Impedance Analysis of a Domestic Induction Appliance with Energy–Efficient Cookware

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***Abstract*— Multi–layer and multi–material induction cookware is increasing market penetration due to its superior cooking performance and efficiency. Resonant converters are usually adopted to achieve an optimal energy transfer at high supply frequency so that the equivalent impedance is a crucial parameter with regard to the system performance. In this work a coupled finite element-circuit model of an induction–efficient appliance is proposed. Equivalent circuit parameters are extracted from the finite element model in order to assess the resonance condition in a typical operating frequency range suitable for designing power electronics. The dependence on materials and layer distribution of the equivalent impedance is investigated by a parametric analysis.**

***Index Terms*—Electromagnetic induction, Cooking, Finite element methods, Frequency response, Impedance.**

I. INTRODUCTION

Induction cooking has become of widespread use because of its advantages in terms of heating speed and efficiency [1]. These are mainly due to the induction cooking working principle, which is based on the local heating generated by eddy current and hysteresis losses at the base of the pan. New manufacturing technology makes it possible to get multi-layer and multi-material pan structures with higher energy efficiency and more uniform cooking temperature compared to traditional single-layered induction cookware.

Some issues concerning induction cooking such as a high cost and power consumption still remain. To date, research has addressed induction cooker optimization [2]–[4], electronic power supply optimization [4]–[6], and analytical and numerical modeling of both induction coils and cookers with single-layer cookware [7]. In order to advance the status of the art of the system analysis, a modeling strategy based on FEA for determining the frequency response of an induction cooking appliance with multi-layer efficient cookware is here proposed. The frequency impedance model can be used for designing power supply systems, based on resonant converters.

II. NUMERICAL MODEL

A two dimensional axisymmetric finite element model with circuit coupling conditions has been implemented to carry out the impedance analysis of the R-L load (inductor + vessel). It is suitable for dimensioning the matching capacitor and identifying the best working frequency of the inductor in order to minimize power losses of the resonant converter and to attain an optimal energy transfer toward the vessel. The finite element model has been implemented by COMSOL package.

Fig. 1 shows the modeled 2d-axysimmetric inductor-vessel system. A multi-turn coil is placed between the vessel and the flux concentrator, made of ferrite. Moreover, a thin aluminum foil is usually adopted for EM shielding of power electronics. Typical shape and sizes of commercial induction systems, as reported in Table I, have been considered. Linear materials, with properties of Table II, have been assumed allowing for the accurate system electrical characterization by means of a frequency-dependent impedance. Hysteresis losses have been taken into account by a complex magnetic permeability [7].

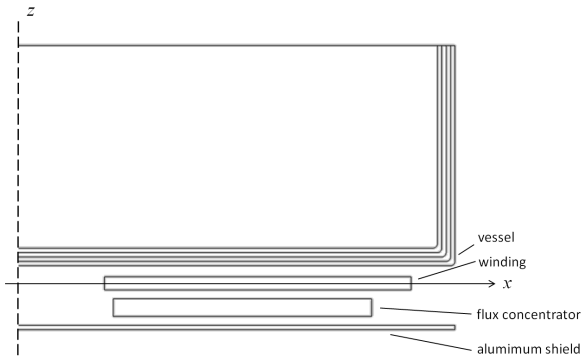

Fig. 1. Model of a typical induction heating appliance: multilayer vessel, coil domain (high frequency inductor), ferrite flux concentrator, aluminum shield.

TABLE I
REFERENCE MODEL DIMENSIONS

	Inner radius [mm]	**Outer radius** [mm]	**Thickness** [mm]	***z*–axis coordinate** [mm]
vessel	0	95-100	1 (layer)	5.5
winding	20	90	1.5	–0.5
flux concentrator	22	81	4	–6
shield	0	100	1	–10.5

TABLE II
MATERIAL PROPERTIES

	Permeability μ_r	**Conductivity** σ [MS m^{-1}]	**Temperature coefficient**
ferrite	2300	0	0
aluminum	1	38.5	$4{\cdot}10^{-3}$
air	1	0	0
copper	1	60	$4{\cdot}10^{-3}$
magnetic steel	400–j175	2	0
stainless steel	1	1.37	0

The induction cooking appliance model of Fig. 1 is meshed into 30.759 second order triangular elements. Since the typical operating frequency of domestic induction appliances ranges from 20 to 100 kHz, eddy current finite element analysis can be performed with good accuracy.

III. IMPEDANCE PARAMETRIC ANALYSIS

Impedance parameters are extracted from 20 to 100 kHz. In order to take into account the emf induced in the multi-turn coil, a voltage driven FE-circuit analysis has been carried out.

The equivalent impedance $\dot{Z}(\omega) = \overline{U}_{coil} / \overline{I}_{coil}(\omega)$ depends on the angular frequency ω, and $\overline{U}_{coil}$, $\overline{I}_{coil}(\omega)$ are the voltage and current phasors at the inductor terminals. In the voltage-driven analysis $\overline{U}_{coil}$ is imposed and the current coil is determined as

$$\overline{I}_{coil}(\omega) = (\overline{U}_{coil} + \overline{U}_{ind}(\omega)) / R_{coil} \quad (1)$$

where $\overline{U}_{ind}(\omega)$ is the emf induced in the inductor, and R_{coil} is the inductor DC resistance. The series equivalent resistance $R(\omega)$ and inductance $L(\omega)$ are finally obtained from the real and imaginary parts of the load impedance, respectively.

The base configuration of the multi-layered pan (Fig. 2) consists of 1) a pair of external layers of stainless steel, 2) one layer of magnetic steel, and 3) an aluminum foil.

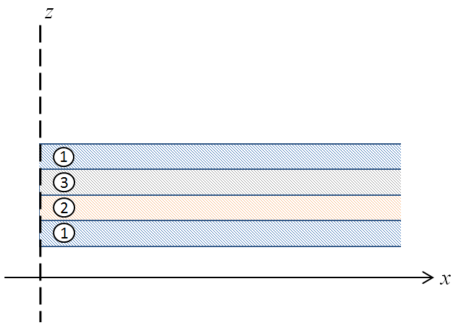

Fig. 2. Multilayered structure of the vessel (base arrangement: 1–stainless steel, 2–magnetic steel, 3–aluminum).

A. Dependence on material properties

Firstly, a single layer pan has been considered, i.e. in the base configuration of Fig. 2 layers 1 and 3 are "air", and the material of layer 2 is varied. Fig. 3 and 4 show that conducting materials (aluminum, copper, stainless steel) provide lower resistance and inductance due to a different energy transfer principle compared to ferrous materials (magnetic steel).

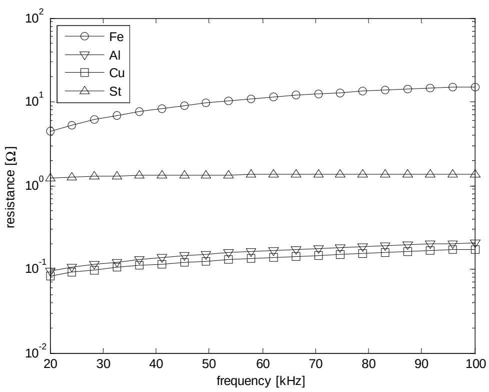

Fig. 3. Equivalent coil resistance vs. frequency (materials: Fe–magnetic steel, Al–aluminum, Cu–copper, St–stainless steel).

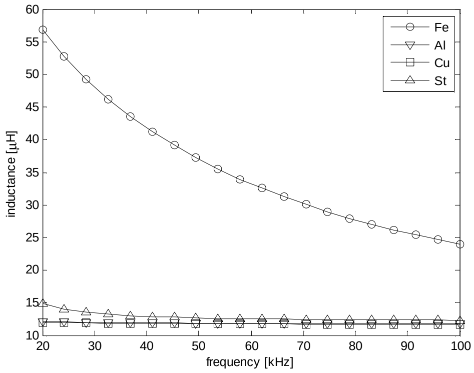

Fig. 4. Equivalent coil inductance vs. frequency (materials: Fe–magnetic steel, Al–aluminum, Cu–copper, St–stainless steel).

B. Dependence on multilayer structure

Secondly, the multilayered structure has been analyzed. With respect to single-layered traditional cookware, the energy transfer efficiency is improved by combining conducting and ferromagnetic materials with complementary electromagnetic behavior. Fig. 5 shows resistance and inductance frequency behaviors for the multilayered arrangement of Fig. 2.

The paper will show that the frequency response of the induction appliance is strongly influenced by vessel structure and depends in particular on the ordering of the layers.

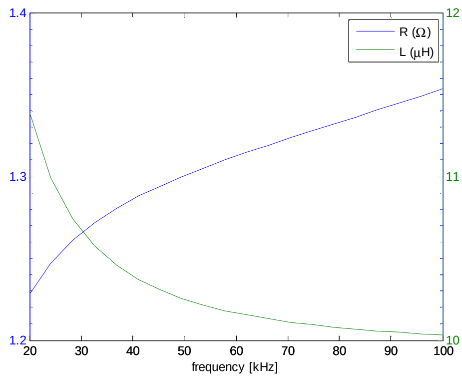

Fig. 5. Equivalent coil resistance (blue line) and inductance (green line) vs. frequency (arrangement 1–3–2–1, Fig. 2).

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