THERMAL ANALISYS FOR A BILATERAL LINEAR INDUCTION MOTOR WITH SECTIONED PLATE ARMATURE

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Abstract

The paper presents an analysis of the thermal regime for a double sided linear induction motor with ring windings and sectioned plate armature which is sectioned with vertical cutting-up. The sectioned armature is done in order to reduce the eddy currents into the plate, which are not useful for the traction force of the linear motor. The motor can operate in an oscillating drive system with fast response and low distance movement or for small and medium movement application. For different forces developed by the motor, a thermal modeling is realized for the linear induction motor and it is compared with experimental data regarding the thermal aspects. The theoretical characteristics of the motor heating overlap the experimental characteristics and confirm the validity of the thermal model.

Keywords: Bilateral linear induction motor, plate armature, thermal, modeling

Introduction

The linear induction motors are used for linear drives where they can replace the rotary electric machines and hydraulic or pneumatic equipments with linear movement.

Thermal regime of the linear induction (LIM) motor operating in an oscillating regime is an important factor which can affect the structure, the winding insulation and finally, the drive operation. The thermal regime depends on the supply system characteristics, on the driven kinematics, as well as on the linear motor structure and on its cooling system. An analysis of the thermal processes with allowance for the technique used for cooling is very important when studying the operation modes of different equipments (Plesca, 2013, Paalvast, 2009) including linear motor high-speed positioning (Yamaji, 2000). The need for this type of analysis can arise when designing an a.c. or d.c. linear motor (Abdou, 2000, Chevalier, 2006), but also for the supplying systems and for the protection of the systems, as in (Plesca, August 2012**,** Plesca, 2011)**.**

Analytical and numerical methods were developed to optimize linear induction motor supply with respect to criteria such as the efficiency or the force (Rinkevičienė, 2004). The analysis uses finite elements calculation in the motionless region; the boundary between the rail and the air-gap requires a special statement (Takorabet, 1997).

In some situation, to improve the thermal behavior, an insulation layer is used. By placing the insulation layer between the primary part of the machine, the temperature difference and temperature fluctuation in the machine due to varying motor load are reduced (Ung, 2003).

The linear induction motor was proposed to be use for dynamic braking in eddy current brake systems. The LIM reduces rail heating, but a thermal analysis of the linear induction motor is still necessary. The reduction ratio of heating is approximately proportional to the frequency (Sakamoto, 2012).

The linear induction motor can be used for the automotive suspension system (Hyniova, 2012) where a three-phase linear motor is used, with a limitation for the maximum temperature of 100 ^{o}C. The linear motors as actuators enable to transform mechanical energy of the vertical car vibrations to electrical energy, accumulate it and use it when needed.

An original application of the LIM can be the wave-energy conversion (Danson, 2008). Moreover, double-sided designs increase the air-gap of the machine, linking more flux than single-sided machines.

Some systems must have high performance such as high precision and high speed. It is, therefore, important to analyze, design and control linear motor used widely as an actuator in the precision stage. For a double-sided linear motor with yoke and multi-segmented array, the coating of the coil cannot stand the temperature more than 120 ^{o}C (Lee, 2006).

Thermal analyses can be conducted by means of analytical or numerical methods. In (Szymczak, 2010) features LIM are considered and three mathematical models are developed with help of detailed thermal equivalent circuits. These circuits are distinguished by different degrees of adequacy.

Another possible application of the linear induction motor is to drive the pantograph collecting system for the electric vehicles, like trains and tramways (Nituca, 2003). In this case the motor assures the contact force for the contact between the catenary and the contact line. Moreover, its control assures a better contact and improves the current collection process and reduces the wear of the pantograph and of the contact line and reduces the detachments of the pantograph skate from the wire (Nituca, 2007). All of these are very important considering the complexity of the electric vehicle supplying from a contact line, especially at very high speed (Cantemir, 2011).

Using the linear induction motors for elevators in high buildings is also a special application (Lim, 2008, Onat, 2010) which needs optimized design and control system.

The end effects are the particular sensitive difficulty to model linear drives. 3D magnetic and thermal models are achieved taking into account the end effects and the multiphysical aspects for a linear motor studied as a braking system with different displacement velocities. The startup thrust force is studied with the coupling between the magnetic and thermal models (Gong, 2010).

The construction of the linear induction motor with ring windings

The linear motor considered (Fig. 1) is a three-phase one, bilateral, with a vertical plate mobile armature (1) from copper. On the two inductors (2a and 2b), we place the ring windings in 24 slots, yielding the coils (3). The mobile armature has an oscillating movement (4) on a distance of about 0÷150 mm. The plate armature is vertical cutting-up sectioned. The sectioned armature is done in order to reduce the horizontal eddy currents into the plate, which are not useful for the traction force of the linear motor.

Moreover, the sectioned plate armature can be seen as a squirrel cage from a rotary asynchronous motor when the cage is cut over a generatrix line and is uncoiled in plan. Thus, we try to simulate the situation of the rotary machine. It is to notice that some special effects of the linear motors (edge effects) are neglected, in order to simplify the thermal model.

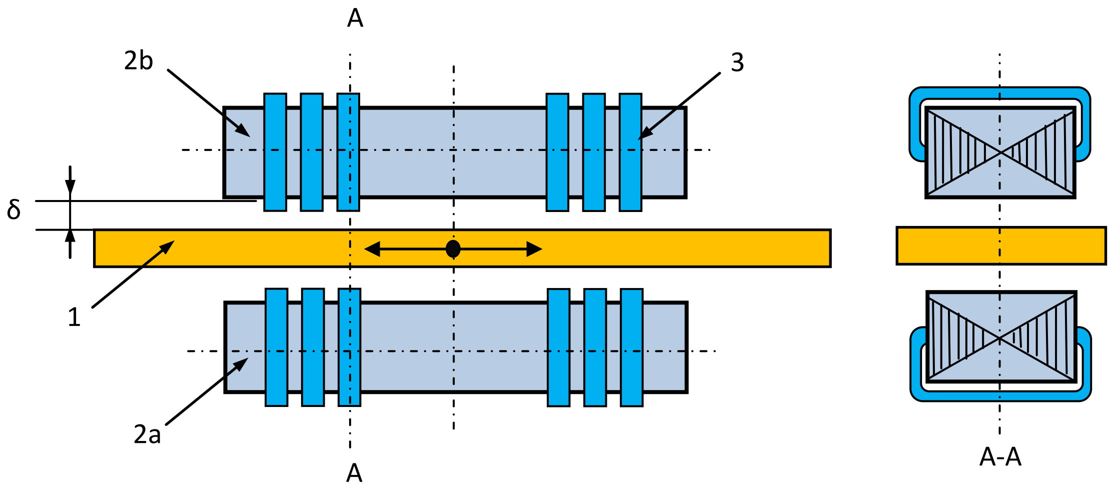

Fig. 1. The double sided linear induction motor.

The synchronous speed v_s of the linear motor depends on the pole pitch τ_p and on the voltage supply frequency f ($v_s = 2\tau_p f$); it results that the length of the head coils will increase with the synchronous speed because of the increasing of the pole pitch. A ring winding eliminates such dependence and, in some situations, it becomes more favourable. Using a ring winding gives a good influence on the induced currents path and distribution and on the starting effort.

Heat transfer is the principal restrictive effect on the motor power. Therefore, the thermal behavior must be taken into account in all motor designs. For the small oscillating movements (les than 100 mm), the armature plate will be almost all the time in the same relative position with respect to the inductors, which will give a higher heating and consequently a modification of the machine's parameters.

The estimation of the temperature of the windings can be made by indirect method (using a mathematical relationship (Livint & Stan, 2001, Plesca, 2008), or by direct method (using specific devices for the temperature measurement and monitoring (Livint & Stan, 2001, Scintee & Plesca, 2009). Finite element method is also used for heat transfer analysis in three-phase linear motor (Huang, 2010).

The vertical cutting-up were made into the plate as in Fig. 2.

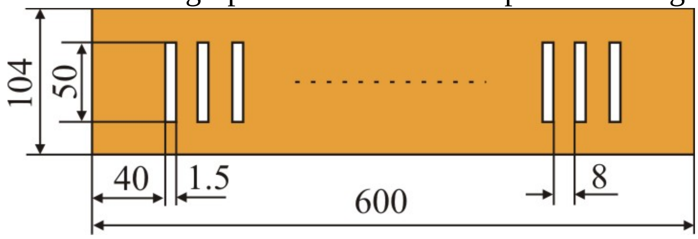

Fig. 2 The armature plate with vertical cutting-up.

The heating differential equation for the linear motor

The linear motors are more difficult to study from the thermal point of view in comparison with the rotary motors because of their specific construction and the related electromagnetic process. The starting point is the power balance equation for each volume element dV,

$$P_c = P_t - P_r + P_a \qquad (1)$$

The left term of the equation is the heating power from the current flow, P_c. It is in balance with the heat stored by temporal change of temperature P_t, the power removed from the element by thermal conduction P_r, and the thermal power dissipated to the surrounding area by the surface convection, P_a. For P_c, P_t, P_r and P_a, the following equations can be written:

$$P_c = \iiint \rho j^2 dV \qquad (2)$$

$$P_t = \iiint \gamma c \frac{\partial \theta}{\partial t} dV \qquad (3)$$

$$P_r = \iiint div(\lambda \cdot grad\theta)dV \quad (4)$$

$$P_a = \iiint k\frac{l}{S}(\theta - \theta_a)dV \quad (5)$$

Thus,

$$\iiint \rho j^2 dV = \iiint \gamma c\frac{\partial\theta}{\partial t}dV - \iiint div(\lambda \cdot grad\theta)dV + \iiint k\frac{l}{S}(\theta - \theta_a)dV \quad (6)$$

The material density, specific heat and thermal conductivity do not have an important temperature variation; thus they can be regarded as constants. On the other hand, the electrical resistivity has a significant temperature variation and can be estimated through a parabolic variation or a linear one. The experimental tests concluded that the difference between these two types of variation is not so important. For the electrical resistivity a linear variation with the temperature has been considered (Plesca, February 2012, Nituca, 2013):

$$\rho = \rho_0[1 + \alpha(\theta - \theta_a)] \quad (7)$$

and with the notation:

$$\vartheta = \theta - \theta_a \quad (8)$$

the following relation is obtained:

$$\iiint \rho_0(1 + \alpha\vartheta)\frac{i^2}{S^2}dV = \iiint \gamma c\frac{\partial\vartheta}{\partial t}dV - \iiint div(\lambda \cdot grad\vartheta)dV + \iiint k\frac{l}{S}\vartheta dV \quad (9)$$

The equation is a nonlinear and nonhomegeneous one, and it can be resolve by numerical methods. By using finit element method it can be estimate the thermal variation within the motor by 3D thermal simulation.

It is to mention that the heat loss by radiation can be expressed as (Chow, 2012):

$$Q = \varepsilon\sigma A\left(T_{surf}^4 - T_{Amb}^4\right) \quad (10)$$

Where:

- ε is the emissivity of a surface depending on the surface orientation and roughness,
- σ is the Stefan-Boltzmann constant.
- j – current density;
- ρ – electrical resistivity;
- γ – material density;
- c – specific heat;
- λ – thermal conductivity;
- θ – temperature;
- θa – ambient temperature;
- α – coefficient of electrical resistivity variation with temperature;

In practice, the amount of the heat loss by radiation is negligible and many researchers prefer to omit it.

Thermal modelling and simulations of the linear induction motor with sectioned plate armature

A thermal model of the linear induction motor with sectioned plate armature was made in order to estimate the heating areas into the motor. The geometrical model of the motor is presented in Fig. 3 , where 1 is the sectioned plate armature, 2 are the inductors, 3 are the ring windings and 4 are the yokes. It is to mention that the plate armature is considered as acting with a constant forceover a drive system.

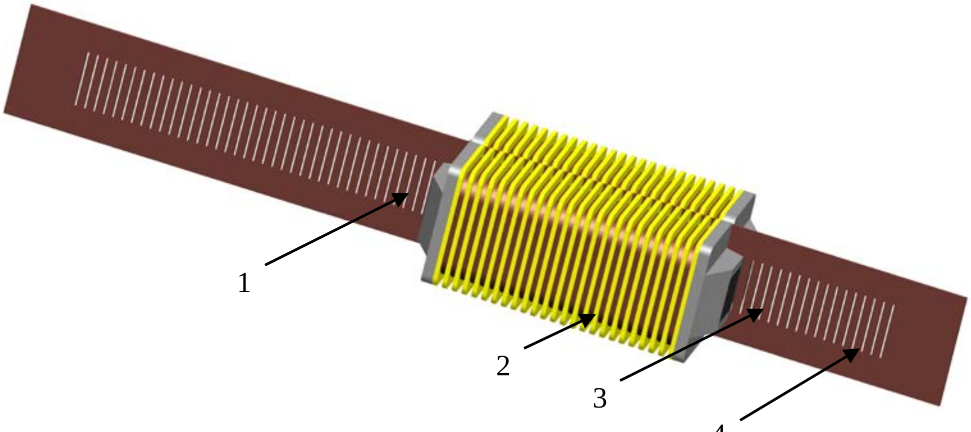

Fig. 3 Geometrical model of the linear induction motor: armature plate and inductors

The thermal distribution over the linear motor is presented in Fig. 4, with an ambient temperature of 20^{o}C. The temperature distribution shows a maximum value in the middle of the inductors, with about 96 ^{o}C, close to the experimental maximumdata of about 89÷90 ^{o}C.

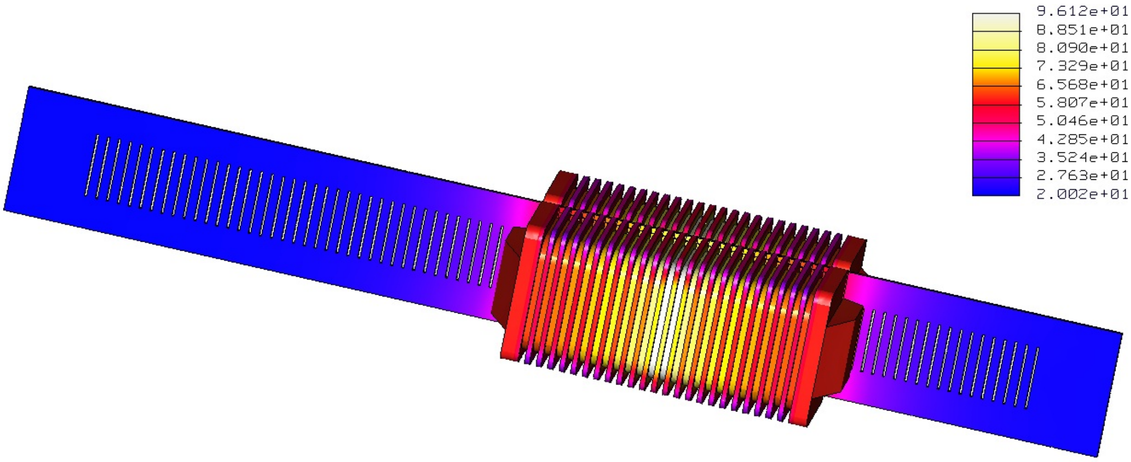

Fig. 4 Thermal distribution for the double sided linear induction motor.

A section through the motor shows a better image of the temperature distribution, with the central area of higher temperatures. This is to explain by the small cooling process between the inductors. At the edges of the inductors the temperatures decrease at about 45÷56 ^{o}C, where the heat can be release easily to the ambient medium. Into the plate armature, the temperatures varies from about 96 ^{o}C inside the inductors space, to less than 30 ^{o}C outside the inductors and to about 20 ^{o}C at the edges of the plate armature.

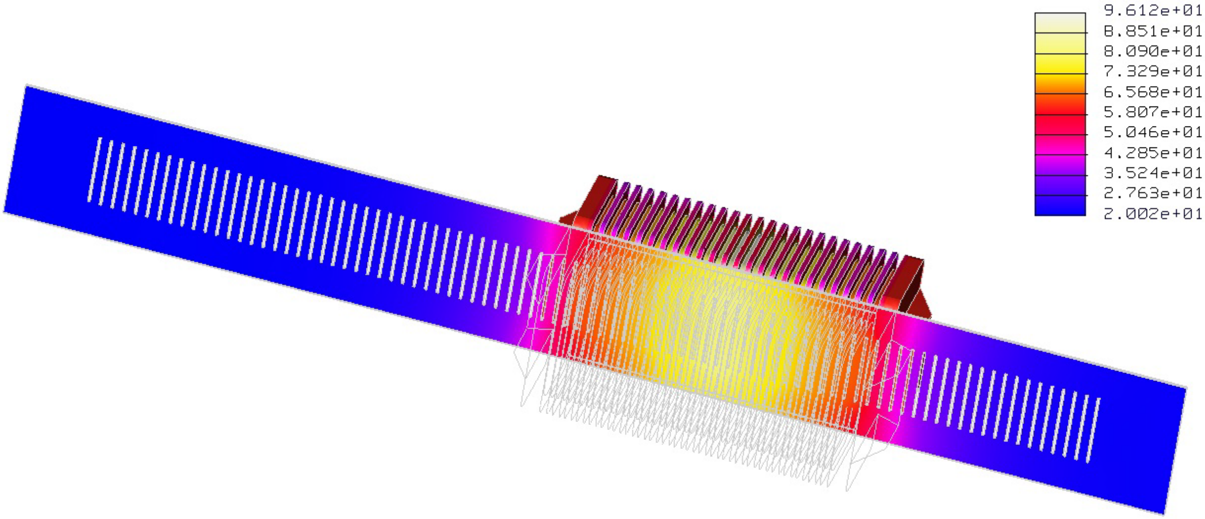

Fig. 5 Thermal distribution for the linear induction motor - section through motor.

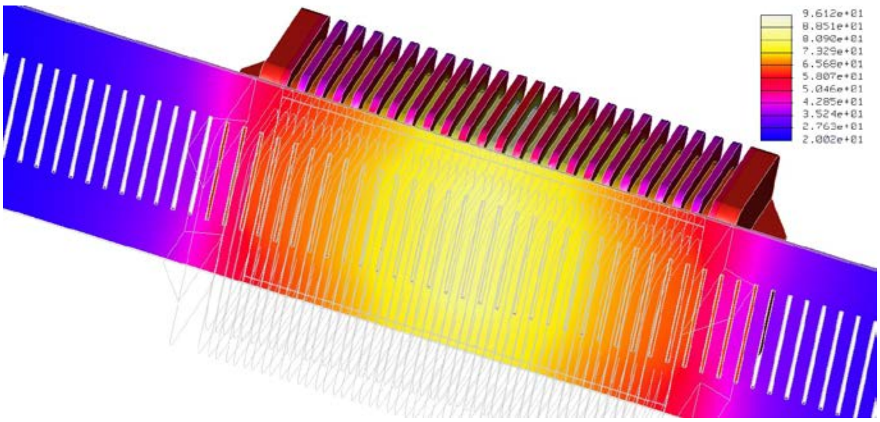

Fig. 6 Thermal distribution for the linear induction motor - section through motor, detail.

Experimental thermal tests of the linear induction motor with ring windings and sectioned plate armature

The estimation of the temperature increase of the windings and of the other parts of the motor is made with a locked armature. The inductor is supplied, for first tests, at rated voltage and rated frequency from a three-phase symmetrical supply system (by a three-phase autotransformer). For the second test the motor is supplied by a alternative voltage variator. The supply schema is given in figure 4. The estimation of the temperature increase of the windings and of the other parts of the motor is made with a locked armature. The inductor is supplied, for first tests, at rated voltage and rated frequency from a three-phase symmetrical supply system (by a three-phase autotransformer). For the second test the motor is supplied by a alternative voltage variator.

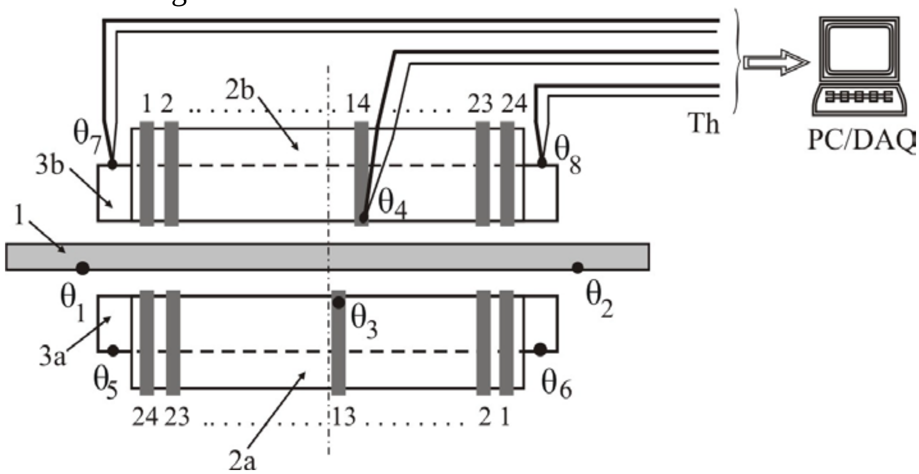

Fig. 7. The measurement points for the temperature on the linear induction motor.

Figure 7 represents the temperature measurements points of the linear motor. On the armature plate (1) the temperatures where measured in points θ_1 and θ_2 at the edges of the plate and between the inductors *2a* and *2b*. For the coils (24 on each inductor) the temperature is measured in point θ_3 on the 13th coil of the inductor *2a* and in point θ_4 on the 14th coil of the inductor *2b* because these are the coils with maximum temperatures. For the yokes *3a* and *3b*, the temperature is measured on the points θ_5, θ_6, θ_7, θ_8. All of these will give a large view over the variation of the temperature in the motor.

Table 1. Measured temperatures at different points of the motor for armature plate with vertical cutting-up for a force of 40N

Time [Min]	$\theta_{armature}$ [C^o]		$\theta_{inductors}$ [C^o]		θ_{yoke} [C^o]			
	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8
0	23	23	23	23	23	23	23	23
10	24	25	34	37	27	28	26	29
20	25	26.5	37	44	32	34	27	30
30	26	28	43.5	51	36	37	36	39

40	27	30	48.5	56	40.5	43	39	42
50	27	31	53.5	62	41	44	39.5	43.5
60	27.5	31.5	56	64	45	47	40.5	46
70	28	32	58	68	48	50	47	49.5

Figure 8 presents the experimental heating curve 1 and the estimated heating curve 2 for a heating time constant of 1300 seconds. According to (Nituca, 2013) the corrections can realised to obtained the heating curve 3 which is more precise and is for a time constant of 1750 seconds.

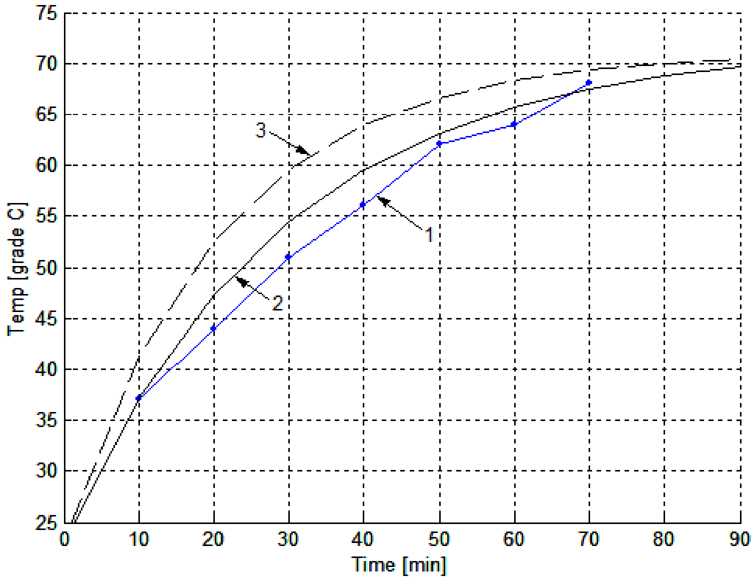

Fig. 8. The heating curves of the inductor number 2 for armature plate with vertical cutting-up.

Table 2 presents the temperatures for a test for 380 [V] and 1,7 [A] and a force of 70 N for the plate armature non-sectioned (Nituca, 2013), the maximum temperature after 60 minutes being 85.5 ^{o}C, the maximum estimated temperature being of 93 ^{o}C.

Table 2. Measured temperatures at different points of the motor for a force of 70 N with plate armature

Time [Min]	$\theta_{armature}$ [C^{o}]		$\theta_{inductors}$ [C^{o}]		θ_{yoke} [C^{o}]			
	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8
0	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5
10	25.5	25.8	44	51	33	34	30	29
20	26	27.5	52	59	43	45	33	33.5
30	28	31	68	71	52	57	38	37
40	29	21.9	71	73.5	56	61	39.5	39
50	30	30.5	76	80.5	65	68	42	44
60	30	31	83.5	85.5	67	69	43	45.7

Table 3. Measured temperatures at different points of the motor for a force of 70 N with sectioned plate armature

Time [Min]	θ armature [C^o]		θ inductors [C^o]		θ yoke [C^o]			
	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8
0	20	20	20	20	20	20	20	20
10	31.3	31	49.7	56.9	37.9	38.6	35.2	34.8
20	31.8	32.7	57.7	64.9	47.9	49.6	38.2	39.3
30	33.8	36.2	73.7	76.9	56.9	61.6	43.2	42.8
40	34.8	27.1	76.7	79.4	60.9	65.6	44.7	44.8
50	35.8	35.7	81.7	86.4	69.9	72.6	47.2	49.8
60	35.8	36.2	89.2	91.4	71.9	73.6	48.2	51.5

Comparing the data for the full plate armature and the sectioned plate armature, it is to see that the temperature variation is higher on the sectioned armature, due to the lower section and lower space for cooling area.

These aspects result also from the experimental data and from the simulations realized for the two cases. For the sectioned armature, the maximum temperature for the thermal modeling is about 96 ^{o}C (Fig. 5) and the maximum temperature from the experimental data is 91.4 ^{o}C. The differences in temperatures are less then 6%, which confirm the validity of the thermal model.

Conclusion

The paper presents a study of the heating phenomena for a double sided linear induction motor with sectioned plate armature and ring windings for different forces of the motor. A thermal model for the linear induction motor with the sectioned plate armature is realized in order to estimate the heating variation in the motor. It results that the theoretical characteristics of the motor heating overlap the experimental characteristics and confirm the validity of the thermal model. The futures researches are to be made with a cooling system place on the linear induction motor, in order to assure lower temperatures during the operating time and a long life of the motor.

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