SUPPLEMENTARY IRON LOSSES IN ASYNCHRONOUS MACHINES WITH EXTERNAL ROTOR

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*Abstract:*The paper presents a comparative analysis of different theoretical iron losses evaluation techniques, coupling finite-element calculations and material modeling. This coupling can be performed at different levels: as a post-processing step or inside the nonlinear solution loop. Comparisons on an induction machine structure are performed and results are compared and discussed.

INTRODUCTION

Magnetic field in different parts of an electrical machine depends on the variation in time of currents and on the magnetic permeability caused by the armature movement. Iron losses are effects of the magnetic field variation. Different points in the electrical machine can have an alternative variation of the magnetic field,where the direction vector remains constant and the value of induction is constantly changing; or when the direction vector of the induction rotates and the induction varies too. Periodical variation of the induction determines two types of losses: hysteresis losses and Joule losses. Hysteresis losses are caused by the hysteresis loop of the material used in the rotor and stator, Joule losses are generated by the variation of the magnetic field. For iron losses, named principal losses, the variation in time and space of the magnetic field is considered sinusoidal.

Specific losses are defined as losses on unity mass[1], [2], [3]. Hysteresis losses are proportional with the surface of the hysteresis loop; with the field variation frequency *f*; and with the value of the induction *B.* For inductions higher than *1 T* hysteresis losses are calculated using the relation: [4], [5], [6].

$$p_{sH} = \sigma_H \cdot B^2 \cdot f \cdot k_H \qquad (1)$$

, where σ_H is constant determined by material proprieties, k_H is a constant value which takes in consideration the non-uniformity of the magnetic field caused by the Eddy currents and by the mechanical processing of the iron sheets.

Joule losses are independent to the magnetization time; they are defined by the thickness of the steel sheets, the variation frequency and the value of the induction. For induction machines the Joule losses are calculated with the relation:

$$p_{sJ} = \sigma_J \cdot (B \cdot f \cdot \Delta)^2 \cdot k_J \qquad (2)$$

, where Δ is the thickness of the steel sheets, k_J is considered k_H. These two categories of losses together are named iron losses. Supplementary losses are caused by the deviation of magnetic field from its sinusoidal form and the relative movement of armatures [2], [6].

The value of induction in the machine is decreased because of the opening of the slots. The variation period of the induction is determined by tooth pitch; and the

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variation of frequency is given by the slot number on the opposite armature and the rotation speed. The variation of induction, as any variations of induction, produces variation in flux on the components surface and induces Eddy currents. As in very fast-changing fields, due to the skin effect the magnetic field does not penetrate completely into the interior of the material. Higher order harmonics of the magnetic field with $\nu = 2 \cdot m \cdot k \pm 1$ order in an armature produces losses in the other armature too. On the surface of the parts appear losses due the Eddy currents called *surface core losses*.

In case of electrical machines with slots on both stator and rotor the reluctance pulsation of the magnetic circuit creates a pulsation in the tooth pitch magnetic field too which frequency is determined by the rotation speed of the machine and the number of teeth in the opposite armature. In the tooth on a small depth are produced losses due Eddy currents named *tooth flux pulsation core losses*.

The calculus of the supplementary losses is complex; in the literature it is considered that supplementary losses are approximately 1.5% of the nominal power [2], [5]. In the case of low-powered machines this percentage can increase to 3% too.

CALCULUS OF SUPPLIMENTARY LOSSES

The equation given for the specific losses on a surface are deduced from the equations of surface current density induced by the magnetic induction of space harmonic B_v. The material constant k_0 is introduced as:

$$k_0 = \frac{1}{4 \cdot \sqrt{\pi \cdot \mu \cdot \rho}} \qquad (3)$$

, where μ is the permeability, ρ is the resistivity of the material. Considering that B_{vs} is the normal component of the v order harmonics of the magnetic induction on the tooth surface of the rotor, Q_r is the number of slots in rotor, n is the relative speed in *r/sec*,τ_{ds} is the stator tooth pitch and k_{rv} is defined by the harmonic order and the reaction of Eddy currents, the *surface core losses* are determined by the equation:

$$p_{0s} = k_0 \cdot (B_{\nu s} \cdot \tau_{ds})^2 \cdot (Q_R \cdot n)^{1.5} \cdot k_{r\nu} \qquad (4)$$

The magnetic induction B_v is determined in the case of harmonics in tooth as the induction between B_d or in the case of harmonics produced by the specific magneto-motive force of the coils [4], [5], [6].

The calculus of the specific losses is given by relation 2 in which the frequency of field variation caused by rotor tooth is considered; and the induction is determined as it is presented below:

$$p_{Js} = \sigma_J \cdot (B_{\nu s} \cdot \Delta \cdot Q_R \cdot n)^2 \cdot k_n \qquad (5)$$

, where σ_j is the specific loss due Eddy currents at the induction of $B=1\ T$, k_n is the product of the reduction constants caused by the reaction and the material processing constant. On load supplementary losses dependent to the MMF harmonics of the stator and rotor; and are proportional with the square value of specific MMF, A. These losses can be deduced from the equations above and using the specific losses on surface and pulsation in stator, having the equations:

$$p_{vs} = k_0 \cdot \mu_0^2 \cdot A^2 \cdot \left(\frac{\tau_{dR}}{\delta'}\right)^2 \cdot \tau_{ds}^2 \cdot \left(f\,\frac{Q_R}{p}\right)^{1.5} \cdot k_{vrp} \tag{6}$$

$$p_{vs} = \sigma_J \cdot \mu_0^2 \cdot A^2 \cdot \left(\frac{\tau_{dR}}{\delta'}\right)^2 \cdot \frac{\tau_{ds}^2}{b_{ds}^2} \cdot \left(\frac{Q_R}{p}\right)^2 \cdot k_{vrpJ} \tag{7}$$

, where f is the frequency of the voltage source, b_{ds} is the stator tooth width, p is the number of pole pairs, k_{vrp} and k_{vrpJ} considers the harmonic orders of the reaction and material processing coefficients.

The calculus of the supplementary losses caused by pulsation was done using a program written in Mathcad for an induction machine with rated power of 0.7kW and with exterior rotor. The results are presented in the table 1.

Table 1
Supplementary losses calculated using Mathcad.

p_{js}	p_{ds}	p_s	p_{jR}	p_{dR}	P_R	p_{sds}	p_{sdr}	p_s	p_{fe}
10.765	13.236	24,002	3.511	0.495	4.006	8.197	13.036	21.233	49.242

, where the indexes are j is yoke, d is tooth, R is rotor, s means supplementary and fe is total losses in iron.

It can be observed that the relative value of supplementary losses is higher than expected with a value approximately 3.5%.

VERIFICATION USING FEM ANALYSIS

To verify the analytical calculus, a finite element based simulation was created using JMAG 13.1. Finite element based simulation was used to create the virtual model of the asynchronous machine because the classical approach of a design of electrical machines the interaction between the various physical domains are only included with simplifications or even neglected.

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. It is uses subdivision of a whole problem domain into simpler parts, called finite elements, and variational methods from the calculus of variations to solve the problem by minimizing an associated error function. [10]

The model of the machine with all the parameters was set accordingly to the analytical calculus. The equivalent virtual machine was connected to a 3 phase voltage source with maximum voltage $\sqrt{2} * U_{ef}$. In the model we considered the skew of the rotor to calculate the working parameters as realistic as it is possible.

The simulation was done for 5 rotations which are enough to pass the transient state and enter in the steady simulation. To present the losses a 2D picture was taken about the losses of the magnetic circuit, which is presented in fig. 1.

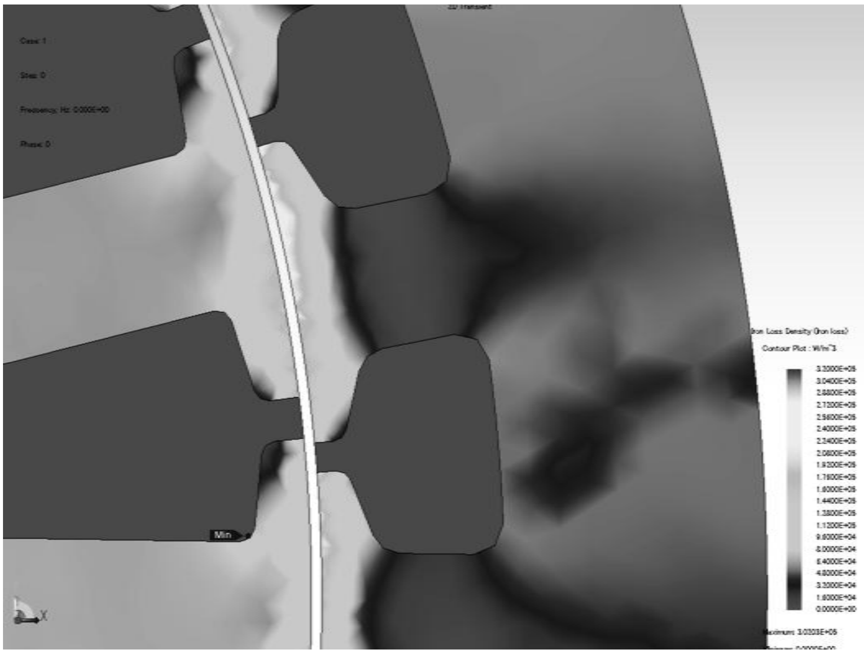

Fig. 1
Losses of the magnetic circuit calculated using JMAG.

On fig. 1 the brightest colors means bigger losses, for example on the surface of the tooth, and darker colors means smaller loss values, like in the core part of the rotor.

In the figure 2 the density variation of hysteresis losses is presented on the surface of the end part of stator teeth. This variation depends on the relative position between stator and rotor.

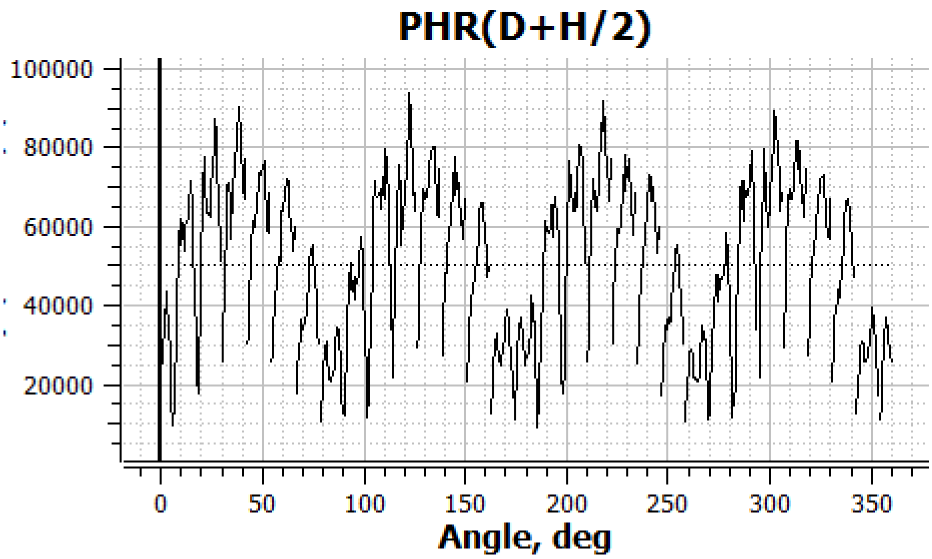

Fig. 2
The density variation of hysteresis losses in rotor tooth.

On the figure 3 presents the variation in density of the Joule losses is presented in the middle of the end part of stator tooth. The width of end tooth is approximately 12 degree. It can be seen that on the tooth width the losses varies in a wide interval.

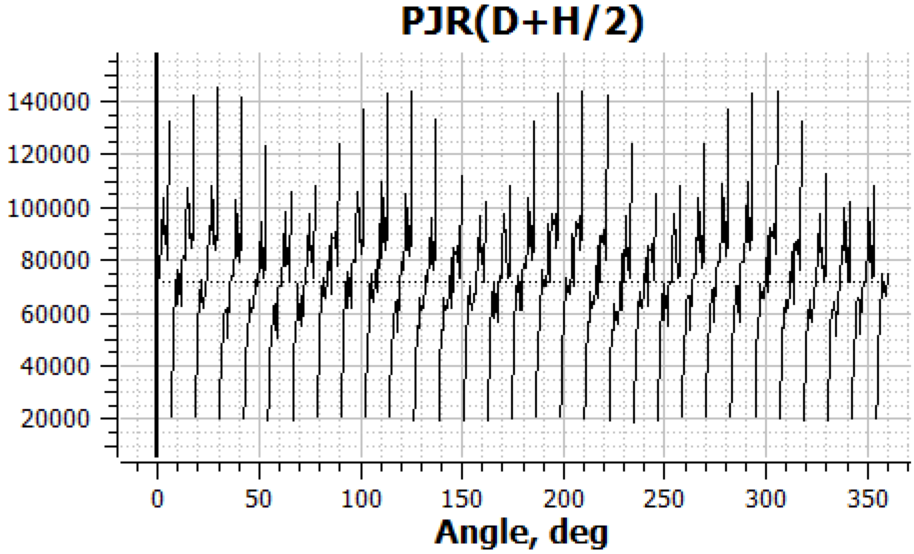

Fig. 3
Density variation of Joule losses in rotor tooth.

For comparison the results given by FEM analysis and analytical calculus, the loss density was calculated in different points of the magnetic circuit. Hysteresis losses presented in table 2 are just primary losses. The Joule losses were calculated on the surface of tooth end in the case of analytic calculus and for the JMAG it was determined in the middle part of tooth end. The results of both analytical calculus and FEM simulation are presented in table 2.

Table 2
Comparison of losses between analytical calculus and results fromFEM simulation.

Losses $*10^4$ w/m^3	Analytical for stator	Analytical for rotor	FEM results for stator	FEM results for rotor
Hysteresis	6.514	1.9311	5.0736	3.6
Joule losses	7.4476	5.9124	6.0941	4.161
Total	13.961	7.8441	11.1698	7.768

CONCLUSION

Supplementary losses of small power asynchronous machines are relatively higher than in case of high power machines. Analytical loss calculation can be done relative precisely if the constant k_0, calculated for the material from which stator and rotor are created, the value of magnetic induction B_v, and the intensity of the magnetic field determined by the magnetization properties of the material. The results for the loss calculus with analytical method and with finite element model are close enough to consider both of the methods correct.

FUTURE SCOPE

This paper presents the supplementary iron losses in asynchronous machine with external rotor. The next step in the development of this machine is to make some optimizations, which can decrease the supplementary and the total losses without decreasing the power output. For this it will be implemented an analytical calculus combined with generic algorithm.

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