THERMAL PHENOMENA ANALYSIS OF 6/4 SWITCHED RELUCTANCE MACHINE BY THE 2D FINITE ELEMENTS METHOD

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Abstract: *The purpose of this paper is to analyze the thermal effects due to copper losses and iron losses in a 6/4 switched reluctance machine (SRM) by the 2D finite element method. The shape of the magnetic induction in the calculation of iron losses by using analytical formulations is being considered. An analytical method is also used for determining the heat transfer coefficients by natural convection. The ANSYS FLUENT software is used to determine the velocity of the fluid inside the machine to calculate the coefficient of forced convection.*

Key words: *Switched Reluctance machine, Finite elements, Thermal modeling*

1. Introduction.

The heating of a switched reluctance machine SRM6/4, except for a malfunction, is mainly due to copper losses, the iron loss and friction losses. For a complete thermal analysis of the machine, knowledge of heat sources and heat exchange coefficients in the different parts becomes very important. With in this scope, several studies have been carried using the method of equivalent thermal circuit [4,5,6] or the finite element method in two and three dimensions [7,8,9,10]. But in all these studies, the data are not considered, such as iron losses sometimes are neglected [9,10] or calculated using standard formulations [5,6,8]. Moreover, the heat transfer coefficient by forced convection, whose dependence with the velocity of the fluid inside the machine is further proof, is calculated by analytical and numerical methods [4,5,9]. In this study, are analyzed the thermal effects due to copper losses and iron losses in a SRM6/4 by the finite element method in 2D. We took into account the shape of the magnetic induction in the calculation of iron losses by the use of existing formulations [2]. In calculating the coefficients of convective heat transfer, we used an analytical method for natural convection [4]. We used the Ansys software [12] to determine the velocity of the fluid inside the machine so as to calculate the forced convection coefficient. In this study, we did not consider the transfer of heat by radiation.

2. Thermal modeling of the SRM6/4

The equation governing the temperature distribution in an SRM is given as follows [1,13]:

$$div(-\lambda grad T) + \rho.C_p \frac{\partial T}{\partial t} = p \qquad (1)$$

In equation (1), λ is the thermal conductivity, p is the density source of heat, ρ is the density and Cp is the heat capacity. Generally, we associate to this equation an initial condition $T = Ta$ and boundary conditions imposed at the border of the study area. These conditions may be of three types: Dirichlet condition, Neumann condition and the condition of heat transfer by convection and / or radiation. Equation (2) represents the latter condition.

$$\lambda \frac{\partial T}{\partial x}l_x + \lambda \frac{\partial T}{\partial y}l_y + h(T - T_a) + \sigma(T^4 - T_a^4) = 0 \qquad (2)$$

In equation (2), the term h(T-Ta) represents the flow of heat by convection and the term $\sigma(T^4-T_a^4)$ represents the heat flow by radiation while lx and ly are cosine directors. The term of the heat density in equation (1) includes the copper and iron losses. If the calculation of losses in the copper is simple, that of iron loss is much more complex. Indeed, in the switched reluctance machine, magnetic flux is not sinusoidal and the use of a conventional formulation is almost impossible. Some authors [2], by changing the conventional formulations which are used for non-sinusoidal induction and which could have a nonzero average value (the case of SRM6/4) have developed a new formulation (3) for determining the iron losses in the SRM. Indeed, this model takes into account the

elements of the geometrical dimensions of the machine and control elements. The control parameters are the D.C voltage at the output of the supply and the angle of magnetization. U is the D.C voltage and f is the frequency of the induction. The terms of the coefficients K1, K2 and K3 are given in Appendix A1.

$$p_{iron}(w) = K_1 U + K_2 \frac{U^2}{f} + K_3 U^2 \qquad (3)$$

The difficult part in this kind of model is the taking into account boundary conditions. Indeed, if the Dirichlet conditions can, in some cases, be easy to impose or define, the boundary conditions of convection type are much more difficult to determine and calculate. The calculation of the exchange coefficient by convection depends on the Nusselt number Nu, the thermal conductivity of the fluid λ and the characteristic length of the thermal exchange surface (Appendix A2). However, the calculation of exchange coefficient by forced convection depends not only on the Nusselt number, the volume density of the fluid and some empirical parameters, but also on the speed of fluid. Relations for calculating these coefficients are given in Appendix A3 [4,13]. To calculate the speed of the fluid, we solved the Navier-Stokes using Ansys Fluent software [12]. This equation was solved in the air gap of the SRM6/4.

The relationship (4) represents the Navier-Stokes equation. In equation (4), v is the fluid velocity and Tr the stress exerted by the fluid depends on the speed of the rotor.

$$\rho(\frac{\partial \vec{V}}{\partial t} + \nabla \vec{V}.\vec{V}) = -\vec{\nabla} T_r + \tilde{\mu} \vec{\nabla}^2 \vec{V} \qquad (4)$$

Following the air gap geometric complexity of the SRM, this geometry is divided into two parts. The first consists of the rotor inter-polar region plus the constant air gap, and the second part represents the stator inter-polar region (Figure 1).

The aerodynamic stresses result from the flow of air in the machine air gap due to the movement of the rotor. To solve this problem, which is a viscous mechanical model, we must identify the nature of each side (solid or liquid). We consider all points and segments the components that define geometry and we need to give the rotor speed.The solution of the problem by the 2D finite element software (FLUENT) gives the results as shown in Figures 2 and 3.

The problem thus solved. Figure 4 shows the different linear regions is the convective heat transfer for both modes: natural or forced, and in Table 1, we give the value of the convection coefficient calculated for each region
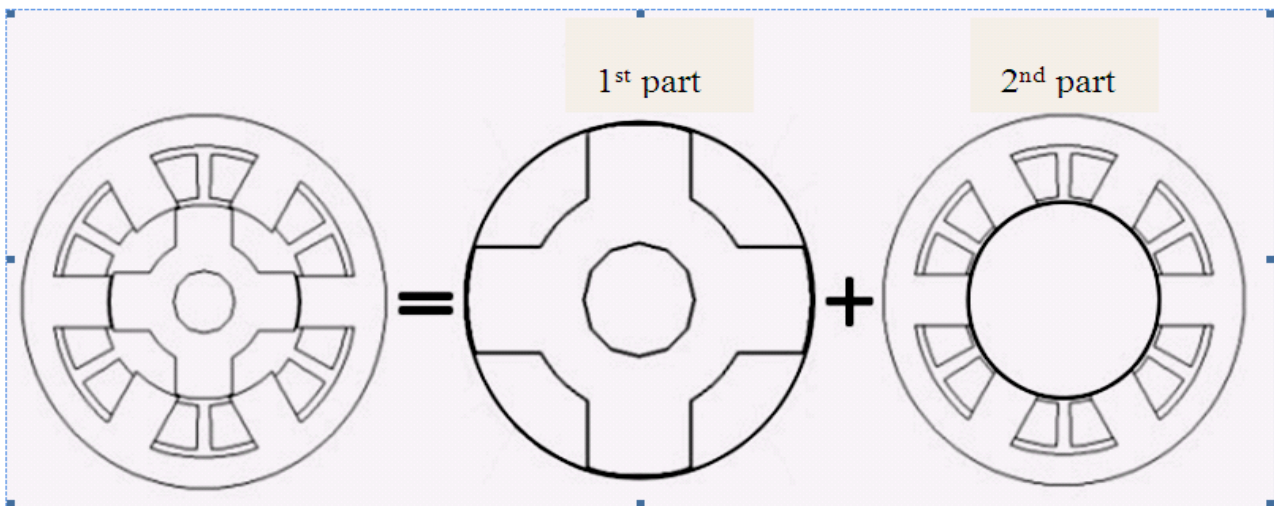

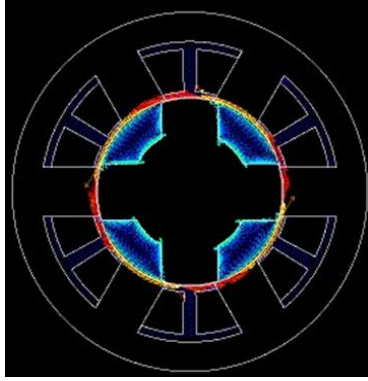Fig. 1. Division of the geometry of the SRM.

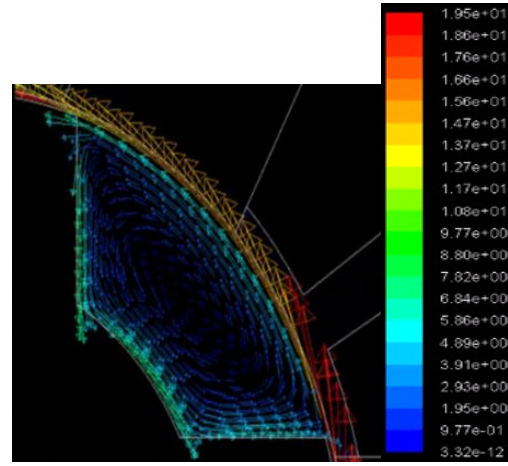Fig. 2. Distribution of fluid velocity in the SRM

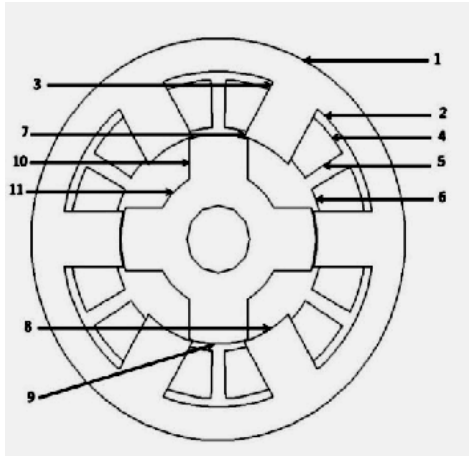Fig. 3. Zoom on the first part showing the rotation of the fluid.

Fig. 4. Different regions in the calculation coefficient "h"

	Coefficient « h » (W/°C.m²)	Convection	Fluid velocity (m/s)
Region (1)	5.86	Natural	
Region (2)	8.86	Natural	
Region (3)	15.6	Natural	
Region (4)	11.18	Natural	
Region (5)	11.21	Natural	
Region (6)	81.53	Forced	7
Region (7)	146.76	Forced	6
Region (8)	91.30	Forced	20
Region (9)	84.44	Forced	20
Region(10)	47.18	Forced	6
Region(11)	62.55	Forced	7

Table. 1. Coefficients of convection for each region of the machine.

3. Thermal simulation results

Figure 5 shows the machine studied. The operating range at constant power is four times the base speed. The base speed is 2500 rpm, which requires a voltage supply. The delivered torque is 103 Nm and the power is 27 kW. Voltage power source is 120 V. Joule losses per phase are calculated to be 540W. The angle of the time voltage application Θp is 100 °. The sheets of the magnetic circuit are FeSi 3%, 0.35 mm thick, which gives: ($k_{h1} = 5$, $k_{h2} = 40$, $\alpha_p = 0.022$) [1,4] and $K_1=0.0908$, $K_2 = 2516$, $K_3 = 0.00884$. Iron losses estimated by the equation (3) are approximately 862W.

The figure 5 shows the geometry of the SRM6/4 and Table 2 gives the main dimensions of SRM6/4. In Table 2, L_a is the length of the machine, e the thickness of the gap, ns the number of turns of a coil, N_s and N_r are the number of stator and rotor theeths. The values of thermal conductivities, heat capacities and material densities for each region are shown in Table 3.

The calculation was performed by exciting a single coil and the conditions applied limits are shown in Table 1. We considered an ambient temperature of 27 ° C. Figure 6 shows the temperature distribution when the fluid velocity is not taken into account. We note that the temperature obeys only natural convection (NC) and exceeds 150 ° C for one hour of simulation. In contrast, Figure 7 shows the temperature distribution when the fluid velocity is taken into account. As a result, the temperature obeys not only to natural convection (NC), but also forced convection (FC). We note that the temperature does not exceed 80 ° C around the excited coils and 60 ° C in the rotor for the same simulation time. This temperature limit is due to the flow of air within the SRM. Figure 8 shows the evolution of the temperature versus time in different parts of the SRM for two hours of simulation.
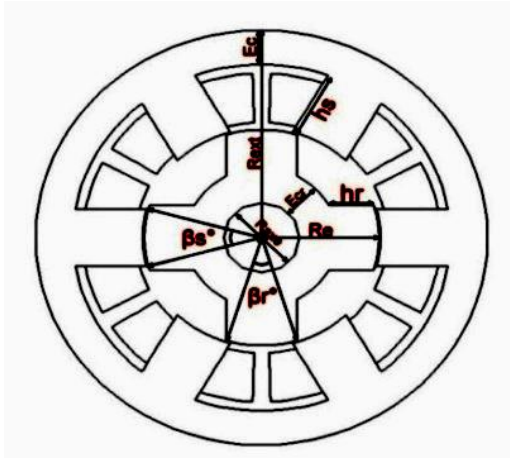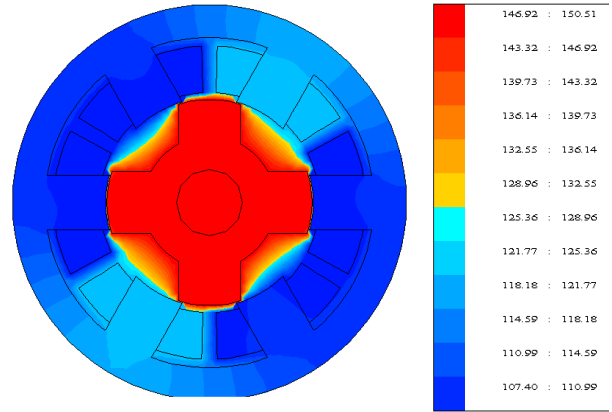
Fig. 5. SRM6/4 Geometry

Fig. 6. Distribution of temperature
without forced convection

N_s	6
N_r	4
R_{ext}	125
R_e	65
R_{axe}	21
L_a	150
E	0.8
E_c	20.5
h_s	38.5
h_r	23
β_s°	30
β_r°	35.1
E_{cr}	21
n_s	22

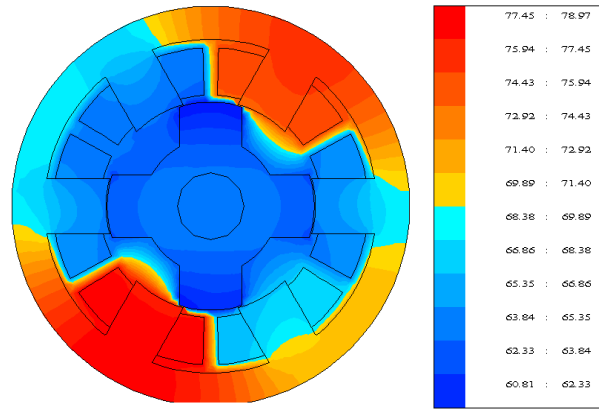Table. 2. Dimensions in mm

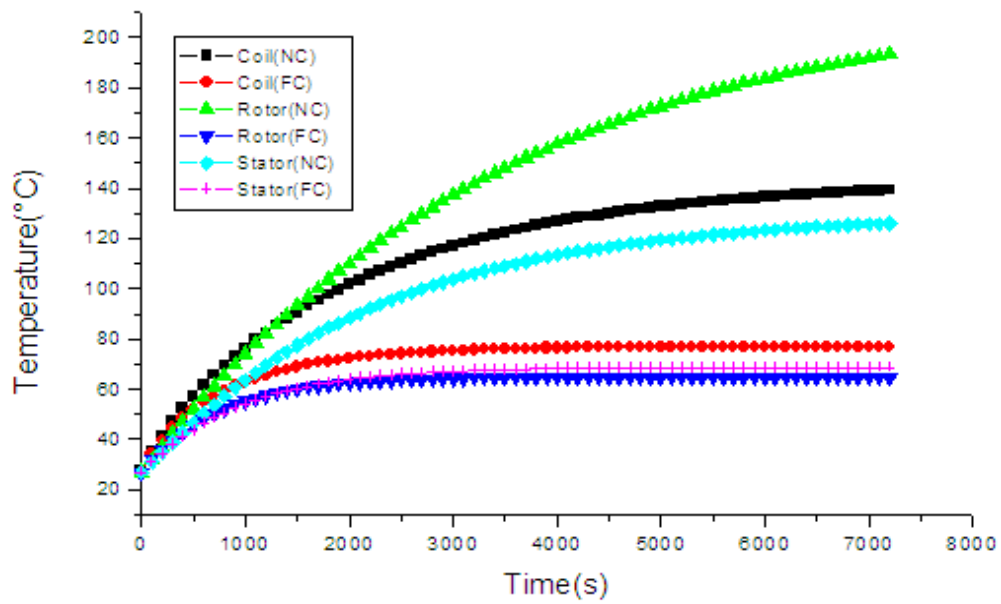
Fig. 7. Distribution of temperature
with forced convection

Fig. 8. Evolution of temperature versus time

	Thermal conductivity (W/°C.m)	Heat capacity (J/kg. °C)	Density (kg/m^2)
Air	2.62 e-2	1006	1.177
Fesi	84	460	7600
Copper	395	385	8918

Table . 3. Properties of materials

4. Conclusion

In this paper we have presented a thermal study of a switched reluctance machine taking into account the Joule losses and iron losses by using the 2D finite element method. In this study, we faced several challenges including the calculation of air velocity, which requires the resolution of the Navier-Stokes equation to be able to identify boundary conditions for forced convection. Moreover, the definition of different heat sources (iron and copper losses) in the SRM6/4 is also another problem to be resolved because their calculation is based on several parameters and does not obey to the conventional formulations. We have also shown that the use of forced convection coefficients could successfully simulate the evolution of temperature in a SRM and take into account the flow of air inside the machine

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Appendices
A$_1$.

for $\dfrac{\pi}{3} \leq \theta_p \leq \dfrac{2\pi}{3}$

$$K_1 = \frac{k_{h1}}{2}\left(\frac{\theta_p}{n_s\pi}\right)\left[N_s h_s + \frac{4-\dfrac{3\theta_p}{\pi}}{2}\pi\left(\frac{R_{ext}^2-(R_{ext}-E_c)^2}{E_c}+\frac{(R_{axe}+E_{cr})^2-R_{axe}^2}{E_{cr}}\right)+N_s h_r\right]$$

$$K_2 = \frac{k_{h2}}{L_a}\left(\frac{\theta_p}{n_s\pi}\right)^2\left[\frac{N_s h_s}{4w_s}+\frac{4+\left(2-\dfrac{3\theta_p}{\pi}\right)^2}{16}\pi\left(\frac{R_{ext}^2-(R_{ext}-E_c)^2}{E_c^2}+\frac{(R_{axe}+E_{cr})^2-R_{axe}^2}{E_{cr}^2}\right)+\frac{N_s h_r}{2w_r}\right]$$

$$K_3 = \frac{\alpha_p}{n_s^2 L_a}\left(\frac{\theta_p}{\pi}\right)\left[\frac{N_s h_s}{w_s}+\frac{48-\dfrac{36\theta_p}{\pi}}{16}\theta_p\left(\frac{R_{ext}^2-(R_{ext}-E_c)^2}{E_c^2}+\frac{(R_{axe}+E_{cr})^2-R_{axe}^2}{E_{cr}^2}\right)+\frac{N_s^2 h_r}{N_r w_r}\right]$$

A₂.

$$h = \frac{\lambda . N_u}{L}, \qquad N_u = c\left(G_r . P_r\right)^m,$$

$$P_r = \frac{C_p . \mu}{\lambda}, \qquad G_r = \frac{\beta . g . \Delta T . \rho^2 . L^3}{\mu^2}$$

A₃.

$$N_u = a\left(R_e\right)^b .\left(P_r\right)^d, \qquad R_e = \frac{\rho . v . L}{\mu},$$

w_s: Average width of the stator tooth [mm]
w_r: Average width of the rotor tooth [mm]
h: Convection coefficient
Nu : Dimensionless Nusselt Number
Re : Dimensionless Reynolds Number
Gr : Dimensionless Grashof Number
Pr : Dimensionless Prandtl Number
λ: Thermal conductivity of fluid [W / C°.m].
ρ: Density of fluid [kg/m³]
C_p: Heat capacity of fluid [J / kg.C°]
L: Characteristic length of the exchange area [m].
μ: Dynamic viscosity of fluid [kg / m.s]
β: Coefficient of cubical expansion of fluid [1/C°]
g: Gravitational force [m/s²]
ΔT: Temperature difference between surface and fluid
[C°]
v: Flow velocity [m / s]
m, a, b, c and d are coefficients determined by
experimental studies