units. Then, the maximum of the resulting objective function is calculated and the optimum skew is obtained.

Next, the resulting objective function for PMLSM-1 is presented with its optimum skew.

$$\max\{O_1(\theta_1)\} = -0.3383\theta_1^2 + 0.516\theta_1 + 0.4154 \quad (7)$$

$$\text{For } \theta_1 \text{ from } \langle 0, 1.5\tau_{s1} \rangle$$

The optimal skew angle is.

$$\theta_1 = 0.76\tau_{s1} \quad (8)$$

Figure 5 shows the objective function for PMLSM-1 that shows the optimum angle near 0.76 τ_{S1}.

The procedures are the same for PMLSM-2.

$$\max\{O_2(\theta_2)\} = -0.0216\theta_2^2 + 0.1259\theta_2 + 0.5183 \quad (9)$$

$$\text{For } \theta_2 \text{ from } \langle 0,\ 1.5\tau_{s2} \rangle$$

The optimal skew angle is.

$$\theta_2 = 1.5\tau_{s2} \quad (10)$$

Figure 6 shows the objective function for the PMLSM-2 that shows the optimum angle is 1.5 τ_{S2}.s

On **Table 3** we can see the values of thrust and ripple, evaluated by means of FEM with optimal skew.

These results indicate that a reduction of 50.9% of ripple in the PMLSM-1 is obtained, whereas thrust only diminishes 9.1%. In the PMLSM-2, ripple is reduced in 54.1% and thrust only diminishes 10.9%.

Figures 7 and **8** shows the thrust without skew and optimal skew.

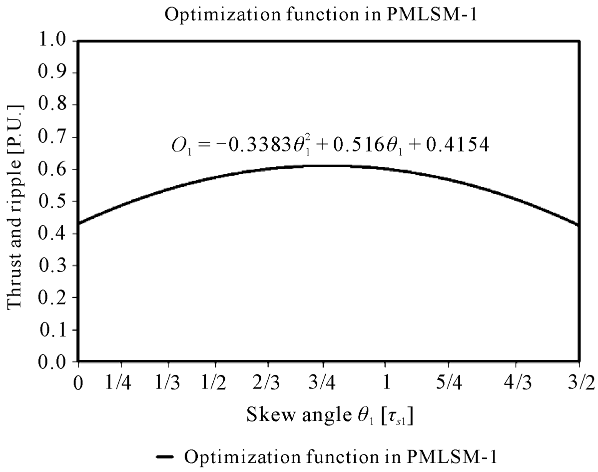


Figure 5. Objective function for PMLSM-1.

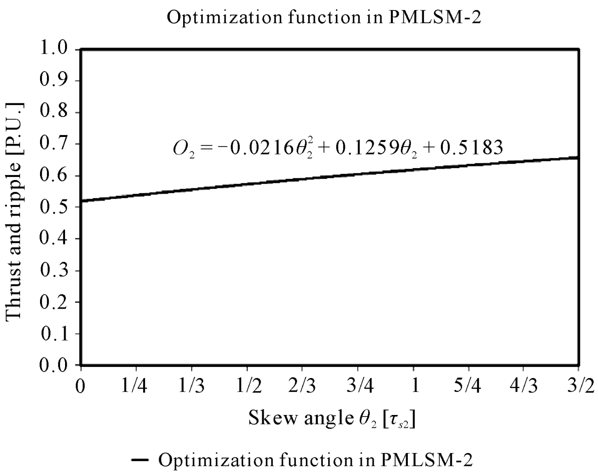


Figure 6. Objective function for PMLSM-2.

Table 3. PMLSM's thrust and ripple by fem.

Description	PMLSM-1	PMLSM-2
Thrust (N)	418.6	322.9
Ripple (N)	138.4	85.1

On the other hand, a common design objective is maximizing the thrust force while keeping the ripple force below a certain percentage of the thrust force, for that, is necessary change the k_1 and k_2 weights and introduce an additional condition [18].

$$k_1 + k_2 = 1 \quad (11)$$

For example, to maintain the ripple force at 30% of thrust force in PMLSM-1, the restrictive condition is

$$R_1 = 0.3T_1 \quad (12)$$

Consequently

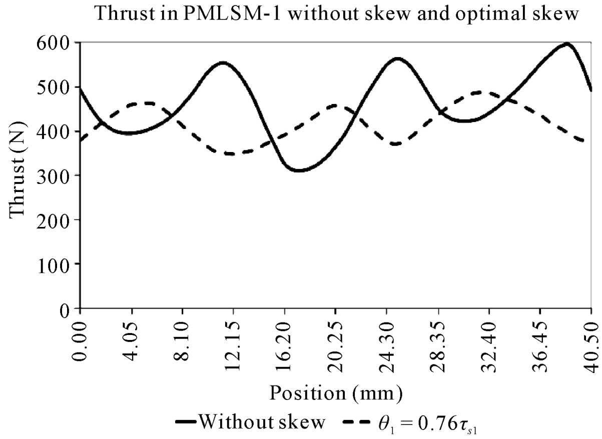


Figure 7. Thrust without skew and optimal skew for PMLSM-1.

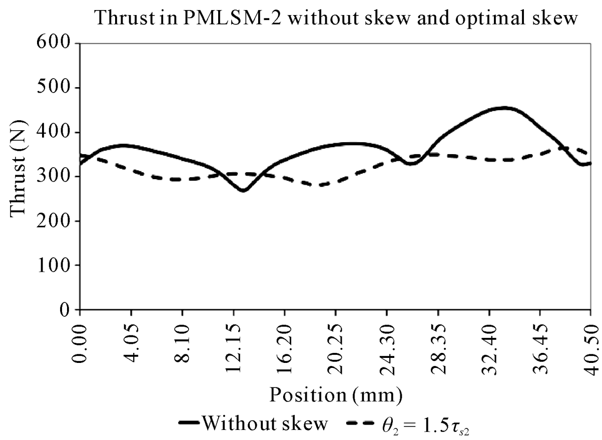


Figure 8. Thrust without skew and optimal skew for PMLSM-2.

$$k_1 = 0.23 \; k_2 = 0.77 \quad (13)$$

The objective function is

$$\max\{O_1(\theta_1)\} = k_1T_1 - k_2R_1 \quad (14)$$

$$\max\{O_1(\theta_1)\} = -0.1802\theta_1^2 + 0.3989\theta_1 - 0.2201 \quad (15)$$

For θ_1 from $\langle 0, 1.5\tau_{s1} \rangle$

The optimal skew angle is.

$$\theta_1 = 1.106\tau_{s1} \quad (16)$$

Computing in the optimal angle, the following results are obtained.

$$T_1 = 0.814 \; P.U. \quad (17)$$

$$R_1 = 0.243 \; P.U. \quad (18)$$

This indicates that the ripple value is 29.8% of the thrust. The difference with 30% is due to decimal taken into account.

Sometimes the priority is to reduce the ripple to the maximum, in other cases; the priority is to maximize the thrust, so it is necessary to give more weight to the role that is more important. To achieve this goal, we change the weights (k_1, k_2), so that, if the priority is to maximize the thrust, then $k_1 > k_2$, but if the priority is to minimize the ripple, then $k_1 < k_2$. Anyway, it is necessary to satisfy the condition (11).

5. Conclusions

The amplitude of ripple can be reduced significantly (50.9% in PMLSM-1 and 54.1% in the PMLSM-2) without diminishing thrust too much (9.1% in PMLSM-1 and 10.9% in PMLSM-2), using the combined method of FEM- Statistical Regression to find optimal skew for the PM's. The advantage of the method is that it is very simple to apply and does not use very complex techniques.

The proposed method has the advantage of using a small number of finite element simulations, because they can perform to a certain number of skew angles and from these data are obtained, and trend curves from these curves are obtained optimal values. Otherwise, it would be necessary to run simulations with very short steps and therefore would have a lot of time consuming simulation.

The methodology can be used also in cases in which it is desirable to limit the ripple to a certain percentage of the thrust. Additionally, the use of weight factors (k_1, k_2), it is useful to find optimal values in different circumstances, as in the case that gives equal importance to the maximization of the thrust and the ripple minimization. Also, the technique can be used for cases in which giving more importance to one of the functions to maximize or minimize.

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