THERMAL ANALYSIS OF A PERMANENT-MAGNET TUBULAR MACHINE

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Abstract **– Permanent-magnet tubular machines are well-suited for industrial applications, as they imply precision, ease of control and position accuracy. The thermal behaviour investigation of a permanent-magnet tubular machine is an interesting issue in order to obtain optimum design and improved dynamic performances. Few studies on this subject can be found in the technical literature. The present paper describes a simple thermal model of the permanent–magnet tubular machine, using analytical predictions and comparing them with experimental results. The results bring out some peculiarities in the machine's performances, related to its unconventional geometry.**

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 (PMT) machines provide good solutions to some applications within the automotive, aerospace and industrial sectors. This machine has 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.

This paper uses a simple analytical method to predict the heat transfer and the losses in a PMT machine. The power dissipations cause the various parts of the machine to heat up, affecting the electric life and the dielectric properties of the insulators, when the temperatures are higher then those allowed by the standard. The main purpose of the present work is to analyze the thermal behaviour of a PMT machine during transients, using a classical model based on a simple thermal network. Experimental evidence helped to point out some peculiarities of the thermal behaviour of the machine that can be easily taken into account in the model.

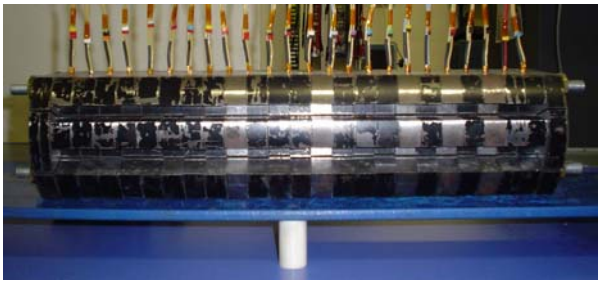

Fig. 1: Prototype of the PMT machine.

The prototype of the PMT machine, built in the DAEMI Department, University of Cassino, Italy, is presented in Fig. 1.

2. THERMAL MODEL

An accurate thermal model of a machine must take into account all the heat-releasing parts, resulting into a complicated thermal-resistances and capacitors network. For the sake of simplicity, a simple 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}.

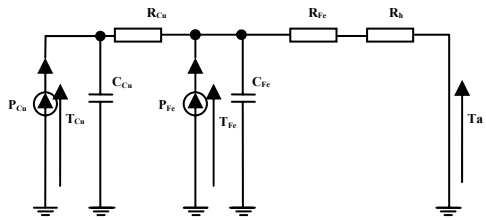

Fig.2: Thermal circuit of the PMT machine under transient operation.

These losses encounter the thermal resistances of the winding, iron and ambient. Capacitors are included in the thermal network to account for thermal capacities of the materials. The whole model is shown in Fig.2, corresponding to the transient state of the PMT machine.

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 ambient, supposed of 23^0 C; C_{Cu}, C_{Fe} are the thermal capacitances of copper and iron, respectively.

Two forms of heat transfer are modelled: natural convection and thermal conduction.

The natural convection is considered between the external surface of the PMT machine and the ambient, 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 is the natural convection coefficient (W/m^2.^{0}C) and A denotes the area in contact to the ambient (m^2).

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 given in Eq.(3). They are used in the model in order to reflect the temperature change in transient stage.

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

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

Iron losses are computed, with only the hysteresis and the classical eddy-currents taken into account, the excess eddy-current component being neglected.

The instantaneous copper loss is given by Eq.(4):

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

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

3. ANALYTICAL STUDY

By solving the thermal model of the PMT machine, one yields the following system of equations:

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

Discretizing these differential equations in the case of transient behaviour, one obtains a system of algebraic equations easier to be solved.

The computation of temperatures is performed by supposing the ambient temperature as the reference one. The discretized system is given by Eq. (6), where Δt represents the time step of the implemented model:

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

In each iteration step of the implemented model, copper and iron losses are calculated, and then the temperatures, until thermal steady-state 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 Fig. 2 are given in Table 1.

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]

Table 1: Values of resistances and capacitances of the thermal network

The thermal resistance of the windings has been obtained considering the air spaces between wires and the insulation. In fact, the wires are insulated with enamel paint, impregnated with epoxy and externally insulated with Kapton® tape.

4. EXPERIMENTAL RESULTS

The model was used to verify the thermal behaviour of the PMT machine, having the parameters and design characteristics given in Tables 2 and 3, respectively. All the experimental tests have been done in the Laboratory of Industrial Electronics of the DAEMI Department, University of Cassino, Italy, during a research project on the subject.
Two thermo-couples have been placed on the PMT machine prototype, one at the external surface of the stator, and the other one, embedded in the windings. As the temperatures change slowly, the measurements were recorded for two hours. A test rig was built using a brushless motor drive to generate alternative motion. The tests were made with the machine operating as a generator.
First, the tests were carried out considering that the heat exchange in the stator is made through the external surface of the iron cylinder:

$$A_{Fe} = 2 \cdot \pi \cdot r_{Fe} \cdot L_{Fe}, \qquad (7)$$

where r_{Fe} represents the stator external radius and L_{Fe}, the stator axial length.
The simulations obtained under these assumptions were compared with the experimental results, as shown in Fig. 3.
It can be observed that, if one considers just the outer surface of the stator, the simulated and the measured temperatures are not the same. Hence, the surface of the amount that comes out of the stator has to be enlarged as

$$A_{Fe} = 2 \cdot \pi \cdot r_{Fe} \cdot L_{Fe} + 2 \cdot \pi \cdot r_{in} \cdot L_{stroke}. \qquad (8)$$

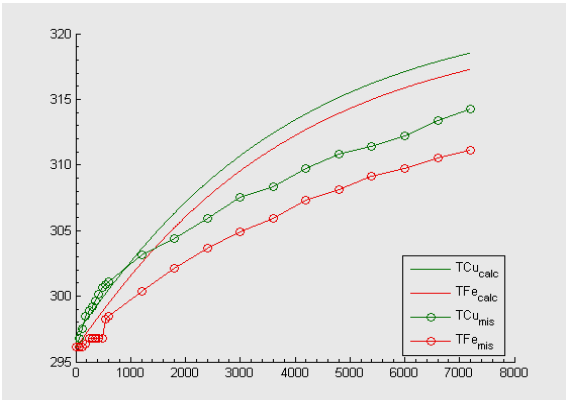

Fig. 3: Calculated and measured temperatures.

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]

Table 2: Electrical parameters of the PMT machine

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

Table 3: PMT machine design characteristics

The effect of the internal tube (moving alternatively) is to remove outside the heat it receives via air-gap, and, finally, to dissipate it towards the environment.
Fig. 4 shows the tested temperatures got by thermo-couples (dotted) and the ones obtained from the improved mathematical model, and it is seen that they are now in good agreement.

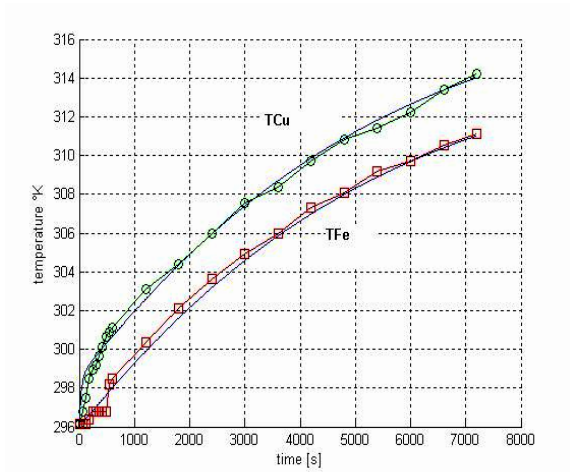

Fig. 4: Temperature results obtained by improved calculations (full lines) and from measurements.

5. CONCLUSIONS

In this paper, a simple thermal model of a PMT machine has been reported. Results of the analytical model are compared with the ones obtained from measurements. Although simple, the model takes into account the most important losses of this type of linear machine. The temperatures both of iron and of copper are correlated with the corresponding thermal resistances and capacitors, which dynamically change in time. The particularity of this machine is the geometry itself, which brings some changes in the thermal model. These are connected to the external design of the stator and with a part of the translator that determines the heat exchange with the external air.

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