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Comparing Heating and Ventilation of Permanent Magnet Synchronous Motor with or without Slots

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ABSTRACT

In this paper is presented design data of two electric motors with permanent magnets, the first synchronous motor with permanent magnet having slotted stator and the second synchronous motor with permanent magnet without slots. The purpose of this paper is to make a comparison between the performances of the two engines on of each loss and heating of each. After projected electrical machines and determine the operating characteristics, it establishes an analogy of an thermal system with an electric system and using your program Motor-Cad is calculated heating and the losses in two electrical machines, being done a comparison between the two.

Keywords: Synchronous motor, permanent magnet, rotor, stator, notches, heat transfer, ventilation.

INTRODUCTION

An electrical machine is an electromechanical converter that converts electrical energy into mechanical energy while motor operates under. The transformation energy takes place by means of the magnetic field can be produced by the permanent magnets for magnetoelectric machines.

To electrical machines appear as any transformation loss of energy, electrical losses produced by current in conductors, magnetic losses produced by the variation of fields in iron machine, mechanicals losses produced by the movement a portion of the machine. Achieving a maximum yield is the purpose of energy transforming.

Because losses be minimal is necessary a magnetic field of a certain amount and form of variation in time and space, the maximum induced electromotive voltages. Losses turns into heat inside the machine the heat to be evacuated, so it is absolutely necessary an efficient cooling system. [1-4].

PROBLEM FORMULATION

The correct designing of electric machines involved an efficient cooling of electrical machine by determining the values and distribution of temperature along the rotor.

For this you need to make a complete and accurate analysis of temperature field in stationary regime that requires knowledge of the and locating loss amounts of temperature, knowledge of the velocity distribution of the cooling fluid in the various cooling channels of the machine, the determination of the values of heat flow and distribution of those values in certain components of the electrical machine. [5]

Synchronous Motor with Permanent Magnet having Slotted Stator

Consider the following data for projection of electrical machine: the nominal torque - M_N = 20,8 Nm; the nominal voltage - U_N = 190 V (the line voltage); the nominal speed - n_N = 4000 rot/min; the

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frequency voltage at nominal speed: f_n = 200 Hz; number of phases: m = 3; insulation class: F; Calculate the nominal power P_N and number of pole pairs:

$$P_N = \frac{\pi n_N M_N}{30} = 8712,7W \tag{1}$$

$$p = \frac{60 f_n}{n_N} = 3, \text{ pole pairs (6 poles)} \tag{2}$$

To calculate the permanent magnet necessary, adopt a Neodymium-Iron-Bohr magnetic material has the following features: B_r = 1,018 T, H_c = 810 kA/m.

Magnet volume required is next:

$$V_m = \frac{2}{\pi^2} \cdot \frac{k_\Phi k_{ad}(1+\varepsilon)}{f_n k_{um} k_{\mathrm{Im}} B_r H_c \eta_m \cos\varphi_m} k_m P_N = 342,46 \cdot 10^{-6} m^3 \tag{3}$$

The diameter of the rotor is determined by the relation:

$$D_r = \sqrt[3]{\frac{2V_m}{\pi\lambda_r(1-\alpha_p)[1-k_1(1-\alpha_p)]}} = 114,7 \cdot 10^{-3} m \tag{4}$$

Adopt λ_r = 1,8 for a long motor and k_1 = 2. Will be considered $D_r = 114,5x10^{-3}$m.

The magnets will have the following dimensions:

- magnet width $b_m = 53,95x\ 10^{-3}$m
- magnet height $h_m = 6x10^{-3}$m
- magnet length $l_m = 200x10^{-3}$m

The length of the magnet passed equal to the effective length of the motor.

The inner diameter of the rotor is calculated by relationship:

$$D_{ir} = D_r - 2 \cdot h_m = 102,5 \cdot 10^{-3} m \tag{5}$$

The inner diameter of the stator is:

$$D_{is} = D_r + 2 \cdot g = 115,9 \cdot 10^{-3} m \tag{6}$$

The size of the air gap is set g = 0,7 mm, for reducing harmonics teeth of electromotive.

Magnetic induction in the air gap is:

$$B_g = \frac{B_r}{\sigma \frac{S_p}{S_m} + \frac{1}{\mu_0} \frac{B_r}{H_c} \frac{2gk_c k_s}{h_m}} = 0,70889 \quad T \tag{7}$$

where: $S_p = S_m = b_m l_m = 106 \cdot 10^{-4} m^2$

S_p- a pole surface, also S_m - surface corresponding to a pole magnet. It adopts B_g = 0,709 T.

Magnetic flux per pole is calculated:

$$\Phi_p = \alpha_p \tau l_m B_g = 77,446 \cdot 10^{-4} Wb \tag{8}$$

Number of spire per phase resulting: $w_s \approx 71$

where: k_d = 0,2 - demagnetization coefficient.

The current drawn of engine estimates for a phase by relation:

$$I = \frac{P_N}{m \cdot U_N \eta \cos \varphi} = 41,25 \ A \tag{9}$$

Current for a conductor from slot will be: $I_c=I/n_c=5,156$ A

Choosing the current density a value j = 5 A/mm^2, for insulation class F, the section required the copper conductor will be: s_{cs}=1,031 mm^2. It adopts from standard SR EN 60317-1-14:2001 copper conductor s_{cs} = 1,131 mm^2, with diameter d_{cs} = 1,25 mm.

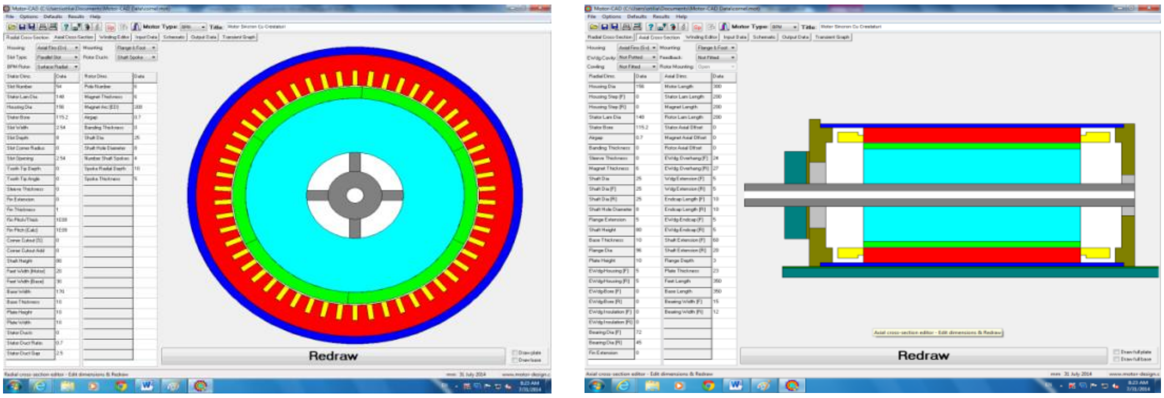

Figure1. *Radial / axial cross section in synchronous motor with permanent magnet having slotted stator*

Shall be considered slot rectangular and the winding in a layer by step diametrical.

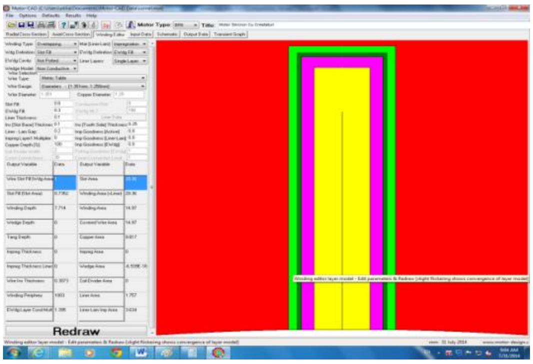

Figure2. *Rectangular tooth for synchronous motor with permanent magnet and slotted stator*

The magnetic induction in the stator teeth [2, 9]:

$$B_{zs} = \frac{B_g t_{zs}}{b_{zs} k_{Fe}} = 1{,}198 \ T \tag{10}$$

Magnetic voltage drop in the stator teeth [2, 9]:

$$F_{zs} = H_{zs} h_{zs} = 4,8 \ A \tag{11}$$

The magnetic induction stator yoke:

$$B_{js} = \frac{\Phi_p}{2 h_{js} l_s k_{Fe}} = 1{,}236 \ T \tag{12}$$

The coefficient of saturation is determined with the relationship:

$$k_s = \frac{2F_g + 2F_{zs} + F_{js}}{2F_g} = 1{,}036 \tag{13}$$

The resistance per phase is determined by the relationship:

$$R = \rho_{\Delta t}\frac{2\omega_s\left(l_s + l_f\right)}{s_{cs}} = 0{,}103 \ \ \Omega \tag{14}$$

Determining the Characteristics of Operation

In table 1 are given the operating characteristics of the synchronous motor with permanent magnets and slotted stator.

Table1. *Operating characteristics of the synchronous motor with permanent magnets and slotted stator*

$\delta[^0]$	20	30	40	50	60	70
$I[A]$	17,5628	25,0978	32,6522	40,0499	47,1917	54,00373
$P_1\ [W]$	7135,23	10406,4	13395,0	16009,9	18171,9	19815,25
$P_1\ [W]$	6406,42	9578,35	12432,0	14880,8	16850,3	18280,58
η	0,89785	0,92042	0,92811	0,92947	0,92726	0,922551
$\cos\varphi$	0,78161	0,81775	0,81583	0,79615	0,76509	0,725332
$M\ [Nm]$	15,2942	22,8666	29,6793	35,5254	40,2271	43,64167

For $\delta = 0 \div 1900$ and nominal torque $M_N = 20{,}8\ Nm$, is obtained $I_N = 22{,}82\ A$, $\cos\varphi_N = 0{,}81$, $\eta_N = 0{,}91$, for a internal angle $\delta_N = 27^0$ (figure 3).

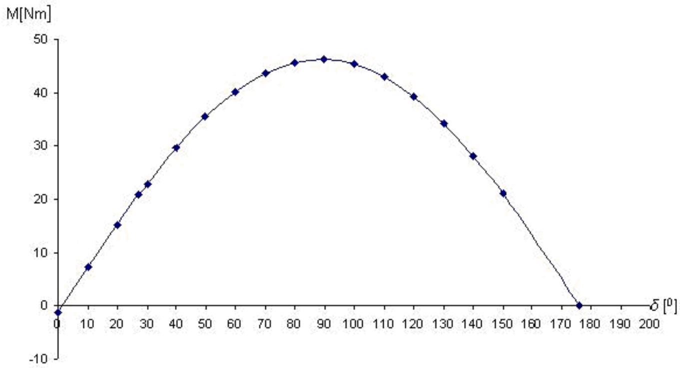

Figure3. *Operating characteristics of the synchronous motor with permanent magnets and slotted stator having nominal torque M_N = 20,8 Nm.*

Synchronous Motor with Permanent Magnet without Slots

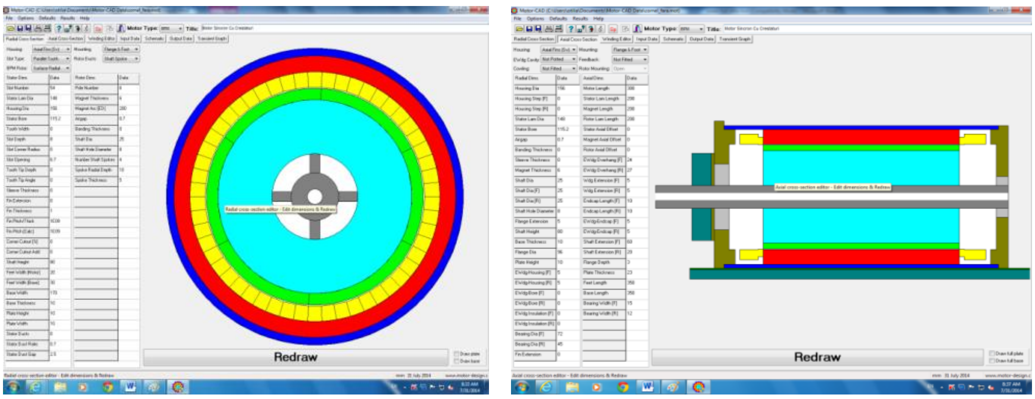

Figure4. *Radial/axial cross section in synchronous motor with permanent magnet without slots*

It keeps overall dimensions obtained by calculation the synchronous motor with permanent magnet having slotted stator teeth are removed, they keep the same geometry of the rotor and repeat the calculations for machine as thus amended.

The induction in air gap is:

$$B_g = \frac{B_r}{\sigma \frac{S_p}{S_m} + \frac{1}{\mu_0}\frac{B_r}{H_c}\frac{2g'}{h_m}} = \frac{1,018}{1,1 + \frac{1}{4\pi \cdot 10^{-7}} \cdot \frac{1,018}{810 \cdot 10^3} \cdot \frac{2 \cdot (0,7+8) \cdot 10^{-3}}{6 \cdot 10^{-3}}} = 0,254\ T \tag{15}$$

where: $S_p = S_m$.

The magnetic flux per pole:

$$\Phi_p = \alpha_p \tau l_m B_g = 0,9 \cdot 60,685 \cdot 10^{-3} \cdot 200 \cdot 10^{-3} \cdot 0,254 = 27,75 \cdot 10^{-4}\ Wb. \tag{16}$$

Number of turns per phase:

$$w_s = \frac{\varepsilon U_{Nf}}{\pi \sqrt{2} f_s k_{ws} \Phi_p k_d} = \frac{0,85 \cdot 110}{\pi \cdot \sqrt{2} \cdot 200 \cdot 0,96114 \cdot 27,75 \cdot 10^{-4} \cdot 0,2} = 197,3\ spire \tag{17}$$

where: $U_{Nf} = \frac{U_{Nl}}{\sqrt{3}} = \frac{190}{\sqrt{3}} = 110\ V,$

and k_d = 0,2 is the coefficient of demagnetization. Number of turns per coil, corresponding the flow of the motor without notches:

$$w_b = \frac{W_s}{n_{bf}} = \frac{197,3}{9} = 21,9 \frac{spire}{coil} \approx 22\ spire/coil \tag{18}$$

Number of conductors in notches, as with in synchronous motor with permanent magnet having slotted stator, is w_b = 8 spire/coil. Remaining free space by removing teeth is filled by modifying section conductors.

The total section tooth + notches:

$$S'_{bobina} = (t_{zs} + b_{zs}) \times h_c = 6,7428 \times 10^{-3} \times 8 \times 10^{-3} = 53,9424 \times 10^{-6}\ m^2 \tag{19}$$

Is considering hiz=0,5 mm insulation for each coil.

$$S_{coil} = (t_{zs} - 2h_{iz})(h_c - 2h_{iz}) = (6,7428 - 2 \cdot 0,5)(8 - 2 \cdot 0,5) \cdot 10^{-6} = 34,457 \cdot 10^{-6}\ m \tag{20}$$

For a filling factor k_u = 0,7:

$$S_{cu} = k_u S_{coil} = 31,011\ mm^2$$

Is thus obtained for a single conductor $S_{conductor} = S_{cu}/n_c = 3,014\ mm^2$.

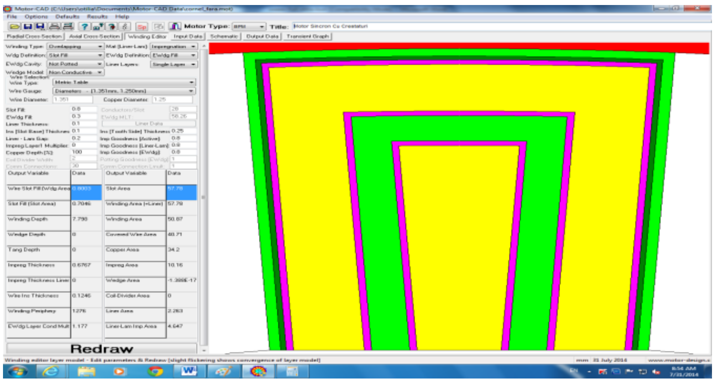

Figure5. *The tooth for synchronous motor with permanent magnet without slots*

Is chosen an conductor with $S_{cu}=2,835\ mm^2$, having diameter $d=1,9\ mm$.

Determining the Characteristics of Operation

In "table 2" are given the operating characteristics of the synchronous motor with permanent magnets without slots

Table2. *Operating characteristics of the synchronous motor with permanent magnets without slots*

$\delta[^0]$	20	30	40	50	60	70
$I[A]$	55,581	58,003	61,137	64,791	68,783	72,945
P_1 $[W]$	4725,4	6527,1	8168,6	9599,9	10777	11665
P_1 $[W]$	4285,1	6086,8	7728,3	9159,6	10337	11225
η	0,9068	0,9325	0,9460	0,9541	0,9591	0,9622
$\cos\varphi$	0,1651	0,2248	0,2708	0,3029	0,3220	0,329
M $[Nm]$	10,235	14,538	18,459	21,878	24,690	26,812

For $\delta = 0 \div 190^0$ and nominal torque $M_N = 13,28\ Nm$, is obtained $I_N = 57,78\ A$, $\cos\varphi_N = 0,21$, $\eta_N = 0,927$, for a internal angle $\delta_N = 27^0$ "figure 4".

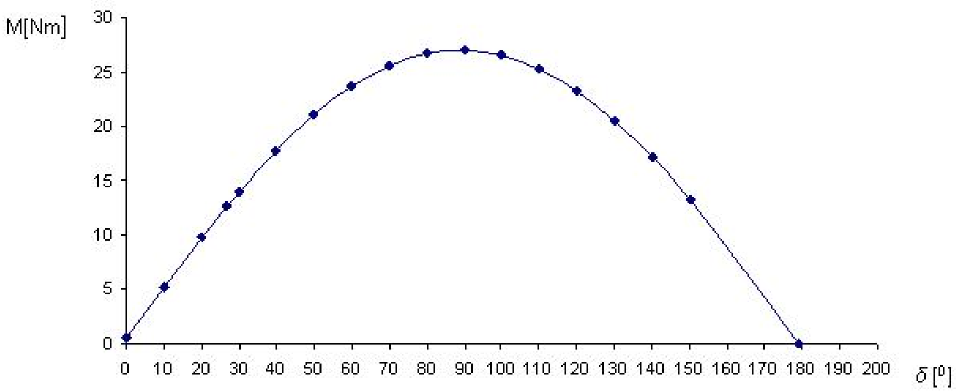

Figure6. *Operating characteristics of the synchronous motor with permanent magnets without slots having nominal torque $M_N = 13,28\ Nm$.*

Heat Transfer and the Analogy with Electrical Systems

The processes which there is a thermal energy conversion from parameters higher in parameters lowered called heat transfer. Quality heat is appreciated with temperature parameter, it is a global measure of the intensity of processes determine the internal energy of a body.

In our case the heat transfer objective is to verify the compatibility of materials used with temperature regime faced by determining the temperature field. Added to this is finding the methods and procedures of intensification, or in some cases, braking heat transfer. [6-8]

The three forms of heat transfer, conduction, convection and radiation are due to temperature differences, but the third form, convection involves an exchange mass.

If the two systems of different nature have similar equations with similar boundary conditions, we can say that these systems are analogous, so the equations that describe the behavior of a system can be transformed into the other system equations by simply changing the variable symbols. Therefore we can make the analogy between an electric and a thermal system. For electrical system will consider the relationship between DC I, difference of potential ΔU and electrical resistance R_e (Ohm's Law), and for thermal system the unitary thermal flow q, the temperature difference (thermal potential) Δt and size called thermal resistance R_t.

$$I = \frac{\Delta U}{R_e}; \quad \dot{q}_s = \frac{\Delta t}{R_t} \tag{21}$$

Taking into account the three basic forms of heat transfer can establish relationships for calculating the thermal resistance which can be in complex processes of heat exchange equivalent diagrams binding series or shunt. Inverse thermal resistance called thermal conductance.

Comparing the two Electrical Machines

The heat evacuation from electrical machine is as important as the phenomena linked with the proper functioning of the machine. The choice of the most appropriate ventilation is even establishing electromagnetic applications.

Comparison of Losses

Utilizing the computing program MOTOR –CAD be observed that the losses in the two electrical machines synchronous motor with permanent magnet and slotted stator and synchronous motor with permanent magnets without slots, have the same total values.

The losses in stator (stator copper, stator back iron and stator tooth), as in sleeve bearings are the same for both cases.

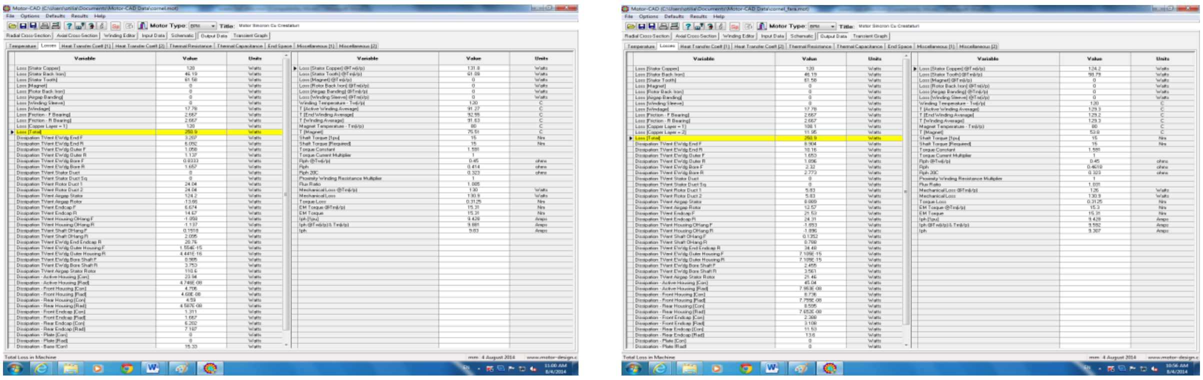

Figure7. *The losses in synchronous motor with permanent magnet and slotted stator (left), The losses in synchronous motor with permanent magnets without slots (right)*

The loses total is 250,9 Watts

So from the point of view of loss of the two motors are equally performant.

Comparing of Heating the two Machines

The orientation of both motors is horizontal, the air is the fluid for ventilaton, and ambiental temperature shall be deemed 40^{0}C.

For the synchronous motor with permanent magnet and slotted stator be seen from temperatures diagram (figure 8 - left) and from the graph of the heating (figure 8 - right) it corresponds as to level heating insulation class F, 100^{0}C heat level, so ventilation is well chosen.

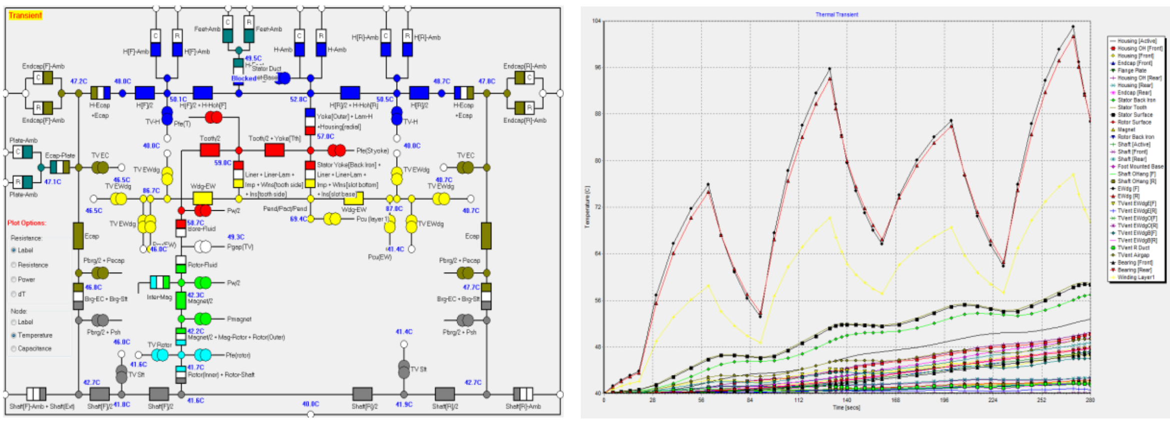

Figure8. *Temperatures and the graph of the heating in different parts of the synchronous motor with permanent magnet and slotted stator*

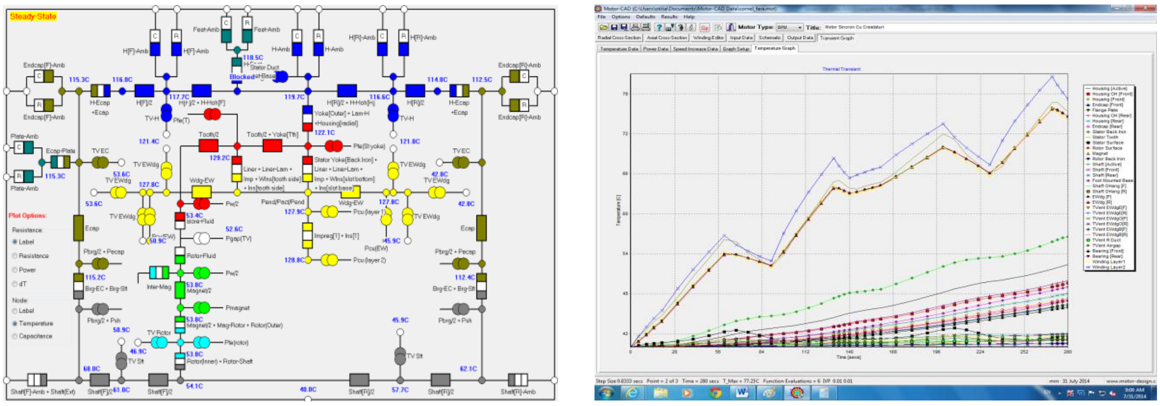

Figure9. *Temperatures and the graph of the heating, in different parts of the synchronous motor with permanent magnet without slots*

In the case of the synchronous motor with permanent magnet without slots it is found that temperatures in certain parts of the electrical machine (housing, rotor, stator) looks an exceeding for its value of 100^{0}C, so the synchronous motor with permanent magnet without slots does not correspond point of view of the heating.

To be able make a comparison between the two types of motors we will maintain the original dimensions of the synchronous motor with permanent magnet without slots but we will reduce the height of stator teeth.

Redesigning the Synchronous Motor with Permanent Magnet without Slots

Is redesigning the synchronous motor with permanent magnet without slots with the same data, changing only the stator teeth height from 8 mm to 3,5 mm and to get the motor of figure 10 left – radial section, figure 10 right – axial section.

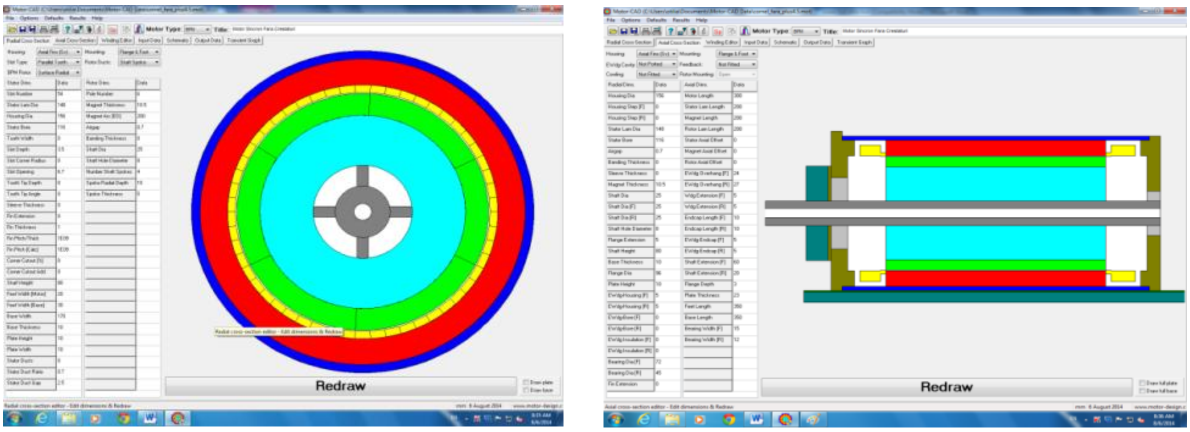

Figure10. *Radial /axial cross section in synchronous motor with permanent magnet without slots new*

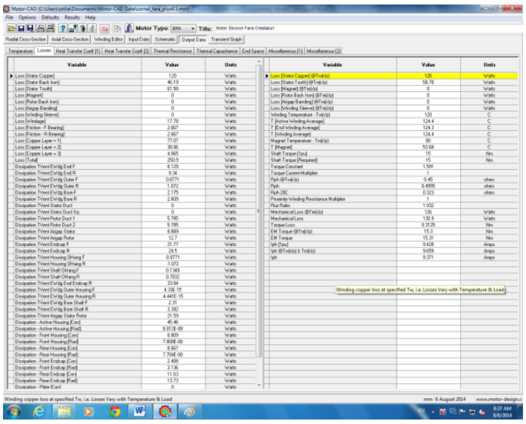

Figure11. *The losses in synchronous motor with permanent magnet without slots new*

The losses of new electrical machine are comparable to those of the electrical machines above (Figure 11), but differs heating.

Heating maximum in new motor is 65,42^{0}C (Figure 12) in the stator teeth, so quite a lot under the admissible limit of 100^{0}C.

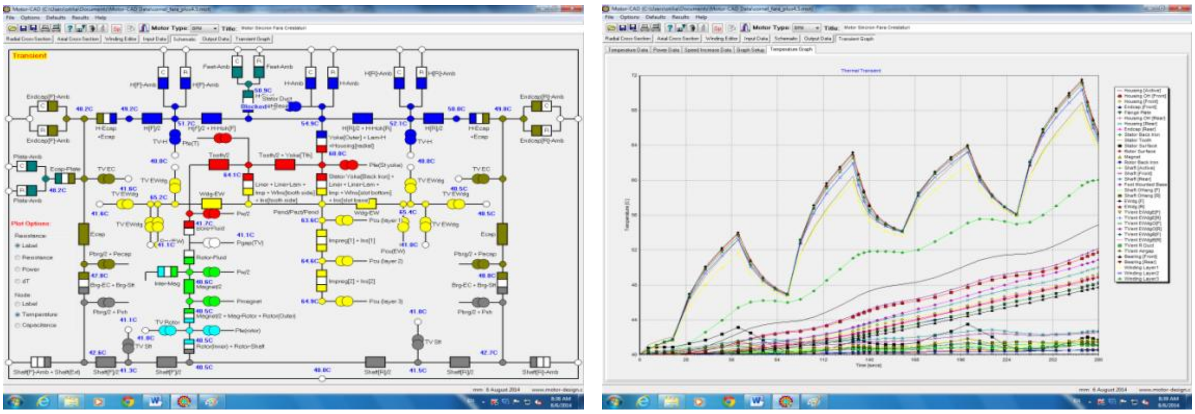

Figure12. *The graph of the heating in the synchronous motor with permanent magnet without slots new*

CONCLUSION

The first conclusion drawn is that synchronous motor with permanent magnets without slots in the first form of design can not to function, due to high heating.

Comparing the synchronous motor with permanent magnets and slotted stator with synchronous motor with permanent magnets without slots new, we obtain the following conclusions:

- Nominal data of both motors are identical except that the height stator teeth differ;
- To set the same type of ventilation for both motors;
- The losses from the two motors are comparable;
- The heating in shaft of the synchronous motor with permanent magnets and slotted stator (maximum 79,7^{0}C) is greater than the heating of on the shaft the synchronous motor with permanent magnets without slots (maximum 42,7^{0}C);
- The heating in the housing of the synchronous motor with permanent magnets and slotted stator (maximum 87,5^{0}C)) is greater than the heating of the housing synchronous motor with permanent magnets without slots (maximum 54,9^{0}C);
- The heating in the stator of the synchronous motor with permanent magnets and slotted stator (maximum 88,9^{0}C) is greater than the heating of the stator synchronous motor with permanent magnets without slots (maximum 64,1^{0}C);
- The heating in the permanent magnets of the synchronous motor with permanent magnets and slotted stator (maximum 75,5^{0}C) is greater than the heating of the permanent magnets synchronous motor with permanent magnets without slots (maximum 40,6^{0}C);
- The heating in the rotor of the synchronous motor with permanent magnets and slotted stator (maximum 75,4^{0}C) is greater than the heating of the rotor synchronous motor with permanent magnets without slots (maximum 40,5^{0}C);

It is found that the synchronous motor with permanent magnets without slots ventilation is much better than the synchronous motor with permanent magnets and slotted stator ventilation, the temperatures are lowers in each part of the synchronous motor with permanent magnets without slots (shaft, rotor, permanent magnets, stator, housing).

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