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Equivalent Circuit for the Consideration of Frequency-Dependent Effects in Electronics Simulations of Induction Hobs

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Introduction

Inductive energy transfer is a widely used technology today, for example in induction cooking. An inductive cooking system usually consists of a coil which is powered by an alternating current and a ferromagnetic cooking vessel, for example a pot (fig. 1), which is heated by induced eddy currents and hysteresis losses.
FEM simulations are a powerful tool for simulating the electromagnetic processes in the coil and ferromagnetic material, but not suitable for electronics development. In electronics development, the coil with the ferromagnetic material is characterized by the frequency-dependent inductance and the resistance (fig. 2).
In frequency domain simulations, these frequency dependencies can be directly defined. In time domain simulations with non-sinusoidal signals this is not possible so that the frequency dependence must be realized with equivalent circuits.
In our study, we compare different equivalent circuits in terms of their suitability of representing the frequency-dependent impedance.

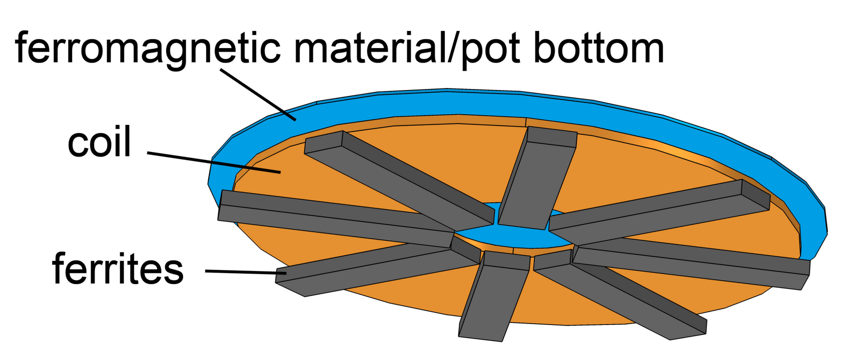

Figure 1: Schematic representation of a coil of an induction hob with ferrites and ferromagnetic material.

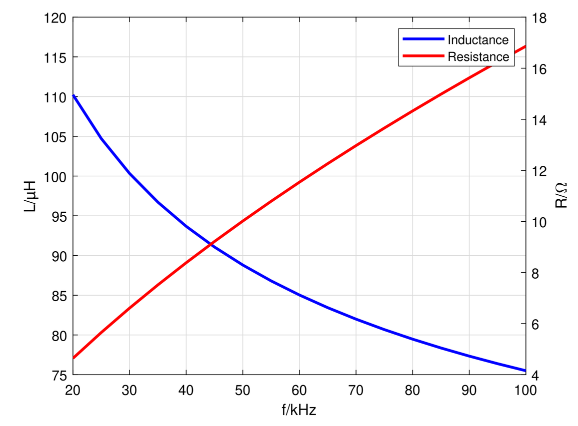

Figure 2: Inductance and resistance of the coil of an induction hob with variation of frequency.

Equivalent Circuits of Induction Hobs

The simplest and often used equivalent circuit to represent the coil-pot-system is a RL-element (fig. 3) with the values of the operation frequency [1]. This representation neglects all frequency-dependent effects [2], these can be taken into account, for example, with the equivalent circuit proposed by Forest et al. in figure 4 [1, 2]. The galvanic isolation between coil and ferromagnetic material is removed here, which makes the model unintuitive. Another possibility to represent the system is a resistively loaded transformer (fig. 5) [3]. In figure 6 we present an improved equivalent circuit based. The parameters for the simple RL-element can be determined by a measurement at the operating frequency. For the other equivalent circuits, the parameters (tab. 1) have to be determined by fitting R and L of the equivalent circuit to the values determined from the FEM simulation or experiment for several frequencies.

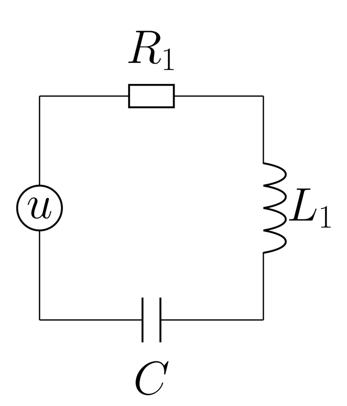

Figure 3: Simple RL equivalent circuit.

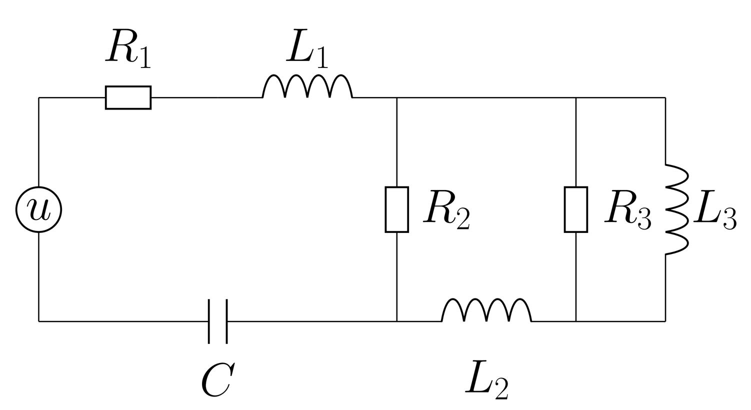

Figure 4: Equivalent circuit proposed by Forest et al. [1].

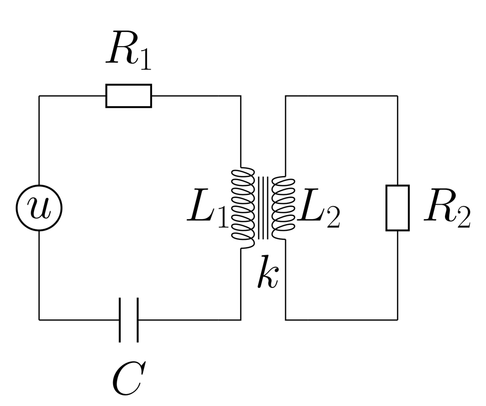

Figure 5: Transformer equivalent circuit.

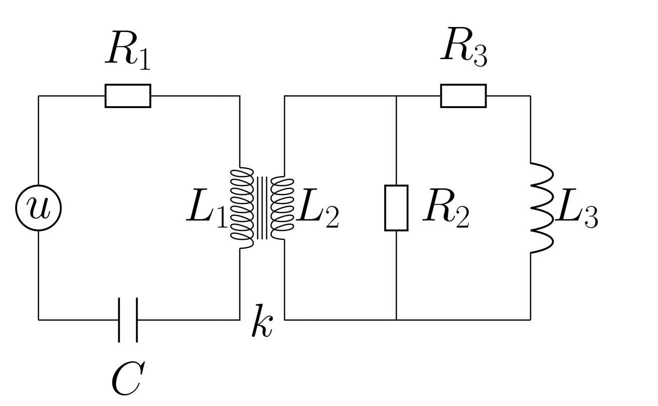

Figure 6: Improved transformer equivalent circuit.

Table 2: Parameters of the equivalent circuits.

	R_1	L_1	R_2	L_2	R_3	L_3	k
RL-element (fig. 3)	$4,64\ \Omega$	$110\ \mu H$					
Forest et. al. (fig. 4)	$1,31\ \Omega$	$54,7\ \mu H$	$29,9\ \Omega$	$47,0\ \mu H$	$5,04\ \Omega$	$21.1\ \mu H$	
Transformer (fig. 5)	$161\ m\Omega$	$136\ \mu H$	$45,9\ n\Omega$	$244\ fH$			$0,751$
Impr. transf. (fig. 6)	$161\ m\Omega$	$151\ \mu H$	$14,1\ n\Omega$	$24,4\ fH$	$12,9\ n\Omega$	$67,0\ fH$	$0,796$

Results

Figure 7 shows that the RL-element (fig. 3) provides reliable values only for the operation frequency of $f = 20\,kHz$. The constant values lead to harmonics being damped too much and shifted in the wrong direction. The equivalent circuit from figure 5 performs better, but also not sufficient. The equivalent circuits from figures 4 and 6 reproduce the frequency dependence of inductance and resistance well. Accordingly, the damping and phase shift for the harmonics also match.

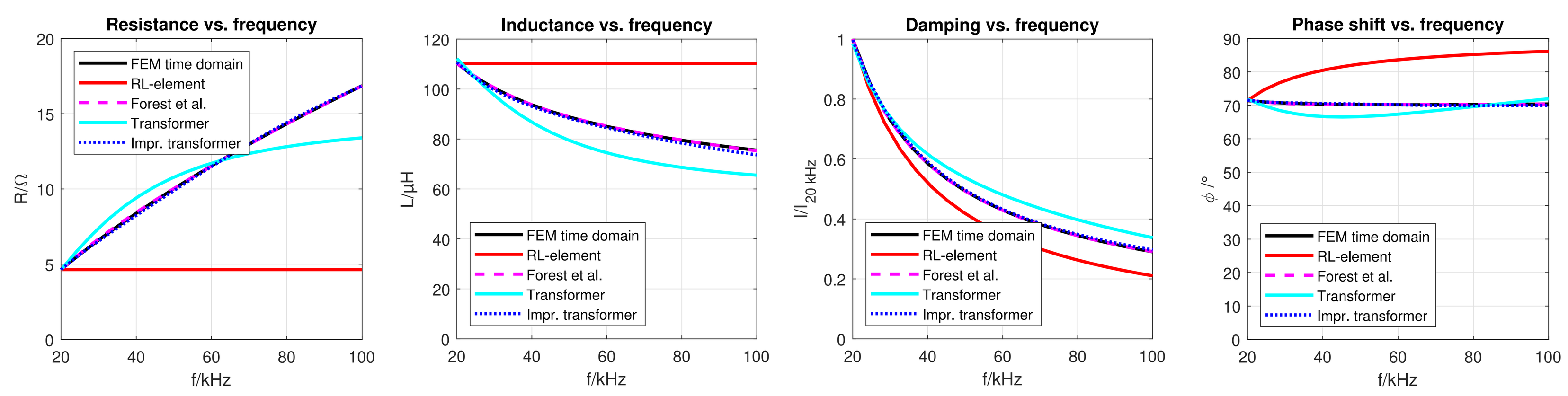

Figure 7: Comparison of resistance, inductance, damping and phase shift of the equivalent circuits to the values from the FEM simulation from figure 2 as reference.

An examination of the coil current shows that for full load operation at the fundamental frequency, all models except the simple transformer model (fig. 5) deliver similar values to the FEM simulation. The simple RL-element can therefore also be selected as a model here. However, if the duty cycle has to be reduced to achieve a lower output power, the simple RL element shows significant deviations in the signal curve and power. The models from figures 4 and 6 show good agreement here. With the model from figure 6, the power in the pot can also be determined well as the power in the secondary circuit.
The results are similar when the excitation frequency is changed. The models from figures 4 and 6 show good correlations with the FEM simulation, while the simple RL element in shows strong deviations.

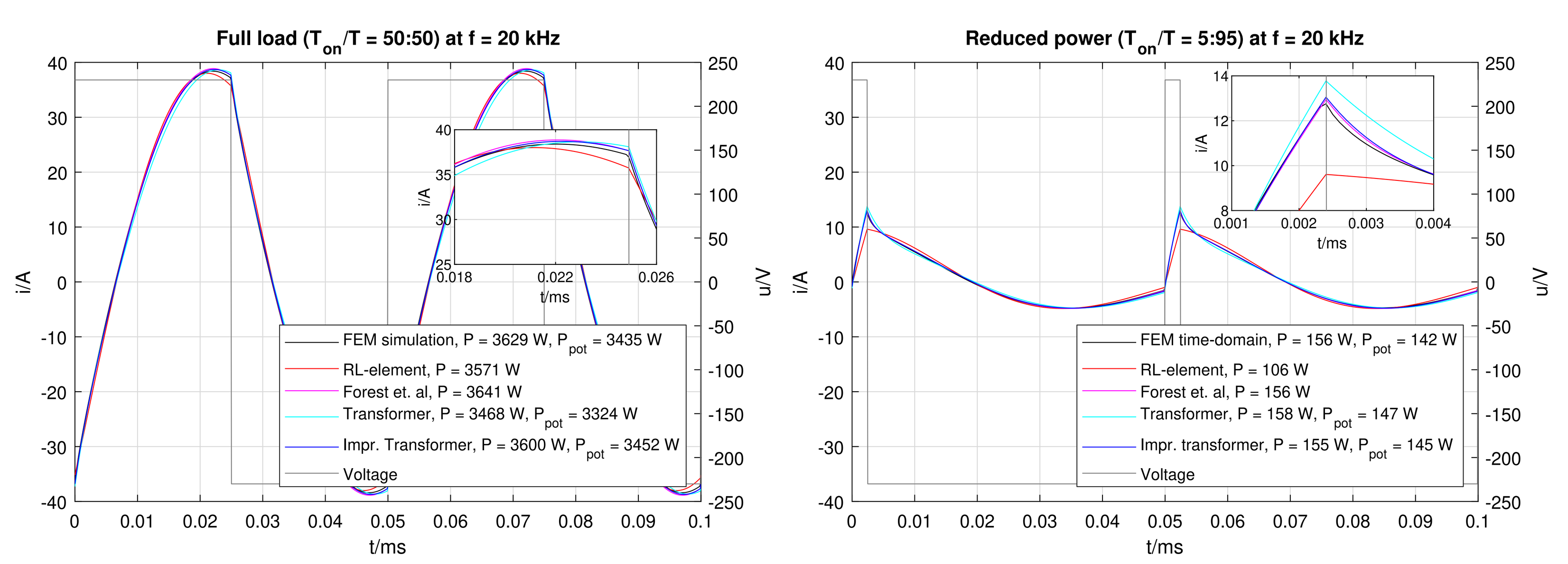

Figure 8: Full load and reduced power at 20 kHz with component values which are fittet for a fundametal frequency $f = 20\,kHz$.

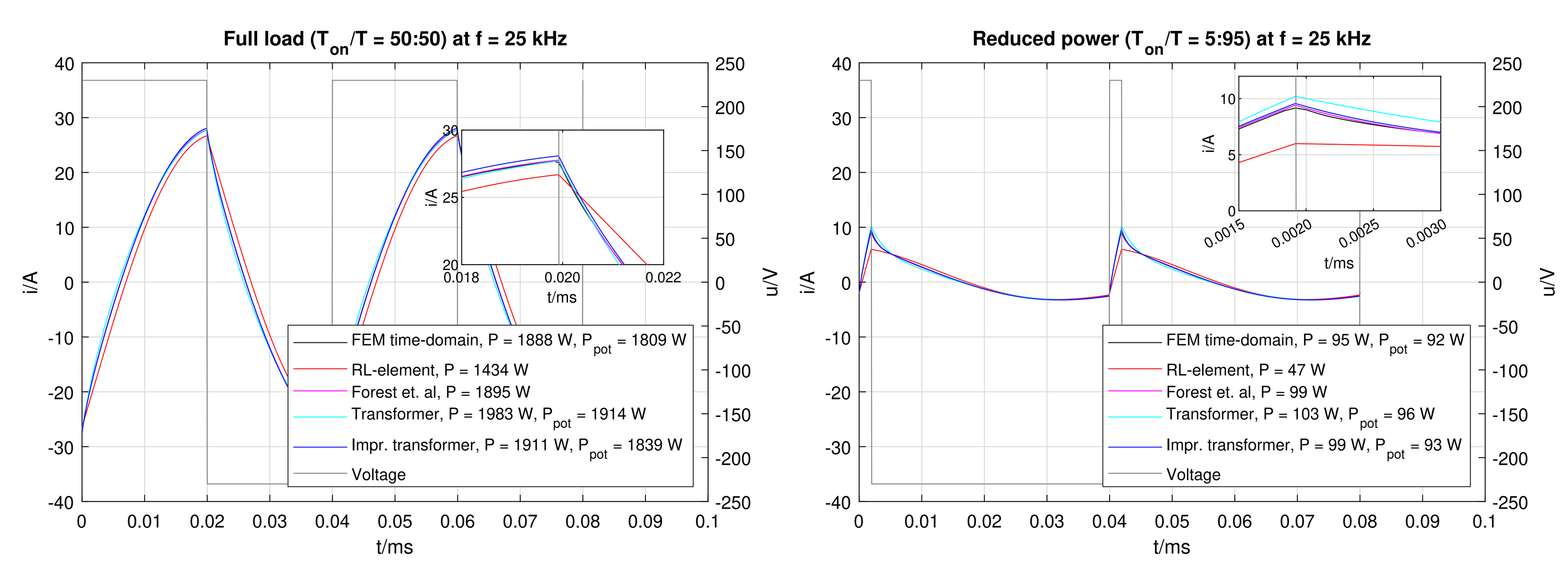

Figure 9: Full-load and reduced power at 25 kHz with the same component values as at 20 kHz.

Discussion

The equivalent circuit presented by Forest et al. and the improved transformer are suitable to represent the frequency dependent impedance of the coil-pot-system. The equivalent circuit presented by Forest et. al. has the advantage of being numerically more favorable. With the improved transformer the simulation takes a long time to settle but also offers the possibility to directly determine the power in the pot.

References

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