Electromagnetic and Thermal Analysis of a Small Permanent-Magnet Tubular Machine

Ioana-Cornelia VESE[(1)], Fabrizio MARIGNETTI[(2)], Roberto DI STEFANO[(2)], Mircea M. RADULESCU[(1)]
[(1)]Small Electric Motors and Electric Traction (SEMET) Group, Technical University of Cluj-Napoca
P.O. Box 345, RO-400110 Cluj-Napoca 1, Romania,
E-mail: ioana.vese@mae.utcluj.ro
[(2)]DAEIMI-Department of Automation, University of Cassino
Via G.Di Biasio 43, I-03043 Cassino(FR), Italy
E-mail: marignetti@unicas.it

Abstract – This paper describes a simple thermal model of a Permanent–Magnet Tubular Machine, using analytical predictions and comparing them with the experimental results. The electromagnetic behavior is also investigated. These issues are important in order to obtain an optimum design and improved dynamic performances. Few studies on the subject can be found in the technical literature regarding thermal analysis of a Permanent–Magnet Tubular Machine. The results bring out some particularities in the machine's performances, related to the unconventional geometry of the machine.

Keywords: Permanent-Magnet Tubular Machine, Thermal Model, Losses.

1. INTRODUCTION

Linear machines are electromechanical converters, capable of linear translation, progressive or oscillatory motion, and offering new solutions for direct-drive systems in fields like household appliances, vehicle accessories, industrial manufacturing, robotics, and microsurgery. In particular, permanent-magnet tubular machines have the advantage of a simple design, high reliability, high force/energy density, fast response and good servo characteristics. In order to obtain an optimized prototype and higher dynamic performances, electromagnetic and thermal investigations are required, even if the latter has not been intensively studied.

The prototype of the permanent-magnet tubular (PMT) machine, built in the Laboratory of Industrial Electronics of the Department of Automation of the University of Cassino, Italy, is presented in Figure 1.

The main purpose of the present work is to analyze the electromagnetic and thermal behaviors of a PMT machine during transients. Experimental evidence helped to point out some peculiarities of the thermal behavior of the machine that can be easily taken into account in the model.

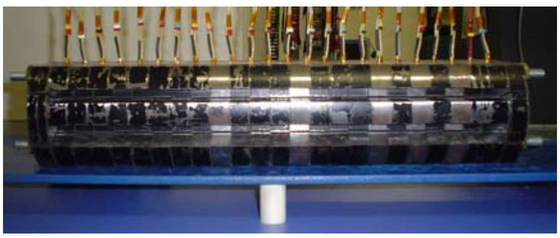

Figure 1: Prototype of the Permanent-Magnet Tubular Machine

2. ELECTROMAGNETIC MODEL

In order to determine machine's parameters and to predict its performances as accurately as possible, Finite Element (FE) analysis was used. The cylindrical symmetry of the structure and the axial symmetry with respect to the central axis, allow establishing a simple model of this machine; based on appropriate Maxwell's equations, FE analysis is then performed.

Figure 2 displays the magnetic flux distributions along one polar pitch for properly set current densities in the slots, when the translator is aligned with the stator *q*- and *d*-axis, respectively.

The first simulation was carried out with only the magnets present, i.e. with no current in the coils. The cogging force generation mechanism is revealed, due to flux lines at the edge of the motor having different

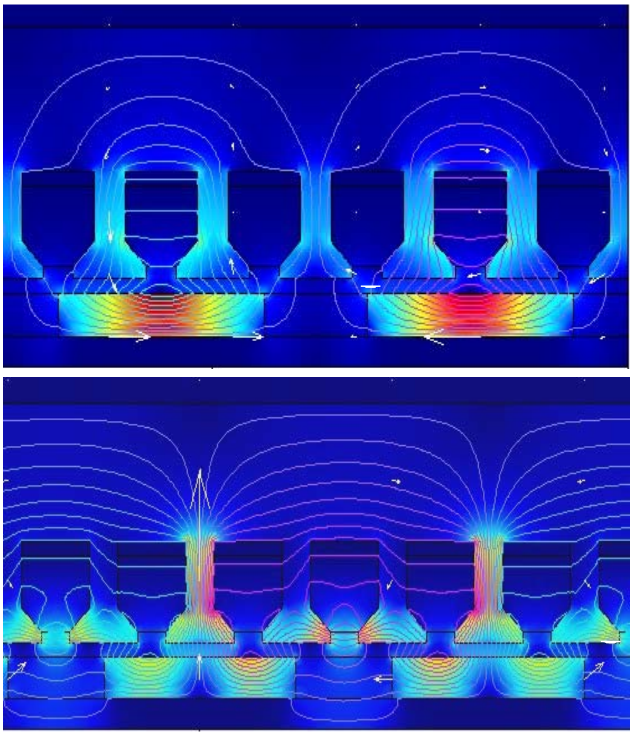

Figure 2: The magnetic flux density along one polar pitch with translator aligned on stator *q*- and *d*-axis, respectively

lengths. Further simulations were carried out with active magnets and currents, in order to provide the magnetic field in the air-gap for both *q*- and *d*-axes.

The measurement of L_q and L_d is detailed, emphasizing the steps that were made. First, the translator was appropriately mounted, while the magnets were replaced by air and the values of current densities in various slots were set so that the generated magnetic flux is in phase with the *d*-axis.

The flux was calculated, thus allowing determination of inductances on *d*- and *q*-axes. Results are listed in Table 1.

Table 1: Values of the inductances

Current [A]	J [A/m2]	Ld [mH]	Lq [mH]
1	763923.115	23.5	73.8
2	1527846.229	23.5	73.8
3	2291769.345	23.5	73.8
4	3055692.459	23.5	73.8
5	3819615.574	23.5	73.8

From the performed simulations, one can notice that the iron parts are not saturated, due to the low magnetic flux density in the air-gap. During the last simulation, thrust is FE-computed, as seen in Figure 3; the obtained loss values will be further used in the thermal model.

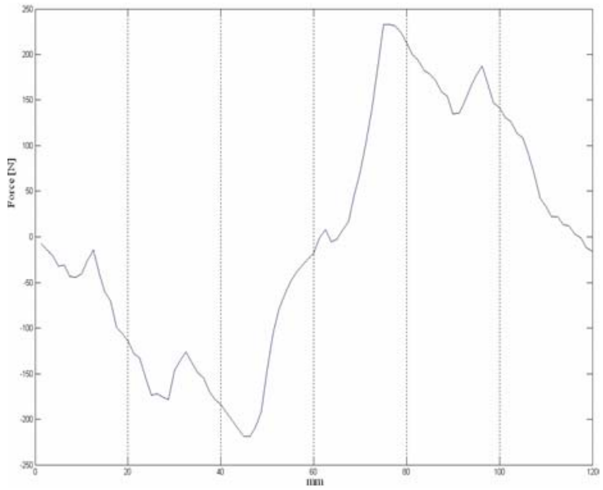

Figure 3: FE-computed thrust of the PMT machine

3. THERMAL MODEL

An accurate thermal model of a PMT machine must take into account all the exothermal parts, resulting into a complicated network of thermal resistances and capacitors. For sake of simplicity, a one-dimensional model is adopted for the analytical study. In this case, one deals with two main loss sources: copper loss P_{Cu} and iron loss P_{Fe}.

These losses encounter the thermal resistances of the winding, iron and environment. The whole model is shown in Figure 4 with reference to the transient state of the PMT machine.

Capacitors are included in the thermal network accounting for thermal capacitances of the materials.

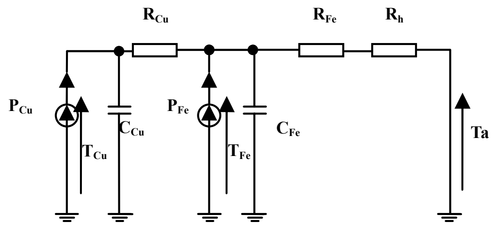

Figure 4: Thermal circuit of the PMT machine under transient operation

In the thermal model, T_{Cu} denotes the temperature of the windings, T_{Fe} is the temperature of the iron, T_h, the temperature of the environment, assumed equal to 23^0 C; C_{Cu}, C_{Fe} define the thermal capacitances of copper and iron, respectively.

Two kinds of heat transfer are modeled: natural convection and thermal conduction.

The natural convection is considered between the external surface of the PMT machine and the environment, and the corresponding thermal resistance R_h is described by

$$R_h = \frac{l}{h \cdot A} \tag{1}$$

where *l* is the specific length of the motor (m), h defines the natural convection coefficient (W/m^2.^{0}C) and A represents the area in contact to the environment (m^2).

The natural convection coefficient is calculated in a mathematical cycle, taking into account the Nussel's number, which dynamically changes with respect to the film temperature of the machine.

The thermal resistances of the copper and iron are conduction resistances given by

$$R_{Cu,Fe} = \frac{L_{Cu,Fe}}{\lambda_{Cu,Fe} \cdot A_{Cu,Fe}}, \tag{2}$$

where $L_{Cu,Fe}$ (m) and $A_{Cu,Fe}$ (m^2) are the specific length and area of the copper and iron, respectively, and $\lambda_{Cu,Fe}$ (W/m.^{0}C) represents the thermal conductivity of the material.

The general relationship for thermal capacitances is

$$C = \rho \cdot V \cdot c\,, \tag{3}$$

where ρ defines the mass density of the considered object (kg/m^3), *V*, its volume (m^3) and *c*, its specific heat (kJ/kg/^{0}C). At steady-state, all capacitors are deleted from the thermal model.

Iron losses are calculated from the electromagnetic analysis. The magnetic hysteresis and the main eddy-currents have been taken into account, while the excess eddy-current component has been neglected.

The instantaneous copper losses are given by

$$P_{Cu} = 3 \cdot R_0 \cdot i^2 \cdot [1 + \alpha(T - T_a)] \tag{4}$$

where *i* is the current, T_a is the ambient temperature, R_0 is the phase resistance measured at the base temperature, *T* is the current temperature and α is thermal coefficient.

4. ANALYTICAL STUDY

The differential equations of the thermal model for the PMT machine can be written as

$$\begin{cases} P_{Cu} = C_{Cu} \cdot \dfrac{dT_{Cu}}{dt} + \dfrac{T_{Cu} - T_a}{R_{Cu}} \\ P_{Fe} = C_{Fe} \cdot \dfrac{dT_{Fe}}{dt} + \dfrac{T_{Cu} - T_{Fe}}{R_{Cu}} + \dfrac{T_{Fe} - T_a}{R_h + R_{Fe}} \end{cases} \tag{5}$$

The time-discretization of these differential equations for the transient operation of the PMT machine leads to a system of algebraic equations to be iteratively solved.

The computation of temperatures is performed by supposing the ambient temperature as the reference one. The discretized system is given by

$$\begin{cases} T_{Cu}^{(i)} = \dfrac{P_{Cu} \cdot \Delta t}{C_{Cu}} + T_{Cu}^{(i-1)} \cdot \left(1 - \dfrac{\Delta t}{C_{Cu} \cdot R_{Cu}}\right) + T_{Fe}^{(i-1)} \cdot \dfrac{\Delta t}{C_{Cu} \cdot R_{Cu}} \\ T_{Fe}^{(i)} = \dfrac{P_{Fe} \cdot \Delta t}{C_{Fe}} + T_{Fe}^{(i-1)} \cdot \left[1 - \dfrac{\Delta t}{C_{Fe} \cdot R_{Cu}} - \dfrac{\Delta t}{C_{Fe} \cdot (R_h + R_{Fe})}\right] + \\ + T_{Cu}^{(i-1)} \cdot \dfrac{\Delta t}{C_{Fe} \cdot R_{Cu}} + T_a \cdot \dfrac{\Delta t}{C_{Fe} \cdot (R_h + R_{Fe})} \end{cases} \tag{6}$$

where Δt represents the time step of the implemented model. In each iteration step of the implemented model, copper and iron losses, and then the temperatures, are calculated, until thermal steady-state behavior is reached. Temperature values change slowly in time due to the thermal capacitance effect. The values of the resistances and the capacitances in the thermal network of Figure 4 are given in Table 2.

Table 2: Values of resistances and capacitances of the thermal network

Parameter	Value
R_h	0.6942 [K/W]
R_{Cu}	0.1189 [K/W]
R_{Fe}	0.0218 [K/W]
C_{Cu}	369 [J/K]
C_{Fe}	7207.6 [J/K]

The thermal resistance of the windings was obtained considering the air spaces between wires and the insulation. Actually, the wires were insulated with enamel paint, impregnated with epoxy and externally insulated with Kapton® tape.

5. EXPERIMENTAL RESULTS

The above-described model was used to verify the thermal behaviour of the PMT machine, having the main parameters and design data given in Tables 3 and 4, respectively. All the experimental tests have been carried out in the Laboratory of Industrial Electronics of the DAEMI Department, University of Cassino, Italy.

Two thermo-couples have been mounted on the PMT machine prototype, one at the outer surface of the stator, and the other one, embedded in the windings. As the temperatures change slowly, the measurements were recorded for two hours. The tests were done with the machine operating in generator mode. A test rig was built using a brushless motor drive to produce alternative motion.

First, the tests were carried out considering that the heat exchange in the stator is made through the external surface of the iron cylinder:

$$A_{Fe} = 2 \cdot \pi \cdot r_{Fe} \cdot L_{Fe} \tag{7}$$

where r_{Fe} represents the stator outer radius and L_{Fe}, the stator axial length.

The simulations obtained under these assumptions were compared with the experimental results, as shown in Figure 5.

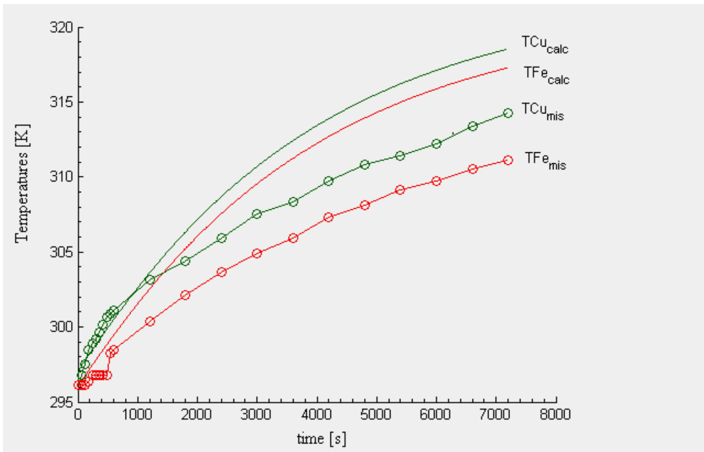

Figure 5: Calculated and measured temperatures.

It can be seen in Figure 5 that, if one considers just the outer surface of the stator, the simulated and the measured temperatures fit not well. Hence, the concerned iron surface of the outer stator has to be enlarged as

$$A_{Fe} = 2 \cdot \pi \cdot r_{Fe} \cdot L_{Fe} + 2 \cdot \pi \cdot r_{in} \cdot L_{stroke} \, . \tag{8}$$

Table 3: Main parameters of the PMT machine

Parameter	Value
Nominal voltage	40 [V]
Nominal current	2 [A]
Number of phases	3
Number of pole-pairs	4
Pole pitch	60 [mm]
Slot pitch	20 [mm]
Maximum velocity	2.2 [m/s]

The effect of the inner tube, moving alternatively, is to conduct outside the heat it receives via the air-gap, and, finally, to dissipate it towards the environment.

Table 4: PMT machine design data

Parameter	Value
Stator length	0.30 [m]
Stator outer radius	0.064 [m]
Stator internal radius	0.03 [m]
Stroke length	0.15 [m]

Figure 6 shows the tested temperatures got by thermo-couples (dotted line) and the ones obtained from the improved mathematical model; it can be seen that they are now in good agreement.

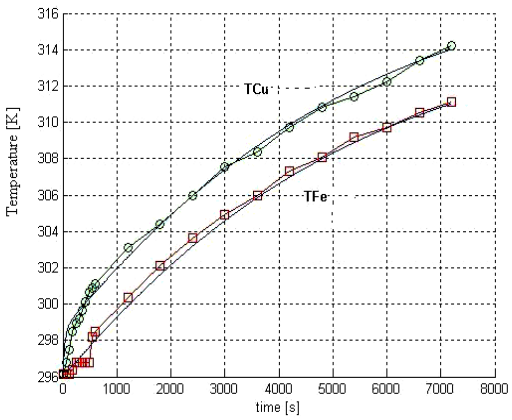

Figure 6: Calculated and measured temperatures of copper and iron

6. CONCLUSIONS

In this paper, a simple electromagnetic and thermal model of a PMT machine has been developed. Results of the analytical model are compared with those obtained from measurements.

Although simple, the thermal model takes into account the most important losses of this type of machine. The temperatures of both iron and copper parts are correlated with the corresponding thermal resistances and capacitances, which dynamically change in time. The particularity of this PMT machine comes from its topology that brings some features in the thermal model. These are connected to the design of the outer stator and to that part of the translator influencing the heat exchange with the external air.

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