THERMAL FIELD ANALYSIS IN DESIGN AND MANUFACTURING OF A PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR

Petar UZUNOV[1]

ABSTRACT: The modern Permanent Magnet Linear Synchronous Motors (PMLSM) has a wide range of applications due to high efficiency, high thrust force density and high acceleration. In order to ensure normal operation and maximum thrust force density, the thermal performance must be done in the design stage. Based on FEMM software, in this paper thermal Finite-Element Analysis (FEA) of a 10-pole, 12-slot flat-type iron core, PMLSM was made. This motor was the first linear servomotor designed and produced in Bulgaria as a main drive unit of one linear electromagnetic transportation system for light industry with multiple moving parts.

KEY WORDS: PMLSM, Thermal analysis, Finite Element Method.

1 INTRODUCTION

The permanent magnet linear synchronous motors (PMLSM) has been widely used in industrial automation, transportation and modern high-precision machine tools due to their advantages – simple structure, low noise, easy maintenance [1]. They convert electrical energy into direct linear motion without gears and chains and have high thrust force density, high efficiency and high acceleration.

Their parameters are in direct connection with temperature rising in work mode when copper and iron losses heat the linear motor parts. Thus it is important to know in design stage how the heating influences the motor electromagnetic parameters.

With the increasing needs for miniaturization, energy efficiency and cost reduction the designers of PMLSM go in the direction of forced current density. To maximize the winding exploitation they need to assume a high current density. But the high density values lead to rapid heating of the motor windings, and consequently to heating of the whole construction, including the built-in permanents magnets [2].

In modern PMLSM the rare earth permanent magnets (PMs) are used. The most popular PMs are NdFeB and SmCo.

It is well known that the PMs magnetic properties, especially of NdFeB ones, depend on temperature. They are unstable with the temperature rising and this decreases the PMLSM life cycle [3].

Thus it is important to calculate the steady–state temperature in the machine parts, caused by the long-time operation. At design stage the temperature distribution can be obtained through thermal field analysis via thermal resistance models, finite-element method (FEM) and computational fluid dynamics, and be verified through experimental results of linear motor prototypes.

In the proposed work the FEM was used for analysis of the PMLSM thermal field under continuous duty, when the final thermal state can be reached due to long operation time, i.e linear motor study-state thermal field was analyzed.

PMLSM can be classified as short primary and short-secondary types. A short primary type implies that the moving part carries the windings (power supply) and the frequency converter mechanism. For increasing the travel length, the secondary (the part carrying the magnetic track) has to be elongated.

Fig.1. shows the 3-D CAD model of the PMLSM under study. This 10-pole, 12-slot motor is constituted by a teethed iron core short primary 1 with three phase concentrated winding. The secondary 2 is composed of a set of alternating NdFeB magnets, mounted over a ferromagnetic back) iron [4].

[1] National-Local Joint Engineering Laboratory of High-Grade Stone Numerical Control Machining Equipments and Technology, Shenyang 110168, China.

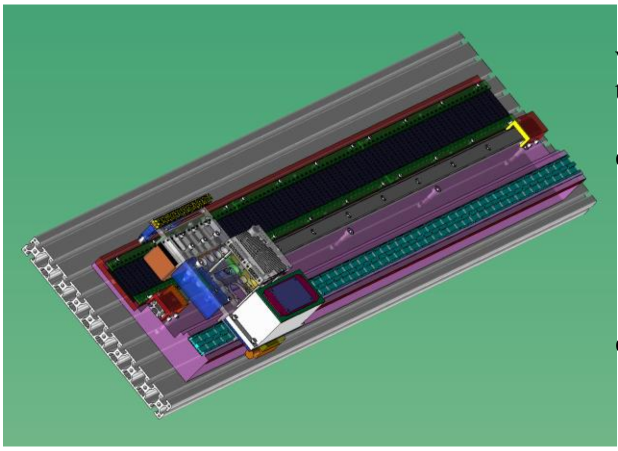

Fig. 1 Model 1.

The body of the moving part is mounted on a carriage which travels on a linear guide. Its main task is to reduce friction in the movement of the moving part and to neutralize the force of attraction to the permanent magnets (PM) with his little friction coefficient.

The motor is without cooling system. It is designed as a main drive unit of one innovation linear electromagnetic transportation system with numerous moving parts. Each of them is wirelessly supplied by planar transformer and is with independent wireless control.

2 FEM MODELING

To simplify thermal analysis, basic assumptions are proposed as follows:

- The impact of the end windings on the temperature distribution is ignored, allowing for the usage of 2D model.
- Iron losses are neglected and only copper losses are regarded as the only heat source.
- Environmental temperature is maintained at 23ºC.
- Due to the relatively low temperature of the machine outer surface, the radiation phenomenon is neglected.

2.1 Relevant equations

The static temperature field could be obtained after Poisson equation solution. The elliptic equation is expressed as [3]:

$$\overline{\nabla}(k\vec{\nabla}T) = -p \qquad 1)$$

where: p – power density generated in unit volume, k – thermal conductivity coefficient, T – temperature.

For the two-dimensional case in Cartesian coordinate system (1) it can be written as follows:

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} = -p\,. \qquad (2)$$

Power density generated in unit volume was calculated as follows:

$$p = \frac{P_{Cu}}{V}, \qquad (3)$$

where: P_{Cu} – copper losses, V – active linear motor volume. The copper losses have been calculated as:

$$P_{Cu} = I^2 R\,, \qquad (4)$$

where: I–motor current, R–motor winding resistance.

To determine the resistance at a higher temperature the well known equation has been used:

$$R = R_{20}\left(1 + \alpha\,(T - T_0)\right), \qquad (5)$$

where: R_{20} - cooper wire resistance by initial temperature T_0=200ºC, $\alpha = 0.0039$, 1/K – copper wire coefficient.

Two different kinds of boundary conditions have been assumed for the 2-D thermal problems. The first is Dirichlet condition, which allows setting fixed temperature value T0 on the outer boundary of the calculation region. The second one is the boundary condition for the convection. The heat transfer trough the outer surface of the motor is expressed as [3]:

$$k\,\overline{\nabla}T\,\vec{n} + h\,(T - T_0) = 0\,, \qquad (6)$$

where: h - heat transfer coefficient, $\vec{n}$ - unit vector normal to the boundary surface of the machine.

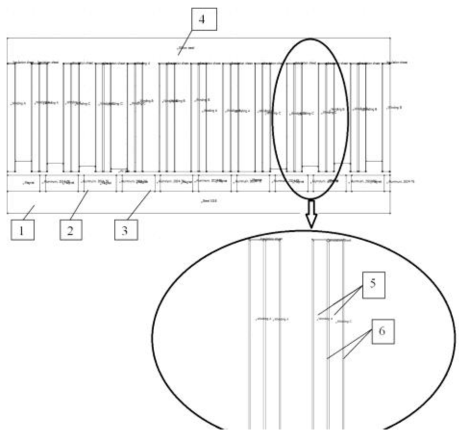

Fig. 2. 2D geometry of PMLSM for thermal modeling: 1-back iron; 2-PMs; 3- PMs nonmagnetic separators; 4-mover core; 5-winding; 6-slot insulation.

2.2 FEM model

The geometry of the 2-D FEM model is shown on Fig. 2.

Coil wires composed of multiple turns of wire are modeled as a bulk structure whose area is equal to bare copper. Because of the large temperature gradient in the area of insulation, the slot needs to be divided in detail in the FEA model. The materials of different motor parts as well as their thermal performance parameters are given in Table 1.

If the thermal conductivity of the material used is a function of temperature, for the analysis the thermal conductive curves (TCC) can be used, i.e. FEMM allows for the solution of non-linear thermal problems [5].

The thermal conductive curves TCC 1 and TCC 2 used in the modeling are shown on Fig. 3. These curves present the heat conduction coefficient versus temperature for the used materials in modeling. The winding resistance of one phase R_{20} = 2.77 Ω was measured at room temperature with the help of RLC – bridge.

Applying (5) the resistance R_{140}=2.77 Ω for one phase of the motor winding was calculated under maximum operating temperature as defined by the insulation class H (180ºC) - the coil is wound with copper wire of diameter 1.25 mm.

With this resistance the values of copper losses $P_{Cu} = 102$ W and power density generated in unit volume p = 687390 W/m3 were calculated.

Table 1. Material Properties

Item	Material	*k* (W/Mk)	P(Kg/m^3)	C_p(J/Kg*K)
Black iron	Steel1018	45	7800	460
Air gap	Air	TCC 1	1.205	1005
Magnet	NdFeB N52	9	7500	440
Winding	Cu	TCC 2	8900	380
Mover core	Silicon steel	66.1	7650	430
Slot insulation	Teflon	0.18	930	1340

2.3 Boundary conditions

For the other surfaces of non-moving motor parts boundary conditions as follows was used:

- Heat transfer coefficient h0 = 11 [W/m^{2}K];
- Ambient temperature T_0 = 23ºC.

The mover of the linear motor under study travels with linear speed of ν = 1.5 m/s and the motor winding was not compounded with epoxy. Therefore, the outer surfaces of the ferromagnetic core and motor concentrated winding have better cooling conditions, and the heat transfer coefficient here must be calculated according to this circumstance. For this purpose equation (7) was used [6]:

$$h_v = h_0 \left(1 + \sqrt{v}\right). \quad (7)$$

The calculated value of heat transfer coefficient in this case is h_v = 24.5 [W/m^{2}K].

The problem domain was discretized on the FEM mesh with 45926 nodes and 91441 triangle finite elements (Fig.4).

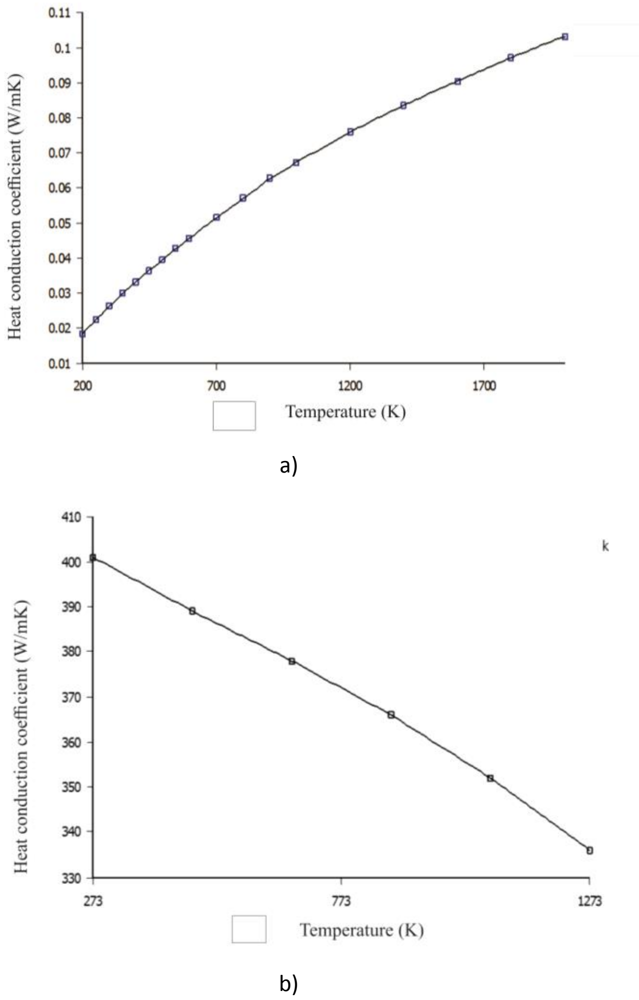

Fig. 3 Thermal conduction coefficient versus temperature: a) TCC 1 for Air; b) TCC 2 for Cooper.

The distribution of linear motor temperature, as a result from FEM solution, is shown on Fig. 5.

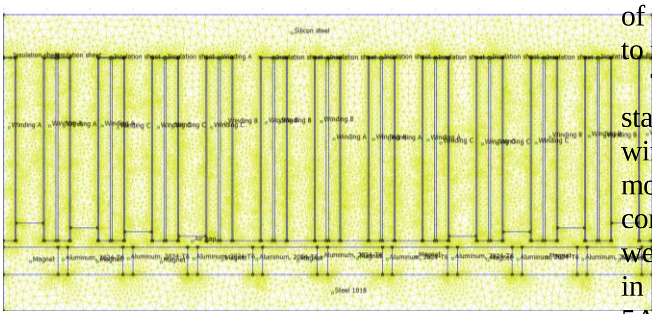

Fig. 4 Discretized problem domain of full FEMM model.

The calculated overheating values of main motor parts in stationary mode were given in Table 2.

Table 2. Values of the overheatings

Item	Point	Temperature (C^0)
Mover core	1	44.5
Motor winding	2	48.45
Permanent magnets	3	33.2

They are reached when during load mode the motor temperature stops rising due to establishment of thermal equilibrium.

As a result from FEA of PMLSM thermal field, in this study it is determined that motor winding overheating is less than the admissible value as defined by the insulation class of the wire conductor.

Furthermore, the operating temperature of the permanent magnets is lower than the permissible temperature of 800 C, above which their magnetic properties change.

3 EXPERIMENTAL VALIDATION OF RESULTS FROM THERMAL

To verify the results from FEA of thermal field one experiment for heating the linear motor in static mode was made.

The aims of the experiment were:

- First – to measure the steady–state temperature in the machine parts, caused by the long-time operation in continuous duty mode;
- Second – to experimentally verify the proposed model for thermal FEA of PMLSM;

The laboratory set system was equipped with a prototype of the investigated linear servomotor PMLSM-3. The experimental setup is shown on Fig. 6.

The main technical specifications of the test linear servomotor are given in Table 3.

As the motor winding was star-connected, first the star must be disconnected. Second, the three phases of the winding must be connected in series according to the scheme in Fig. 7.

The so connected motor winding was fed from DC stabilized source. The DC-current through the winding is 5A, equal to the r.m.s value of the rated motor current, according Table 3. Since under continuous duty the main heat source for motor coils were copper losses caused by the r.m.s current value, in this experiment the r.m.s current is defined by the 5A DC current. Such approach is fully justified because in Electrical Engineering the r.m.s value of AC current is defined by the DC current which generates the same heat amount in one and the same resistor.

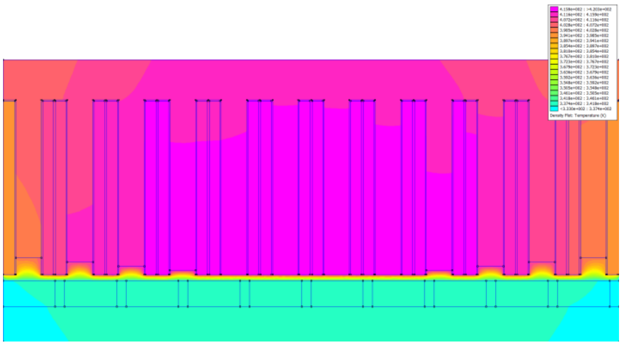

Fig. 5 Thermal field of linear motor.

Table 3. Specifications of the test bench

No.	Quantity	Value
1	Number of phases	3
2	Number of poles	10
3	Slots number	12
4	Rated phase voltage,	70 V
5	Rated phase current	5 A
6	Efficiency	0,6
7	Power factor	0,9
8	Air gap	1 mm
9	Pole pitch	15 mm
10	Tooth pitch	12,5 mm
11	Thrust	185 N
12	Speed	3 m/s
13	Mover mass	6 kg

Table 4. Comparison between simulation and experimental results

Item	Temperature (C^0)		
	FEM calculations	Experiment	Error, ε_M %
Mover core	44.5	40	11.2
Motor winding	48.45	44	10
Permanent magnets	33.2	30	10.6

The temperature measurements for different linear motor parts were provided using a thermocouple sensor included in the FLUKE 179 multimeter kit [7]. Measurements shall be terminated upon reaching the steady-state temperature.

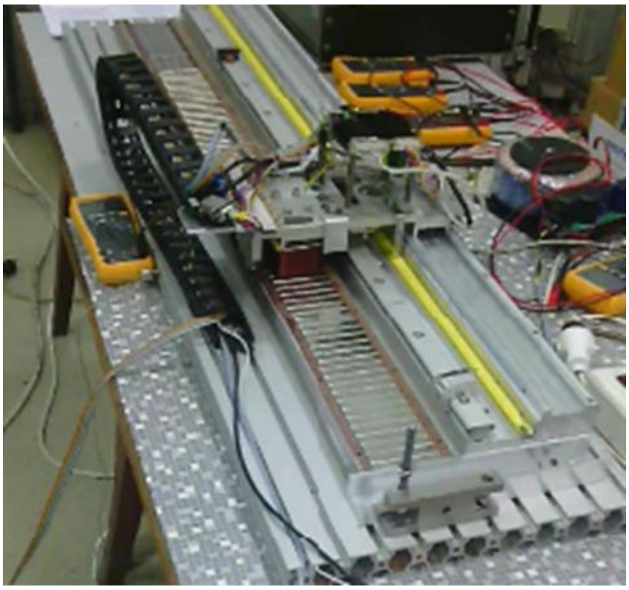

Fig. 6 Experimental test setup for linear servomotor PMLSM-3.

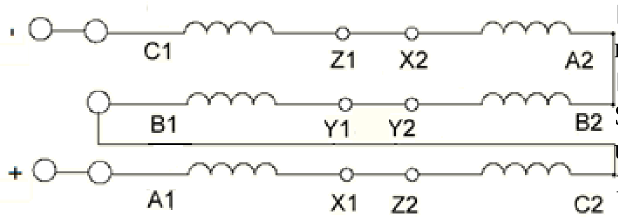

Fig. 7 Winding of PMLSM-3 series connected for the experiment.

The results from temperature measurements are given in Table 4.

The results from thermal FEA show good coincidence with the experimental results.

4 CONCLUSION

In this paper, a 2-D finite element package FEMM was used in order to perform thermal simulation of one iron core PMLSM in continuous duty mode.

The proposed model for thermal FEA of PMLSM was used in design simulations of the first in Bulgaria linear synchronous servomotor [4] and was experimentally verified with the prototype PMLSM-3 experimental study.

In design stage this model allows for the calculation of motor temperature distribution and the selection of proper current density for motor winding via coupling electromagnetic and thermal FEA.

5 REFERENCES

► [1] Gieras, J. F., Zbigniew J. , 2000, Piech, Linear Synchronous Motors: Transportation and Automation Systems, 2nd ed., Boca Raton, FL, USA: CRC Press LLC.

► [2] X. Zhang, Q. Lu, C. Cheng, Y. Ye, 2012, Magnetic and thermal analysis of a water-cooled permanent magnet linear synchronous motor, Journal of International Conference on Electrical Machines and Systems, 1/4: 498–504.

► [3] Waindok, A., 2012, Analysis of permanent magnet linear motor parameters taking heating into account, Archives of Electrical Engineering, 61/4: 471–482.

►[4] Uzunov, P. M., 2015, Linear electromagnetic transportation system, Mechatronica SC, Technical Report on Contract NIF-02-22 , Executive Agency for Promotion of Small and Medium-sized Enterprises, Gabrovo, Bulgaria .

► [5] Meeker, D., 2015, FEMM reference manual.[Online].Available:http://www.femm.info/Archives/doc/manual42.pdf.

► [6] Shastlivii, G., 1966, Heating of induction motors, Science community, Kiev.

► [7] Fluke 179/IMSK Industrial Multimeter Service Combo Kit. [Online]. Available:http://en-us.fluke.com/products/¬digital-multimeters/fluke-179-imsk-digital-multimeter-kit.html