

A NEW HIGH EFFICIENCY TECHNOLOGY FOR THE INDUCTION HEATING OF NON MAGNETIC BILLETS

F. Dughiero⁽¹⁾, M. Forzan⁽¹⁾, S.Lupi⁽¹⁾, F. Nicoletti⁽¹⁾, M.Zerbetto⁽²⁾

⁽¹⁾ University of Padua, Department of Electrical Engineering,
Via Gradenigo, 6/A., 35131 Padova (Italy)

⁽²⁾ Inova Lab srl, Via Torino, 213., 10040 Leinì (Italy)

INTRODUCTION

In recent years, an innovative DC induction heating concept has been proposed in order to increase the efficiency of the induction heating of low electrical resistivity metal billets [1-3]. In this approach the billet is forced to rotate inside a transverse DC magnetic field by means of an electric motor drive. Due to the change of magnetic flux an induced current distribution reacts to the driving torque during the rotation and generates thermal power within the billet. This concept has been successfully applied and some installations are working in some aluminum foundries. The main drawback of this approach is related to cost of installation because of the presence of a superconductive coil.

A more convenient solution, proposed in this paper, allows to achieve the same high efficiency at lower cost. In this solution the billet is kept still and a series of permanent magnets, positioned in the inner part of a ferromagnetic frame is rotated.

DESCRIPTION OF THE PROBLEM

The heating of a aluminum billet can be obtained thanks to the eddy currents induced by rotating the induction field B produced by a system of permanent magnets around the billet itself.

Two possible sketches of the system are presented in Fig.1: the first one describes ¼ of the entire geometry for a 4 poles system while the second one shows the entire geometry of a 8 poles system. In this paper, some preliminary results are presented only for the second configuration, with an aluminum billet 100 mm radius (R1) and 500 mm length, applying for the electro-magnetic solution an analytical method as well as a FE commercial code. The analytical solution requires very short computational time and can be conveniently applied to an automatic optimization process. On the other hand, the FEM model has been solved by means of a transient magnetic solution that reaches the steady state condition only when a high number time steps have been solved.

The solution requires the computation of the induction field inside the billet, B, produced by the permanent magnets and the induced currents produced by the motion:

$$\vec{E}_i = \omega r \vec{u}_\theta \times \vec{B} \quad (1)$$

where u_θ is the azimuthal unit vector.

In the hypothesis of a rotational speed ω in the range between 500 – 3000 rpm, the magnetic Reynolds number, R_M :

$$R_M = \sigma \mu U_0 L_0 \quad (2)$$

(where σ - the electrical conductivity, μ - the magnetic permeability, U_0 and L_0 - the characteristic velocity and length respectively) is much bigger than one and, obviously, the motional term must be considered.

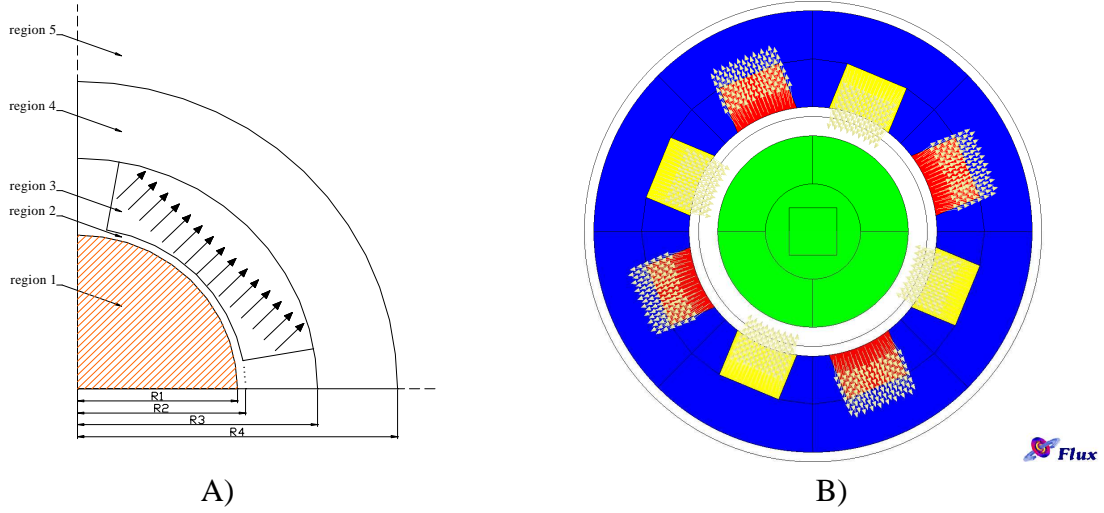


Fig.1: system geometry. A), a 4 poles system. Region 1 - the aluminum billet; region 2 - the air-gap (it takes into account also the thermal insulating material to protect permanent magnets); region 3 - the permanent magnets; region 4 - the back iron; region 5 - the external air. B), a 8 poles model is shown.

SIMULATION STRATEGY

FEM Solution

The FEM model has been solved taking into account the rotational movement of the permanent magnets by means of a transient magnetic solution.

The computation conditions for a transient magnetic solution are the following:

- The state variable are time dependent $d/dt \neq 0$
- The computation concerns only the \mathbf{B} , \mathbf{H} and \mathbf{E} fields (\mathbf{D} is not computed)

The 2D electromagnetic formulation is based on the following PDE:

$$\nabla \times \left(\frac{1}{\mu_r \mu_0} \nabla \times \mathbf{A} - \mathbf{H}_c \right) + \sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V \right) = 0 \quad (3)$$

where μ_r - the relative permeability of the medium, \mathbf{A} - the vector potential [Wb/m], \mathbf{H}_c - the coercive magnetic field for the permanent magnets, σ - the conductivity of the medium [S], V - the electric scalar potential.

The constitutive equations for magnetic materials are described by:

$$\mathbf{B} = \mu \mathbf{H} \Rightarrow \mu_r \mu_0 \mathbf{H} \text{ for soft magnetic materials, e.g. region 4 of Fig.1} \quad (4)$$

$$\mathbf{B} = \mu_r \mu_0 \mathbf{H} + \mathbf{B}_r = \mu_r \mu_0 \mathbf{H} + \mu_0 \mathbf{M} \text{ for hard magnetic materials, e.g. region 3} \quad (5)$$

where \mathbf{B}_r is the remanence and \mathbf{M} the magnetization vector.

The displacement of the rotating part modifies the geometry of the modelled device; consequently the computation domain must be re-meshed at each time step.

The state variable, the magnetic vector potential \mathbf{A} and the electric scalar potential V are initialized to zero for $t = 0$.

The state variables are time dependant and the differential equations of first order with respect to time:

$$\frac{dX}{dt} = F(X, t) \quad (6)$$

are integrated by means of the Euler implicit method in time domain. The time domain is subdivided into small time steps; during each step the unknowns are supposed to vary linearly with respect to time. The numerical code applies then an implicit method where the derivative is computed by means of values at the current and the previous steps:

$$\frac{dX}{dt} = \frac{X_{i+1} - X_i}{\Delta t} \quad (7)$$

For the preliminary computations presented in this paper, the real mechanical behaviour, which must take into account the inertia and other resistive torques (e.g. the torque due to the ventilation), is not considered and a constant velocity of rotation is imposed.

For the 8 poles case, some results are presented in Fig. 2, where the colour maps describe the induced current density in the aluminium billet and the lines are the flux lines.

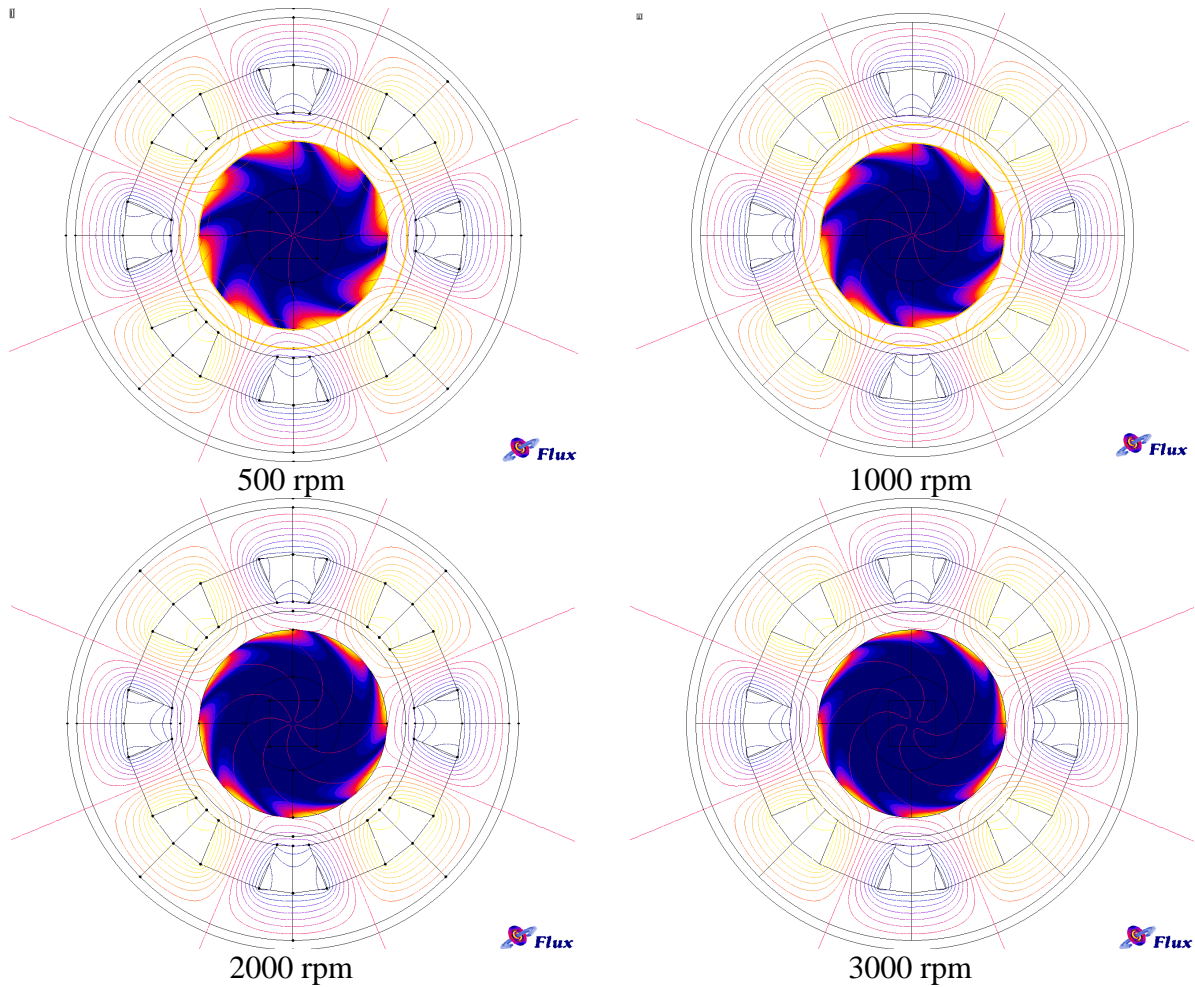


Fig.2: Induced current density distribution (color shade plot) and equiflux lines resulting in the steady state condition of a transient FEM solution at different rotational speeds.

Analytical solution

The analytical solution of the problem has been developed using a cylindrical coordinates system (r, ϑ, z) with the origin in the center of the billet. In the following formulas, the index of the regions makes reference to the description of Fig.1.

Maxwell's equation are taken into account neglecting the displacement currents:

$$\vec{\nabla} \times \vec{H} = \vec{j} \quad (8)$$

with the constitutive equation:

$$\vec{J} = \sigma(\vec{E} + \vec{v} \times \vec{B}) \text{ where: } \vec{v} = \Omega \cdot \vec{r} \cdot \vec{u}_\vartheta \quad (9)$$

Computation of the magnetization M .

In the permanent magnets (region 3), the constitutive equation is [5]:

$$\vec{B}_3 = \mu_3 \vec{H}_3 + \mu_0 \vec{M} \quad (10)$$

Considering magnets having a linear second quadrant demagnetization characteristic and with remanence B_r , the amplitude of \vec{M} is:

$$M = \frac{B_r}{\mu_0} \quad (11)$$

The direction of the vector \vec{M} depends on the magnetization of the magnets, in polar coordinates we have:

$$\vec{M} = M_r \vec{u}_r + M_\vartheta \vec{u}_\vartheta \quad (12)$$

M_r and M_ϑ can be expressed by Fourier series:

$$M_r = \sum_{n=1,3,5,\dots}^{\infty} M_{rn} \cos(np\vartheta) \quad (13)$$

$$M_\vartheta = \sum_{n=1,3,5,\dots}^{\infty} M_{\vartheta n} \sin(np\vartheta) \quad (14)$$

where $2p$ is the number of poles.

Using magnets with parallel magnetization, M_{rn} and $M_{\vartheta n}$ are:

$$M_{rn} = \frac{B_r}{\mu_0} \alpha_p (\xi_{1n} + \xi_{2n}) \quad (15)$$

$$M_{\vartheta n} = \frac{B_r}{\mu_0} \alpha_p (\xi_{1n} - \xi_{2n}) \quad (16)$$

where α_p is the magnet pole-arc to pole-pitch ratio and ξ_{1n}, ξ_{2n} are for $2p$ greater than 2:

$$\xi_{1n} = \frac{\sin \left[(np + 1) \alpha_p \frac{\pi}{2p} \right]}{(np + 1) \alpha_p \frac{\pi}{2p}} \quad (17)$$

$$\xi_{2n} = \frac{\sin \left[(np - 1) \alpha_p \frac{\pi}{2p} \right]}{(np - 1) \alpha_p \frac{\pi}{2p}} \quad (18)$$

The two components of the magnetization are illustrated in figures 3 and 4, for a 8 poles system.

General solution: diffusion equation.

For the problem solution we introduce the magnetic vector potential [6]:

$$\vec{B} = \vec{\nabla} \times \vec{A} \quad (19)$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} \quad (20)$$

Substituting (5) and (9) in (8) we get:

$$\vec{\nabla} \times \frac{1}{\mu} \cdot (\vec{B} - \vec{M}) = \sigma(\vec{E} + \vec{v} \times \vec{B}) \quad (21)$$

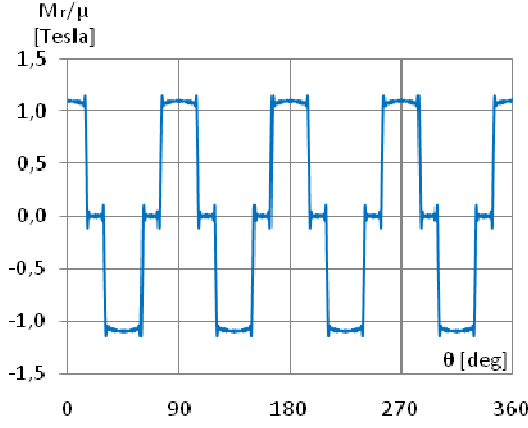


Fig.3. magnetization M_r

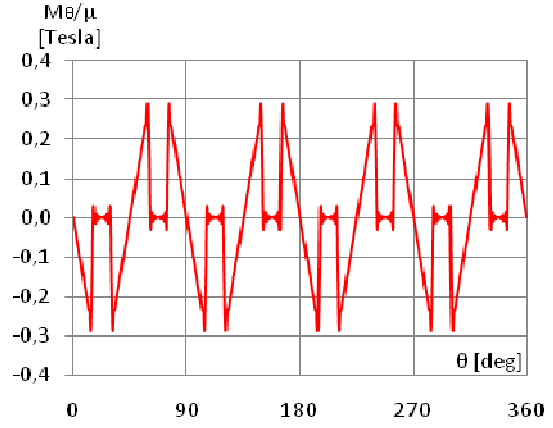


Fig.4. magnetization M_θ

Substituting (19) and $\vec{E} = 0$, (21) becomes:

$$\vec{\nabla} \times \frac{1}{\mu} \cdot (\vec{\nabla} \times \vec{A} - \vec{M}) = \sigma(\vec{v} \times \vec{\nabla} \times \vec{A}) \quad (22)$$

We can rewrite (22) as:

$$\vec{\nabla} \times \vec{\nabla} \times \vec{A} = \sigma \cdot \mu(\vec{v} \times \vec{\nabla} \times \vec{A}) + \vec{\nabla} \times \vec{M} \quad (23)$$

Considering the Coulomb gauge ($\vec{\nabla} \cdot \vec{A} = 0$) we obtain:

$$\nabla^2 \vec{A} = \sigma \cdot \mu(-\vec{v} \times \vec{\nabla} \times \vec{A}) - \vec{\nabla} \times \vec{M} \quad (24)$$

The magnetic vector potential has only one component along z direction, then the equation (24) becomes:

$$\frac{\partial^2 A}{\partial r^2} + \frac{1}{r} \frac{\partial A}{\partial r} + \frac{1}{r^2} \frac{\partial^2 A}{\partial \vartheta^2} = \sigma \mu \Omega \frac{\partial A}{\partial \vartheta} + \frac{1}{r} \frac{\partial M_r}{\partial \vartheta} - \frac{1}{r} M_\theta - \frac{\partial M_\theta}{\partial r} \quad (25)$$

Eqn. (25) can be written for each region of the model.

General solution applied in each region of the model.

The general solution of equation (25) considering the form of the magnetization of the PM (13) is:

$$A_i = \sum_{n=1,3,5,\dots}^{\infty} A_{ni} \sin(np\vartheta + \varphi) \quad (26)$$

Thus the calculus can be simplified using the complex domain, (26) becomes:

$$A_i = \text{Im} \left\{ \sum_{n=1,3,5,\dots}^{\infty} \underline{A}_{ni} e^{jnp\vartheta} \right\} \quad (27)$$

where:

- $\text{Im}\{\dots\}$ indicates the imaginary part of the complex number
- $\underline{A}_{ni} = A_{ni} e^{j\varphi}$

The solution in all regions are obtained by applying the separation of variables method.

In each regions we get:

- In region 1 (aluminum billet) equation (25) in the complex domain becomes:

$$\frac{\partial^2 \underline{A}_1}{\partial r^2} + \frac{1}{r} \frac{\partial \underline{A}_1}{\partial r} - (p^2 + jk^2 r^2) \underline{A}_1 = 0 \quad (28)$$

where:

$$k^2 = \sigma_1 \mu_1 np\Omega \quad (29)$$

thus the solution is:

$$\underline{A}_1 = \sum_{n=1,3,5,\dots}^{\infty} \left[C_{1np} J_{np} \left(j^{\frac{3}{2}} kr \right) \right] \text{ with } j^2 = -1 \quad (30)$$

where J_{np} is the Bessel function of first kind and order np .

- In region 2 (air-gap) equation (25) in the complex domain becomes:

$$\underline{A}_2 = \sum_{n=1,3,5,\dots}^{\infty} \left[C_{2np} r^{np} + D_{2np} r^{-np} \right] \quad (31)$$

- In region 3 (permanent magnets) equation (25) in the complex domain becomes:

$$\underline{A}_3 = \sum_{n=1,3,5,\dots}^{\infty} \left[C_{3np} r^{np} + D_{3np} r^{-np} + \frac{\mu_0 M_n r}{(np^2 - 1)} \right] \quad (32)$$

where

$$M_n = np M_{rn} + M_{\vartheta n} \quad (33)$$

In region 4 (iron) equation (26) in the complex domain has the same terms of equation (31) while in region 5 (external air) the governing equation contains only the r^{-np} term.

Boundary conditions.

The integration constants $\underline{C}_{1np}, \underline{C}_{2np}, \underline{D}_{2np}, \underline{C}_{3np}, \underline{D}_{3np}, \underline{C}_{4np}, \underline{D}_{4np}, \underline{D}_{5np}$ are computed by writing the boundary conditions at the interface between regions:

$$\underline{A}_i|_{r=R_{ij}} = \underline{A}_j|_{r=R_{ij}} \quad \underline{H}_{\vartheta i}|_{r=R_{ij}} = \underline{H}_{\vartheta j}|_{r=R_{ij}} \quad (34)$$

where i, j are the indexes of two regions, R_{ij} is the radius at the interface.

Computation of eddy currents and power density.

The induced current density in the complex domain is [6]:

$$\underline{J}_1 = -j \frac{k^2}{\mu_1} \underline{A}_1 \quad (35)$$

Thus the eddy current density in the billet is:

$$J_1(r, \vartheta) = \text{Im} \left\{ \underline{J}_1 e^{jnp\vartheta} \right\} \quad (36)$$

The power loss density is given by:

$$p(r, \vartheta) = \frac{J_1^2(r, \vartheta)}{\sigma} \quad (37)$$

And the instantaneous value of the power losses in the billet, integrated over the volume of the cylinder, is:

$$P = \int_0^{R_1} \int_0^{2\pi} \frac{J_1^2(r, \vartheta)}{\sigma} r d\vartheta dr \quad (38)$$

RESULTS

Some comparisons between the results obtained by the analytical formulation and the ones resulting from the FEM solution are presented in the following for a 8 poles system, solved with different rotational velocities. The main geometric dimension of the system, taken into account as reference for this comparison with reference to Fig.1, are: $R_1 = 100$ mm; $R_2 = 130$ mm; $R_3 = 180$ mm ; $R_4 = 230$ mm; α_p , the magnet pole-arc to pole-pitch ratio, = $30/45 = 0.666$; the axial length is set 0.5 m.

The rare earth permanent magnets have a remanence $B_r = 1.1$ T and a coercive field $H_c = 838$ kA/m.

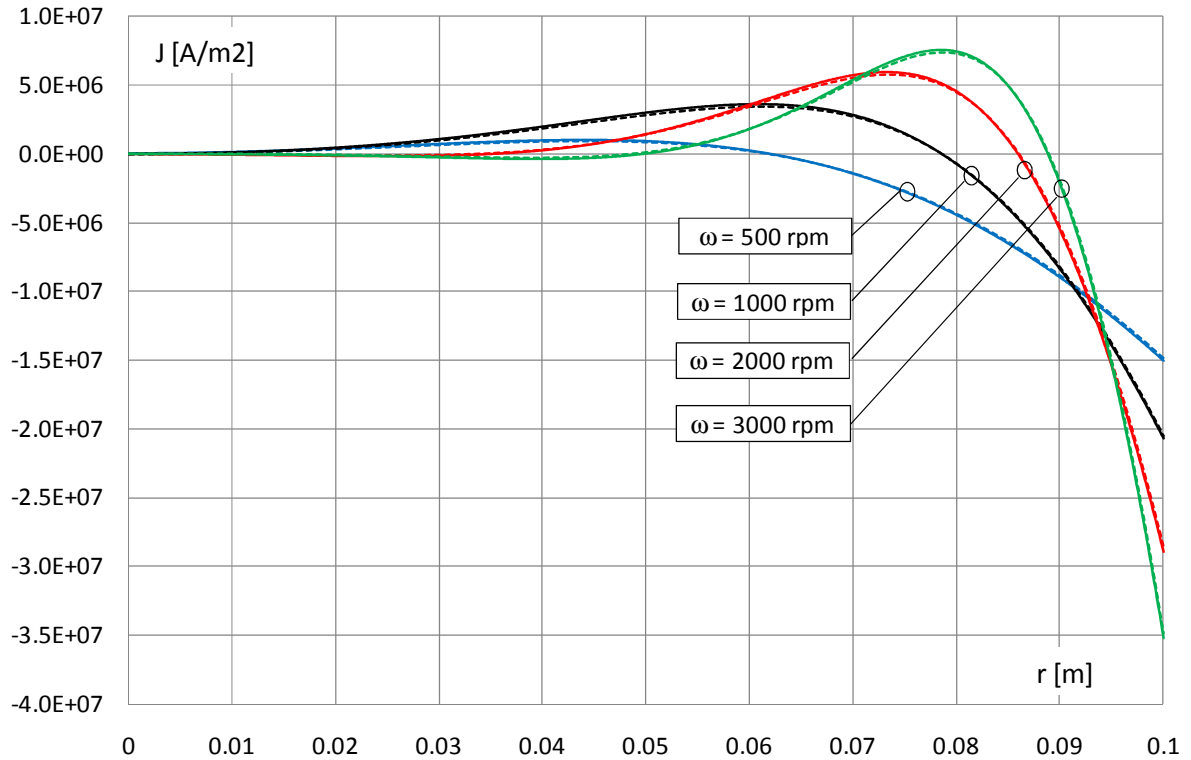


Fig.5: Current density distribution evaluated along the radius for different rotational speeds.
FEM solution - dotted lines; analytical solution - continuous lines

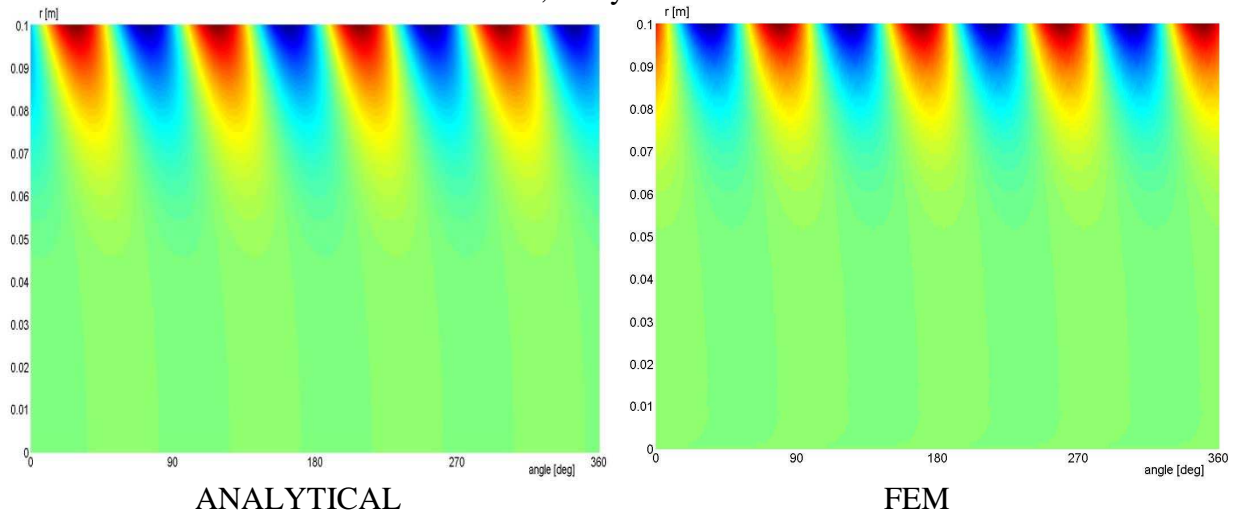


Fig.6: Current density distribution as resulting from the analytical solution and the FEM one:
on x axis the azimuth [angle in degree], on y axis the radial position [m].

CONCLUSIONS

In the paper, a comparison between numerical and analytical methods for the prediction of current and power density induced in a conductive billet inside a rotating magnetic field is proposed. The two different methods can be used in order to design and optimize this innovative technique to heat billets.

The proposed method looks very attractive because it overcomes the main drawback of the previously proposed approach where the billet is forced to rotate inside a DC induction field produced by superconductive coils, that requires an adequate refrigerating system. The system reaches the same efficiency values of the previously proposed approach, efficiency that mainly depends upon the efficiency of the motor and its driving system, achieving strong induced power values using a set of rare earth permanent magnets instead of a much more expensive superconductive system.

REFERENCES

- [1] F. Dughiero, M. Forzan and S. Lupi, (2006). Induction heating of aluminium billets rotating in a DC magnetic field. *Proc. of VIII Int. Conf. on Problems of Control and Modeling Complex Systems*, Samara - Russia, June 24-29, pp. 171-176.
- [2] Araneo R., Dughiero F., Fabbri M., Forzan M., Geri A., Lupi S., Morandi A., Ribani P., Veca G. (2008). Electromagnetic and thermal analysis of the induction heating of aluminum billets rotating in dc magnetic field. *HES-07 – Heating by Electromagnetic Sources*. June 19-22, 2007, vol. 1, pp. 487-496. ISBN 88-89884-07-x, Padua: Sgeditoriali (Italy); printed in COMPEL, vol.27, No.2, 467-479, ISSN 0332-1649.
- [3] Fabbri M., Forzan M., Lupi S., Morandi A., Ribani P.L. (2009). Experimental and Numerical Analysis of DC Induction Heating of Aluminium Billets. *IEEE Trans. on MAGNETICS*. Vol.45, n.1, January 2009, 192-200.
- [4] Watanabe T., Todaka T., and Enokizono M. (2005). Analysis of a New Induction Heating Device by Using Permanent Magnets. *IEEE Trans on MAGNETICS*. Vol. 41, NO. 5, May 2005, 1884-1887.
- [5] Zhu Z. Q., Howe D., and Chan C. C. (2002). Improved analytical model for predicting the magnetic field distribution in brushless permanent-magnet machines, *IEEE Trans. on Magnetics*, vol. 38, no. 1, pp. 229-238.
- [6] Lubin T., Netter D., Leveque J., and Rezzoug A. (2009). Induction Heating of Aluminum Billets Subjected to a Strong Rotating Magnetic Field Produced by Superconducting Windings;. *IEEE Trans. on MAGNETICS*. Vol.45, n.5, May 2009, 2118-2127.
- [7] Boughrara K., Chikouche B. L., Ibtouen R., Zarko D., and Touhami O.(2009). Analytical Model of Slotted Air-Gap Surface Mounted Permanent-Magnet Synchronous Motor With Magnet Bars Magnetized in the Shifting Direction. *IEEE Trans. on MAGNETICS*. Vol.45, n.2, February 2009, 747-758.
- [8] Markovic M., and Perriard Y.(2007). An analytical determination of eddy-current losses in a configuration with a rotating permanent magnet. *IEEE Trans. on MAGNETICS*. Vol.43, n.8, August 2007, 3380–3386.
- [9] Markovic M., and Perriard Y.(2008). Analytical solution for rotor eddy-current losses in a slotless permanent magnet motor: the case of current sheet excitation. *IEEE Trans. on MAGNETICS*. Vol.44, n.3, March 2008, 386–393.
- [10] CEDRAT, <http://www.cedrat.com/>, FLUX users guide.