Rigorous Electromagnetic Modelling Of Domestic Induction Heating Systems

Curriculum: Elettromagnetismo e Bioingegneria

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Abstract. This work is dedicated to developing of an electromagnetic model of an induction cooking system which consists of analytical model and its numerical solution. The analytical modeling is the characterization of the whole system based on field theory concept analogous to the circuit theory compensation-theorem. Currents in each part of the system and both electric and magnetic fields generated by these currents were defined and composed into a system of the potential balance equations. The generated fields were defined via electric and magnetic vector potential definitions. The obtained solving system is the analytical description of the mutual electromagnetic interactions between different parts and applying boundary conditions it defines the current densities in every part of the system. A matrix linear equation was proposed as the numerical solution of the system that provides all the electric and magnetic currents of the system. The left part of the equation is the voltage vector. The right part is the multiplication of the impedance coefficient matrix and unknown vector of currents. The solution of the matrix equation is finding the currents and hence their distribution in all the parts of the system. Finally, the proposed model has been validated experimentally by dint of measuring of the input impedance and comparing it with the calculated one.

Keywords. Induction heating, induction cooker, magnetic device, impedance measuring, Litz wire

1 Introduction and objectives

Developing of a rigorous electromagnetic model of induction heating system is a quite complex task. Since the model should describe electromagnetic prospective of the system operation it should consider different parameters such as inductor properties, its geometry, material and feeding voltage, load material properties, thickness, ferrite characteristics and aluminum shielding. More than that, the model must cope all the magnetic couplings and interactions of the system.

The main object of the following work was to develop a design tool which would allow to simulate the full-wave system and its operation taking into account either geometrical or electromagnetic parameters of the system. The design tool should posses the parametrical flexibility in order to analyze different cases of use, different configurations of the system sizes and distances between internal parts. It should allow to carry on simulations of the system operation and to calculate all the induced currents in the load, their distribution and values, to evaluate current distribution in ferrite substrate and aluminum shielding. The model must give a rigorous evaluation of the input impedance of the system, because the input impedance is the main parameter for the electronic control system.

More than that, induction coils transfer the electrical power delivered by the inverter into the vessel through a magnetic coupling. The windings for domestic induction heating must fulfill several conditions such as sizing restrictions, power ratings, and high efficiency in the transmission of the electromagnetic energy. Normally, flat-type spiral windings are used for cooking purposes [1], [2]–[5], with an external diameter defined by the size of the burners. The number of turns of an inductor is determined once the required nominal power, the inverter topology, and the mains voltage are known. Therefore, for designing an inductor, the main degree of freedom is the winding yarn, which is closely related with the induction efficiency [6]–[8].

For designing a domestic induction system, it is also essential to define the yarn that minimizes the self-losses in the inductor. Different kinds of copper-wire profiles have been used for domestic inductors: foils or tapes [9], [10], round wires [11], and multistranded wires. The last ones are often divided into Litz-wires (those constructed according to a careful strand-transposition pattern) having up to tens of strands [12] and twisted wires (those with the strands simply twisted or bunched) that can group up to thousands of fine strands [13], [14].

Today, litz wires are extensively used because a good ratio between the cost and the performance is achieved; furthermore, the number of strands of the cable and its diameter can be designed to maximize gind at a specific working frequency [15]. However, the FEA methods, which have been traditionally used to design the domestic induction systems, become impractical, especially for wires with a high number of fine strands.

Considering this fact, one of the object was also to develop accurate model of the complex geometry of a Litz-wire.

2 Model developing

As far as electromagnetic problem of induction system operation has to be analyzed, the system was considered to be composed of 4 main parts which define the operation process and which are necessary by the construction requirements in every domestic induction appliance. These parts are: a) load disk, b) inductor, c) ferrite bars and d) aluminum shielding (Figure 1).

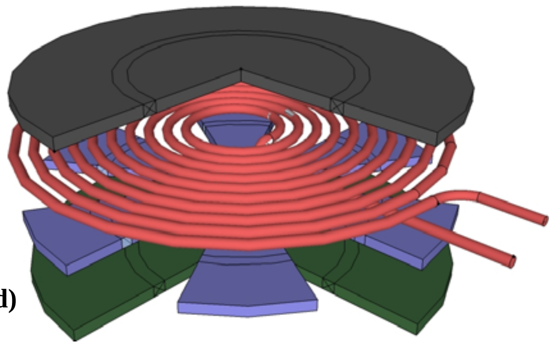


Figure 1 - Four parts of induction cooking appliance.

Analytical electromagnetic model was developed as the system of electric and magnetic fields equations based on potential balance equations and boundary conditions. The numerical solution of this system is the linear matrix equation.
Thus the system is presented as a linear matrix equation where in the left part there is a multiplication of the impedance matrix and current vector and in the right part there is the voltage vector. To solve this equation means to find unknown current vector.

$$
\begin{array}{cc}
\begin{pmatrix}
Z^{e,e}_{cu,cu} & Z^{e,e}_{cu,a} & Z^{e,e}_{cu,AL} & A^{e,m_\rho}_{cu,a} & A^{e,m_z}_{cu,a} & A^{e,m_\rho}_{cu,F} & A^{e,m_z}_{cu,F} \\
Z^{e,e}_{a,cu} & Z^{e,e}_{a,a} & Z^{e,e}_{a,AL} & A^{e,m_\rho}_{a,a} & A^{e,m_z}_{a,a} & A^{e,m_\rho}_{a,F} & A^{e,m_z}_{a,F} \\
Z^{e,e}_{AL,cu} & Z^{e,e}_{cu,a} & Z^{e,e}_{AL,AL} & A^{e,m_\rho}_{AL,a} & A^{e,m_z}_{AL,a} & A^{e,m_\rho}_{AL,F} & A^{e,m_z}_{AL,F} \\
B^{m_\rho,e}_{a,cu} & B^{m_\rho,e}_{a,a} & B^{m_\rho,e}_{a,AL} & Y^{m_\rho,m_\rho}_{a,a} & Y^{m_\rho,m_z}_{a,a} & Y^{m_\rho,m_\rho}_{a,F} & Y^{m_\rho,m_z}_{a,F} \\
B^{m_z,e}_{a,cu} & B^{m_z,e}_{a,a} & B^{m_z,e}_{a,AL} & Y^{m_z,m_\rho}_{a,a} & Y^{m_z,m_z}_{a,a} & Y^{m_z,m_\rho}_{a,F} & Y^{m_z,m_z}_{a,F} \\
B^{m_\rho,e}_{F,cu} & B^{m_\rho,e}_{F,a} & B^{m_\rho,e}_{F,AL} & Y^{m_\rho,m_\rho}_{F,a} & Y^{m_\rho,m_z}_{F,a} & Y^{m_\rho,m_\rho}_{F,F} & Y^{m_\rho,m_z}_{F,F} \\
B^{m_z,e}_{F,cu} & B^{m_z,e}_{F,a} & B^{m_z,e}_{F,AL} & Y^{m_z,m_\rho}_{F,a} & Y^{m_z,m_z}_{F,a} & Y^{m_z,m_\rho}_{F,F} & Y^{m_z,m_z}_{F,F}
\end{pmatrix}
&
\begin{array}{c}
\\ 1\cdots i\cdots N_a \\ 1\cdots l\cdots N_{AL} \\ 1\cdots i\cdots N_a \\ 1\cdots i\cdots N_a \\ 1\cdots q\cdots N_F \\ 1\cdots q\cdots N_F
\end{array}
\\
\begin{array}{ccccccc}
 & 1\cdots i'\cdots N_a & 1\cdots l'\cdots N_{AL} & 1\cdots i'\cdots N_a & 1\cdots i'\cdots N_a & 1\cdots q'\cdots N_F & 1\cdots q'\cdots N_F
\end{array}
&
\end{array}
\cdot
\begin{pmatrix}
I_{cu} \\ I_a \\ I_{AL} \\ I_{ma\rho} \\ I_{maz} \\ I_{mF\rho} \\ I_{mFz}
\end{pmatrix}
=
\begin{pmatrix}
V_0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0
\end{pmatrix}
$$

The main diagonal of the impedance matrix consists of self-impedance coefficients of the elementary path under observation, other coefficients represent mutual impedances between elementary turn located either in the same disk or in different parts of the system.

But since load disk, ferrite and aluminum disk are represented as a set of elementary turns, then each member of the impedance matrix is in its turn submatrix or subvector with the dimensions defined by the number of elementary turns.

The numerical solution of this equation has been implemented in the program code in “C”.

3 Analysis of main results

In order to validate experimentally the proposed model the frequency dependence of input impedance has been calculated and measured. The comparison between calculated and measured results is represented on the figure.

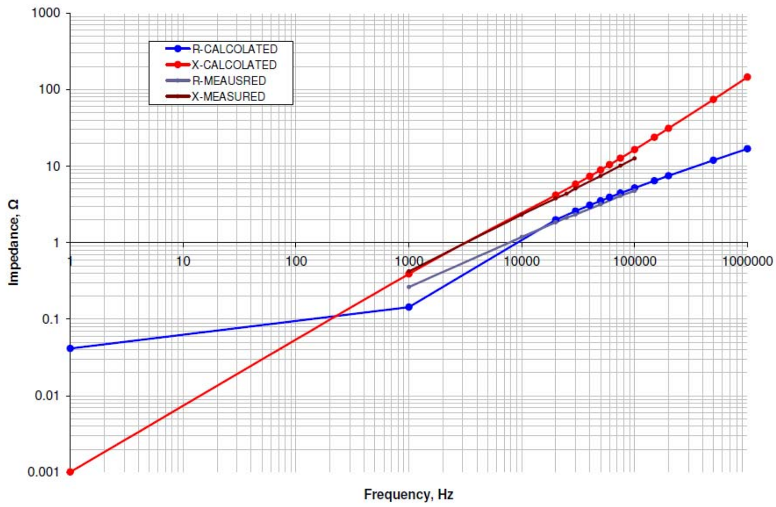
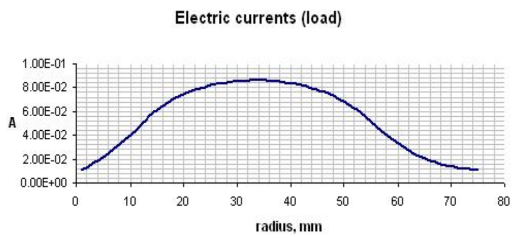
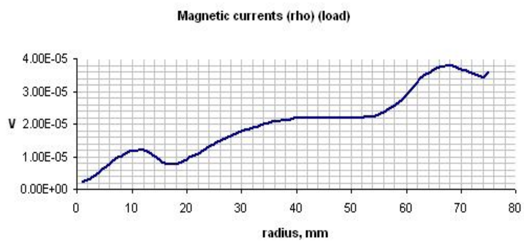


Figure 2 – Comparison between measured and calculated input impedances

As it can be observed calculated and measured results perform quite good agreement. These results allow to use the model in order to carry out different parametrical analysis.

The proposed model allows to obtain all the currents in the system. Using the symmetry and knowing currents in each elementary path the radial distribution in each part of the system with the parameters used for previous test and for the frequency *f = 20 kHz* is represented on figures





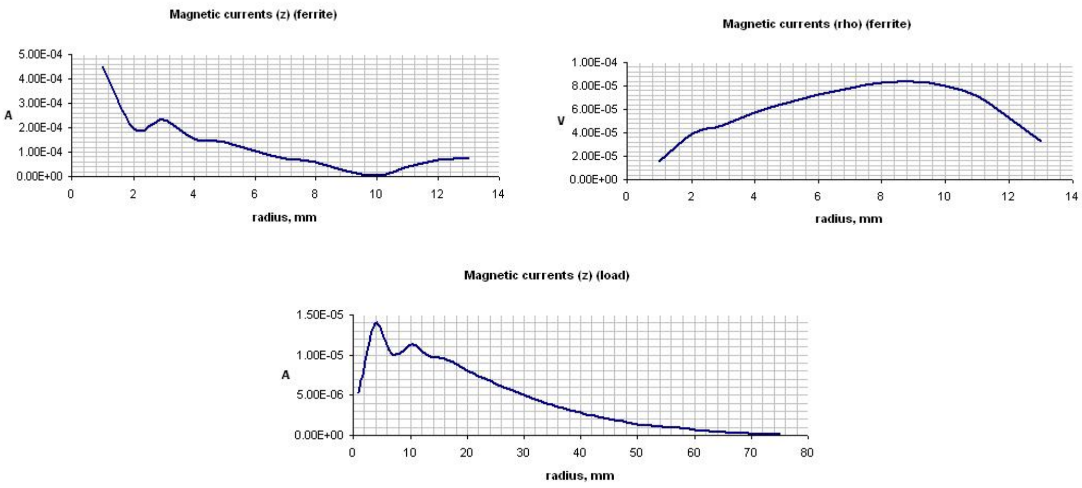


Figure 3 – Current distributions in different parts of the system

3 Analysis of main results

The objective of the present work was to develop an analytical rigorous model for the induction cooking system. The model was developed and fully validated experimentally. Beginning from the simple configurations the model has been defined in basic equations which describe the idea of the detailed definition of all the internal and external electromagnetic interactions and couplings. After the full system has been completed it was solved numerically. The numerical solution was implemented in a program code written in the program language “C”.

As the result it has been developed a design tool which allows to analyze the induction system operation and also develop new construction solutions, test them and investigate the operation of the proposed system. The model is parametrically flexible as the design tool should be. That means that once the model has been developed and tested the parameters which characterize the system can be easily changed in order to test or to simulate its operation.

Main attention was paid to the input impedance of the system because it is main control output parameter for electronic system which controls the hob. The input impedance reflects all the changes in the system through its sensibility to every electromagnetic change caused by magnetic couplings and interaction inside the system.

Current distribution in the load allows to analyze directly the heating process and hence to get initial distribution of the heat in the pan bottom. Current distribution in other part of the system provides necessary knowledge about effectiveness of each single part and their compatibility in the system.

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