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Analysis of the Influence on the Thermal Regime of the Slot Shape within an Induction Machine

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The paper analyzes the influence of the slots shape pertaining to induction motor armatures on the temperature development within its structure. The analysis of the temperature distribution within the studied motor was made using the Motor-CAD programming environment. The stated aim of the study was to emphasize the importance of choosing the geometrical shape of the slots of a classic rotating electric machine, still in the design phase, in order to obtain the validation - by thermal calculation - at the end of the design, of the geometrical structure that offers the highest technical and economic performance.

Keywords*: induction motor, thermal analysis, constructive optimization*

1. Introduction

In electromagnetism, the shape has a strong influence on the performance of a structure. For classic- electric machines, the design algorithms [1], [3] give a proportionality of the total power developed with the volume of the geometric structure in which there is a magnetic field distribution. On the other hand, this relationship is valid for an ideal machine that has smooth armatures. The actual manufacturing) of electrical machines unfortunately requires the indenting of the armatures, which certainly affects the level of developed power. Moreover, the new geometry of the slotted machine will also record a redistribution of active power losses within the structure.

In the new conditions, the electric machine will record a new temperature distribution [1], [2] within the structure with indented armature in relation to an ideal machine with smooth armatures. It is clear, therefore, that only the simple indenting of the machine armatures influences the thermal regime in an electric machine.

In this paper we wanted to emphasize the influence of the slots shape on the two armatures of a rotating electric machine on the temperature distribution within its integrating structure (armatures, framework, bearings etc.). The purpose of this approach is to clarify the different thermal behavior in practice of electric machines having virtually the same macroscopic functional characteristics (power, speed, voltage, current, etc.). What is different - otherwise easy to check in practice - is the internal geometric structure of these machines (finally, the shape of the slots used on one or both of the electrical machine armatures).

To fix ideas, but also because of the widespread use in the economy today, the study targeted the three-phase induction (asynchronous) machine [7], [8], [10]. The analysis of the heat field distribution in the induction electric machine was done using the Motor-CAD programming environment [9], [11].

2. The constructive and functional particularities of the analyzed structures. Working hypotheses

The analyzed induction machine (asynchronous) works as a motor (the most extensive practical application of this electric machine). The asynchronous motor studied has cylindrical symmetry and the armatures - stator and rotor – are indented. Throughout the analysis, the geometric dimensions of the structure (internal and external diameter of stator, stator thickness, casing thickness, external diameter of rotor, rotor shaft diameter, etc.) were kept constant (the same regardless of the shape of the slots). In addition, the following variables were kept the same: the number of stator slots, the number of rotor slots, the air gap, the materials used and the size of the stator conductors. The modification was made only on the shape of the slots on the two armatures of the Induction motor with squirrel cage rotor. Thus, two types of slots (in terms of shape) were analyzed: trapezoidal slot (rectangular tooth), rectangular slot (trapezoidal tooth) respectively.

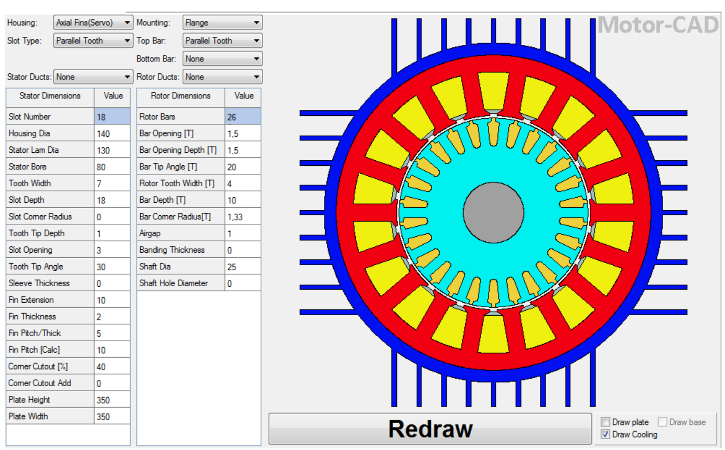


Figure 1. Cross-section through motor, highlighting the dimensions of the base constituent elements (trapezoidal stator slot)

The cross-sectional and longitudinal sections in the induction motor analyzed for the two forms of stator slots are shown in Figures 1-4.

The analysis performed for the structures outlined in the figures below was done with the same geometric shape for the rotor slot.

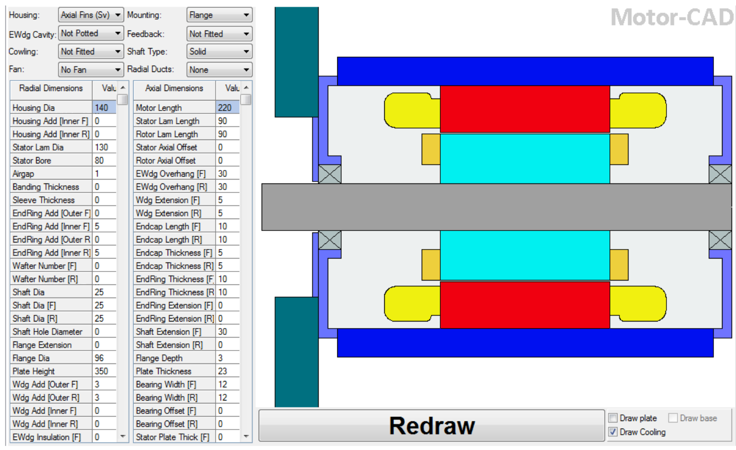


Figure 2. Longitudinal section through motor, highlighting the basic geometric dimensions (trapezoidal stator slot)

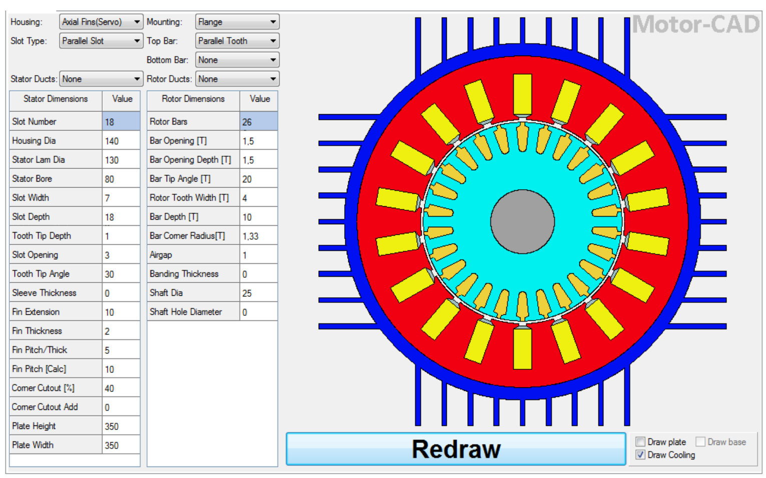


Figure 3. Cross section through motor, highlighting the dimensions of the base constituents (rectangular stator slot)

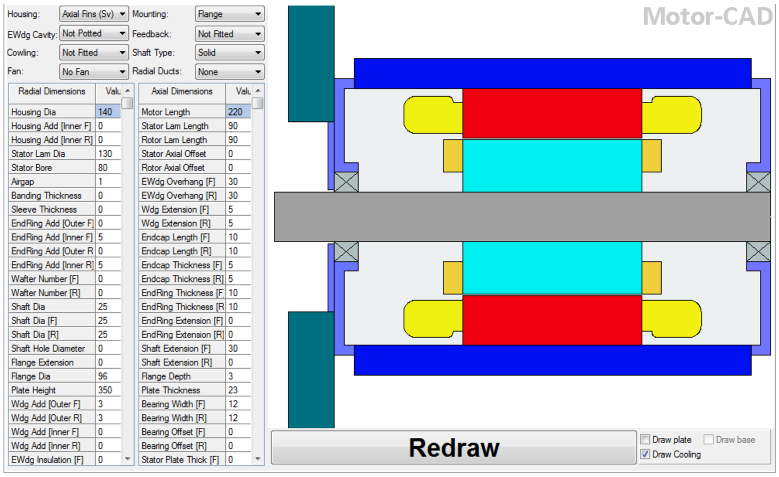


Figure 4. Longitudinal section through motor, highlighting the basic geometric dimensions (rectangular stator slot)

In Figures 5 and 6, only the cross-sections are shown, for the situation when a unilateral change of the rotor slot form occurred.

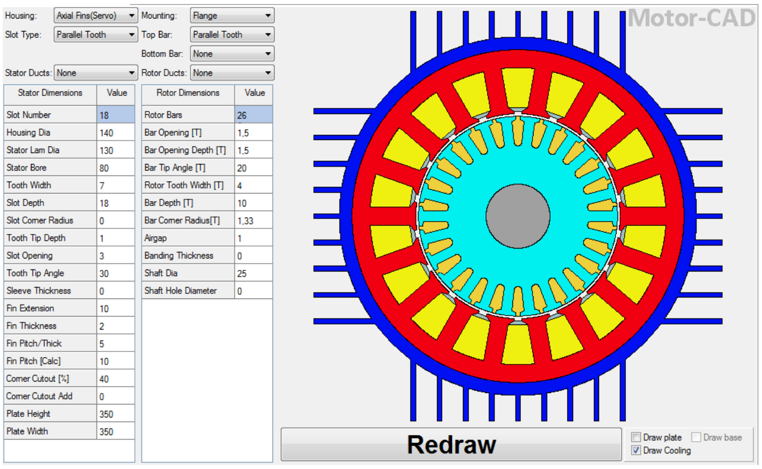


Figure 5. Cross-section through motor, highlighting the dimensions of the base constituent elements (trapezoidal rotor slot/pear; rectangular rotor tooth)

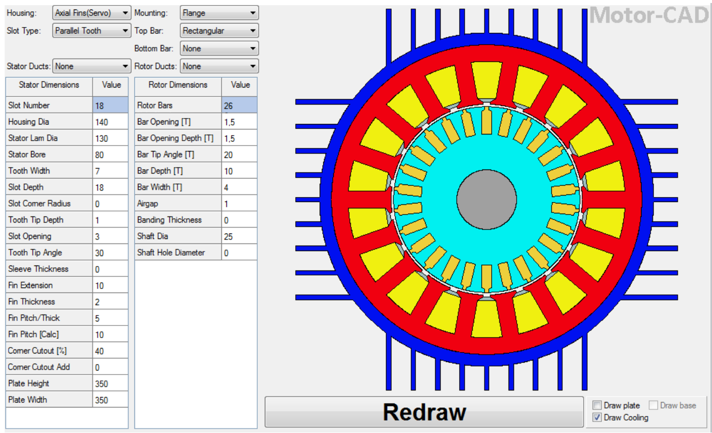


Figure 6. Cross-section through motor, highlighting the dimensions of the base constituent elements (rectangular rotor slot; trapezoidal rotor teeth)

3. Obtained results. Discussions

3.1. Changing the shape of the stator slots

Following the analysis carried out for the trapezoidal stator slot (Figure 7) - in stationary regime – we obtained the temperature distribution from the induction motor shown in Figures 8 and 9. It is worth mentioning that for the studied type of motor, there are 18 slots on the stator armature, and 26 slots on the rotor armature.

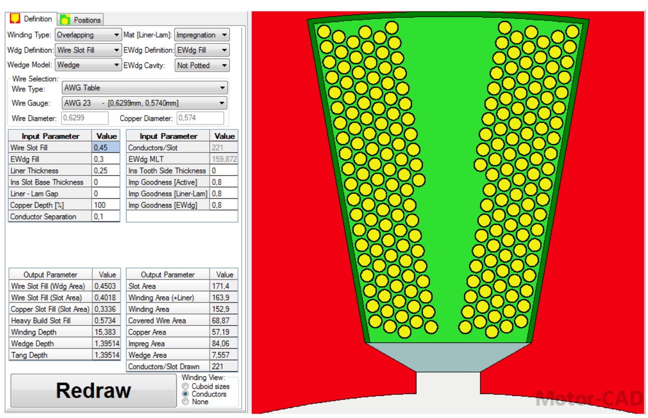


Figure 7. Trapezoidal stator slot - highlighting the issues of interest

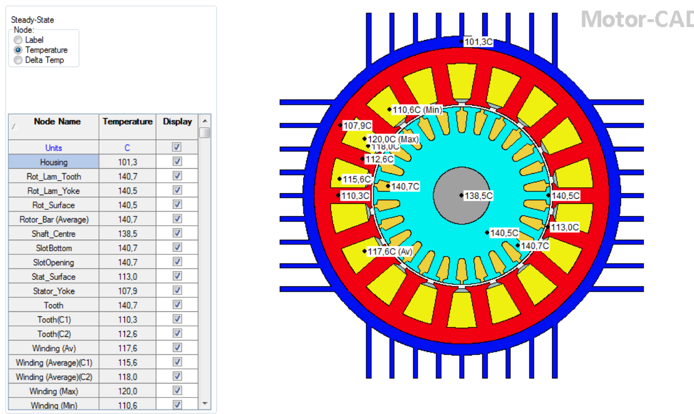


Figure 8. Highlighting the induction motor temperatures (cross section, trapezoidal stator slot)

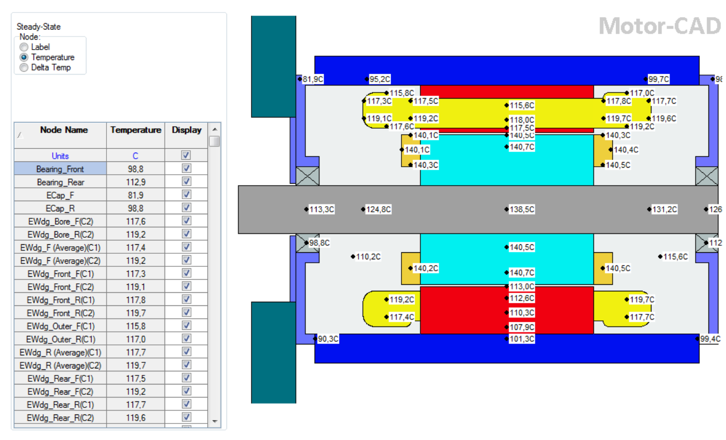


Figure 9. Highlighting the induction motor temperatures (longitudinal section, trapezoidal stator slot)

Figure 10 shows the temperature evolution in the various constructive parts of the induction motor during the dynamic/transient regime. It is worth mentioning that the maximum temperature allowed in the temperate climate was the temperature of 40 °C.

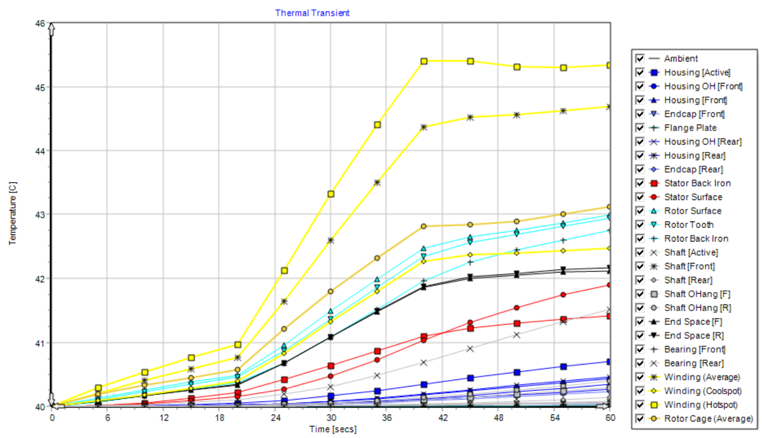


Figure 10. Temperature variation in the structure of the induction motor for trapezoidal stator slots - dynamic regime

As expected, the fastest rising temperature recorded - dynamic/transient regime - is for the stator slot area.

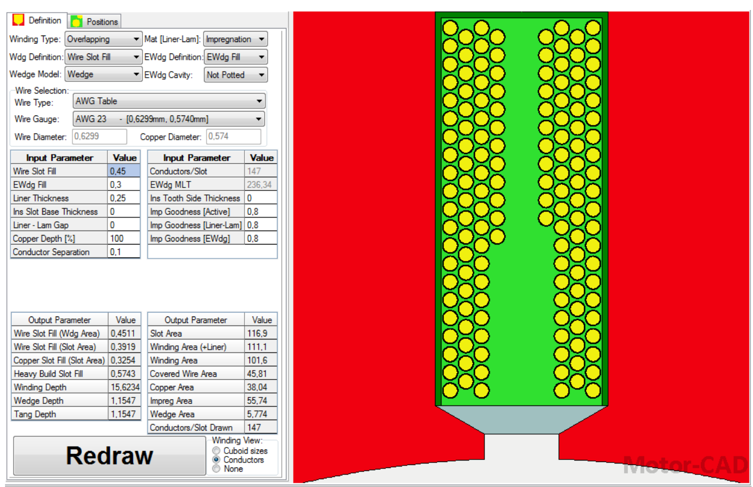
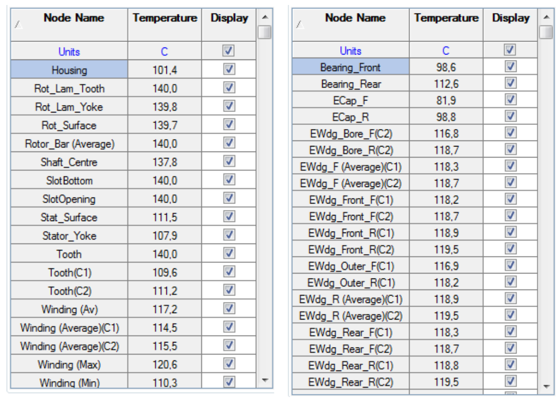


Figure 11. Rectangular stator slot - highlighting the issues of interest

In the case of the rectangular stator slot (Figure 11), for the induction motor operating in stationary regime, Figure 12 show the temperature distribution inside the structure in.



Node Name	Temperature	Display
Units	C	☑
Housing	101,4	☑
Rot_Lam_Tooth	140,0	☑
Rot_Lam_Yoke	139,8	☑
Rot_Surface	139,7	☑
Rotor_Bar (Average)	140,0	☑
Shaft_Centre	137,8	☑
SlotBottom	140,0	☑
SlotOpening	140,0	☑
Stat_Surface	111,5	☑
Stator_Yoke	107,9	☑
Tooth	140,0	☑
Tooth(C1)	109,6	☑
Tooth(C2)	111,2	☑
Winding (Av)	117,2	☑
Winding (Average)(C1)	114,5	☑
Winding (Average)(C2)	115,5	☑
Winding (Max)	120,6	☑
Winding (Min)	110,3	☑

Node Name	Temperature	Display
Units	C	☑
Bearing_Front	98,6	☑
Bearing_Rear	112,6	☑
ECap_F	81,9	☑
ECap_R	98,8	☑
EWdg_Bore_F(C2)	116,8	☑
EWdg_Bore_R(C2)	118,7	☑
EWdg_F (Average)(C1)	118,3	☑
EWdg_F (Average)(C2)	118,7	☑
EWdg_Front_F(C1)	118,2	☑
EWdg_Front_F(C2)	118,7	☑
EWdg_Front_R(C1)	118,9	☑
EWdg_Front_R(C2)	119,5	☑
EWdg_Outer_F(C1)	116,9	☑
EWdg_Outer_R(C1)	118,2	☑
EWdg_R (Average)(C1)	118,9	☑
EWdg_R (Average)(C2)	119,5	☑
EWdg_Rear_F(C1)	118,3	☑
EWdg_Rear_F(C2)	118,7	☑
EWdg_Rear_R(C1)	118,8	☑
EWdg_Rear_R(C2)	119,5	☑

Figure 12. Highlighting the induction motor temperatures (rectangular stator slot)

Figure 13 shows temperature evolution inside the induction motor structure during the dynamic/transient regime - in the case of the rectangular stator slot - in is shown in.

Although the evolution of the temperature (in the dynamic regime) and the temperature distribution (in the stationary regime) is, in principle, the same, there are differences - easier to highlight in the stationary regime - with regard to the thermal regime of the electric machine, differences caused by the change of the shape of the slot stator.

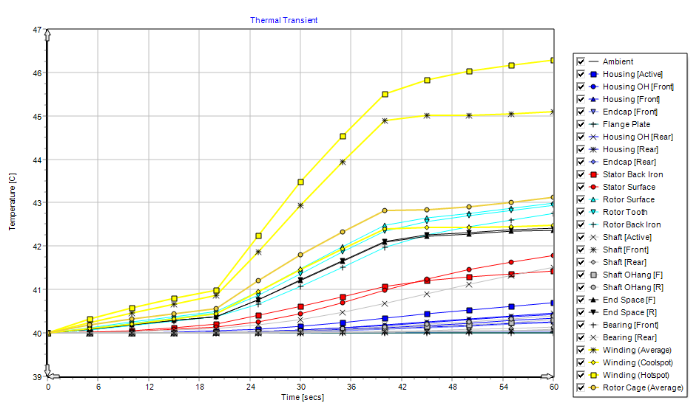


Figure 13. Temperature variation in the induction motor structure for rectangular stator slot - dynamic regime

Following the comparative analysis of Figures 8 and 9 with Figure 12 respectively, it results that, in the stationary regime, the temperatures in the integrated structure of the studied induction motor (viewed at the level of its various constituent elements: carcass, armatures, rotor shaft, bearings etc.) - are - lower within the range 0.1 °C - 1 °C when comparing the version using rectangular stator slots to the version using trapezoidal stator slots.

It is also worth mentioning the fact that there are, in the case of rectangular slots, also areas where the situation is thermally reversed, in the sense that slightly increased temperatures are registered as compared to the version using trapezoidal slots (e.g. at the carcass level, it is recorded a slight increase in temperature by 0.1 °C in the case of rectangular slots as opposed to the other studied design).

On the whole, however, simplifying things, from the point of view of the thermal regime, the version using rectangular slots is better than the version incorporating trapezoidal slots on the stator armature.

3.2. Changing the shape of the rotor slot

For the analysis in this paper, we referred to the trapezoidal slot as the stator reference slot. The trapezoidal (pear) slot was used as the rotor reference slot also. That is why when changing the shape of the rotor slot, we preserved the reference shape that is the trapezoidal shape of the stator slot.

For this reason, the results obtained in terms of temperature distribution for the trapezoidal shape of the rotor slot - in the stationary and dynamic regime - observed within the integrated structure of the induction motor are precisely those shown in Figures 8-10.

When changing the shape of the rotor slot (for example, the adoption of a rectangular shape slot) as the stator reference slots, Figure 14 show the temperature distribution - in stationary regime, and Figure 15 shows the evolution of the temperature - in dynamic/transient regime of the induction motor.

Node Name	Temperature	Display
Units	C	☑
Housing	101,3	☑
Rot_Lam_Tooth	140,7	☑
Rot_Lam_Yoke	140,5	☑
Rot_Surface	140,5	☑
Rotor_Bar (Average)	140,7	☑
Shaft_Centre	138,5	☑
SlotBottom	140,7	☑
SlotOpening	140,7	☑
Stat_Surface	113,0	☑
Stator_Yoke	107,9	☑
Tooth	140,7	☑
Tooth(C1)	110,3	☑
Tooth(C2)	112,6	☑
Winding (Av)	117,6	☑
Winding (Average)(C1)	115,6	☑
Winding (Average)(C2)	118,0	☑
Winding (Max)	120,0	☑
Winding (Min)	110,6	☑

Node Name	Temperature	Display
Units	C	☑
Bearing_Front	98,8	☑
Bearing_Rear	112,9	☑
ECap_F	81,9	☑
ECap_R	98,8	☑
EWdg_Bore_F(C2)	117,6	☑
EWdg_Bore_R(C2)	119,2	☑
EWdg_F (Average)(C1)	117,4	☑
EWdg_F (Average)(C2)	119,2	☑
EWdg_Front_F(C1)	117,3	☑
EWdg_Front_F(C2)	119,1	☑
EWdg_Front_R(C1)	117,8	☑
EWdg_Front_R(C2)	119,7	☑
EWdg_Outer_F(C1)	115,8	☑
EWdg_Outer_R(C1)	117,0	☑
EWdg_R (Average)(C1)	117,7	☑
EWdg_R (Average)(C2)	119,7	☑
EWdg_Rear_F(C1)	117,5	☑
EWdg_Rear_F(C2)	119,2	☑
EWdg_Rear_R(C1)	117,7	☑
EWdg_Rear_R(C2)	119,6	☑

Figure 14. Highlighting of induction motor temperatures (rectangular rotor slot)

It should be noted that although the shape of the rotor slot was changed, in the case of the same shape of the stator slot (trapezoidal), there is no perceptible difference between the group of Figures 8-10 (which contain the temperature distribution in the induction motor in the case of the trapezoidal rotor slot), and the group of Figures 14-15 (which contain the temperature distribution in the induction motor in the case of the rectangular rotor slot). The natural conclusion is that changing of the shape of the rotor slots within the induction motor has no influence on its thermal regime.

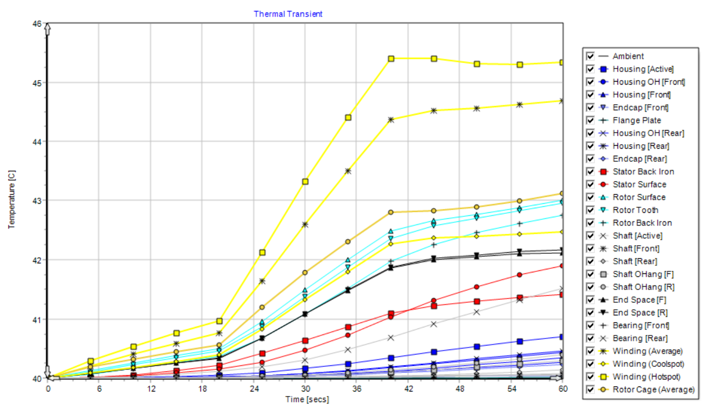


Figure 15. Temperature variation in the induction motor structure for rectangular rotor slots - dynamic regime

4. Conclusions. Discussion

The analysis carried out - in the initial part of the study - pointed out that, when changing the shape of the slots for only one armature, this influences in a relatively small manner the thermal regime within the motor.

Finally, the study was completed with a comparative analysis of two geometrically identical induction motors and of dimensions but with the shape of the slots changed on both armatures. The distribution of the temperatures in the stationary working regime for the two classes of motors - one having only trapezoidal slots on both armatures and the other having only rectangular slots on the two armatures - is shown in Figure 16.

Node Name	Temperature	Display
Units	C	☑
Housing	101,4	☑
Rot_Lam_Tooth	140,3	☑
Rot_Lam_Yoke	140,1	☑
Rot_Surface	140,1	☑
Rotor_Bar (Average)	140,3	☑
Shaft_Centre	138,1	☑
SlotBottom	140,3	☑
SlotOpening	140,3	☑
Stat_Surface	112,9	☑
Stator_Yoke	108,0	☑
Tooth	140,3	☑
Tooth(C1)	110,4	☑
Tooth(C2)	112,5	☑
Winding (Av)	115,0	☑
Winding (Average)(C1)	113,8	☑
Winding (Average)(C2)	115,2	☑
Winding (Max)	116,5	☑
Winding (Min)	112,2	☑

Node Name	Temperature	Display
Units	C	☑
Bearing_Front	98,6	☑
Bearing_Rear	112,5	☑
ECap_F	81,9	☑
ECap_R	98,7	☑
EWdg_Bore_F(C2)	115,7	☑
EWdg_Bore_R(C2)	116,4	☑
EWdg_F (Average)(C1)	115,0	☑
EWdg_F (Average)(C2)	115,9	☑
EWdg_Front_F(C1)	115,0	☑
EWdg_Front_F(C2)	115,9	☑
EWdg_Front_R(C1)	115,3	☑
EWdg_Front_R(C2)	116,3	☑
EWdg_Outer_F(C1)	114,5	☑
EWdg_Outer_R(C1)	115,0	☑
EWdg_R (Average)(C1)	115,3	☑
EWdg_R (Average)(C2)	116,3	☑
EWdg_Rear_F(C1)	115,0	☑
EWdg_Rear_F(C2)	116,0	☑
EWdg_Rear_R(C1)	115,3	☑
EWdg_Rear_R(C2)	116,3	☑

a)

Node Name	Temperature	Display
Units	C	☑
Housing	101,3	☑
Rot_Lam_Tooth	140,3	☑
Rot_Lam_Yoke	140,1	☑
Rot_Surface	140,0	☑
Rotor_Bar (Average)	140,3	☑
Shaft_Centre	138,1	☑
SlotBottom	140,3	☑
SlotOpening	140,3	☑
Stat_Surface	111,5	☑
Stator_Yoke	107,8	☑
Tooth	140,2	☑
Tooth(C1)	109,5	☑
Tooth(C2)	111,1	☑
Winding (Av)	119,4	☑
Winding (Average)(C1)	115,8	☑
Winding (Average)(C2)	116,7	☑
Winding (Max)	124,0	☑
Winding (Min)	109,5	☑

Node Name	Temperature	Display
Units	C	☑
Bearing_Front	98,8	☑
Bearing_Rear	112,9	☑
ECap_F	81,9	☑
ECap_R	98,8	☑
EWdg_Bore_F(C2)	117,9	☑
EWdg_Bore_R(C2)	120,5	☑
EWdg_F (Average)(C1)	121,2	☑
EWdg_F (Average)(C2)	121,4	☑
EWdg_Front_F(C1)	121,1	☑
EWdg_Front_F(C2)	121,3	☑
EWdg_Front_R(C1)	122,0	☑
EWdg_Front_R(C2)	122,5	☑
EWdg_Outer_F(C1)	118,7	☑
EWdg_Outer_R(C1)	120,6	☑
EWdg_R (Average)(C1)	122,0	☑
EWdg_R (Average)(C2)	122,4	☑
EWdg_Rear_F(C1)	121,3	☑
EWdg_Rear_F(C2)	121,4	☑
EWdg_Rear_R(C1)	122,0	☑
EWdg_Rear_R(C2)	122,4	☑

b)

Figure 16. Comparison - from a thermal perspective - between the induction motors having slots of the same shape on the two armatures (stator and rotor)
a) The situation when there are only trapezoidal slots on the armatures;
b) The situation when there are only rectangular slots on the armatures.

The whole analysis allows the following conclusions:

• For a given motor with stated geometrical dimensions (volume, total power) changing the geometric shape of the slots - on the motor armatures - influences its thermal regime both in stationary and dynamic regime;

• Changing the shape of only the rotor slots (preserving the shape of the stator slots) has a much smaller influence on the thermal regime of the motor, than compared to the shape alteration of only the stator slots (preserving the same shape of the rotor slots);

• Changing the geometric shape of both the stator and rotor slots (global change for the whole motor) has a major influence on the engine's thermal regime (the temperature increases in certain areas of the engine by 5 - 7 °C, in the version using only rectangular slots on the two armatures compared to the version using only trapezoidal slots);

• Major differences - in terms of thermal regime - for the same motor, but with different shape slots will require either the use of high quality materials, thus increasing costs, or using classic materials (the same type of materials as in this study) in which case the life span of the motor is drastically reduced. Specialized studies acknowledge [4], [5] that an increase of 9 °C above the I threshold of the insulation class of dielectric materials leads to a reduction by half of the life span structure that incorporates them.

This study provides new insights into the optimization of the geometric structures of electrical machines and equipment, with the stated aim of achieving the best functional performance, for a suitable thermal regime that allows the longest possible life.

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