Quick Estimation of Coupling Coefficient in an Electric Vehicle Wireless Charging System

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***Abstract*—Wireless charging of Electric Vehicles (EVs) is becoming popular as it mitigates issues such as handling heavy cables, safety risks in harsh weather, and vandalism. It also matches wired efficiency in the present day. Estimation of coupling coefficient requires time-consuming finite element method (FEM) simulations, and this paper presents a quick, real-time method for estimating it for a 11-kW wireless charging system for EVs. This approach uses obtained FEM simulation data which is fitted with curve-fitting polynomial equations and further post-processed to estimate the coupling coefficient, mutual inductance and power transfer efficiency. Experimental measurements confirm the accuracy of this method, offering a time-saving solution for the initial developmental phase of EV wireless charging systems.**

***Keywords*— electric vehicle wireless charging, FEM simulation, coupling coefficient, coupled coils, power transfer efficiency, online estimation**

I. Introduction

Inductive Power Transfer (IPT) systems for EV wireless charging use coupled coils to transfer power through an air gap [1–3]. Estimating coupling coefficient, self-inductance, and quality factors are crucial for designing such a system and maximizing power transfer efficiency [4],[5]. Initial estimation can be done using online tools for parameters like self-inductance and mutual inductance [6–9], however, further design stages require FEM simulations due to complexities in coupled-coil interactions, despite their time-consuming nature. The method proposed in [10] considers mutual inductance based on coil geometry, number of turns, and the air gap but overlooks the impact of ferrites and shielding materials. As a result, it isn't accurate for estimating parameters in a real-life EV charging systems. Alternative polynomial methods such as the one mentioned in [11] aim to reduce estimation time focusing on constant current control but do not consider any measurements on the secondary side.

In this paper we propose a novel approach that considers the simulated dependence of the coupling coefficient on the air gap between the primary and secondary sides and the number of turns of each coil in order to quickly estimate coupled-coil parameters based on curve fitting and post-processing of simulation results of an 11 kW IPT system for EVs. The graphical user interface of the estimator is presented in Fig. 1. Since it is based on an initial simulation of a real system, it considers the effects of ferrites and shielding materials and offers accurate real-world estimates, following the SAE J2954-2020 Wireless Charging Standard for EVs [12]. The estimator can assess coupling coefficient, mutual inductance and power transfer efficiency. The experimentally measured values of the coupling coefficient show strong correlation with its estimated values therefore verifying the working principle of the quick estimator.

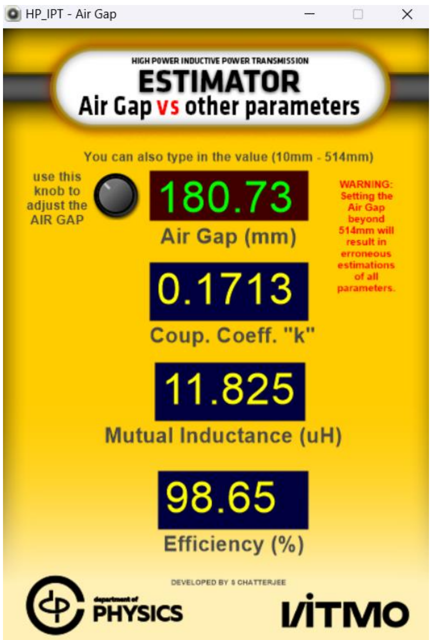

Fig. 1. Graphical user interface of the estimator

II. Experimental Measurement of the Coupling Coefficient

We performed experimental measurements on a fully constructed IPT system prototype as described in [13] using vector network analysis, where the IPT system is the device under test (DUT). The system's primary and secondary coils have 10.5 turns each and are placed on 3D-printed PLA holders to maintain their spiral geometry. The coils are positioned on ferrite rods which are secured to custom aluminum screens using several 3D-printed PLA holders and nylon bolts. Discrete air gaps of 160 mm, 220 mm, and 280 mm were maintained using removable fiberglass slabs on both sides. A 2-port Vector Network Analyzer (VNA) was used to measure the system's S-parameters, with the primary and secondary coils connected to the VNA via high-frequency coaxial cables and SMA connectors. The experimental setup is shown in Fig. 2.

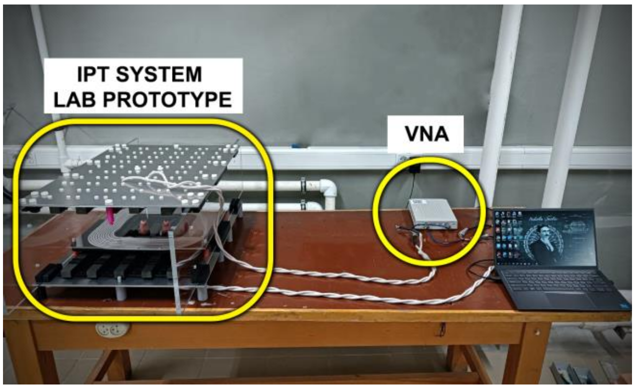

Fig. 2. Experimental Setup for the measurement of S-parameters of coupled coils of the 11 kW IPT system

From the measured S-parameters, the Z-parameters were obtained in MATLAB and the self-inductances of the primary and secondary coils and the mutual inductance between them were calculated from the imaginary part of the impedance using the relation: *Inductance (L) =imag* $(Z_{xx})/\omega$, where Z_{xx} could be driving point impedances Z_{11} and Z_{22} for obtaining the self-inductances of the individual sides, and the forward transfer impedance Z_{21} for obtaining the mutual inductance. Furthermore, the coupling coefficient can be calculated using the relation: $k = M/(L_1 \times L_2)^{1/2}$. The values of the coupling coefficient obtained experimentally are displayed in Fig. 3 by markers and summarized in Table 1.

III. Simulation and Estimation Processes

The two processes involved are the *A) Simulation process*, which runs once for several discrete air gaps and coil turns, and the *B) Estimation process*, which uses polynomial based curve-fitting and post-processing on the simulation results to estimate the coils' self-inductances, mutual inductance, coupling coefficient, and power transfer efficiency. The processes are discussed as follows:

A. Simulation Process

We consider an IPT system for wireless EV charging, composed of primary and secondary sides (Fig. 4) as described in [13]. Using Ansys Maxwell's eddy-current solver for 3D FEM simulations, we model the two identical structures separated by an air gap.

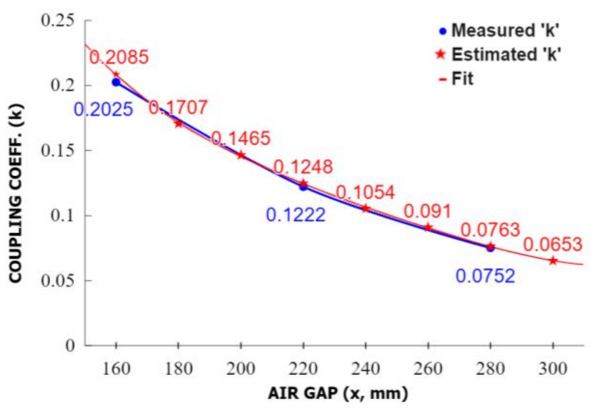

Fig. 3. Graphical plot of measured "k" and estimated "k"

Each side has a square spiral coil made of 5 mm thick copper Litz wire placed on ferrite rods (I-cores) made of Manganese-Zinc N87 material with a relative permeability of μ'=2000 [15]. Aluminum screens at the base of the ferrite rods work as shields for the electromagnetic field and are designed to comply with ICNIRP 2020 safety guidelines [16] based on prior simulations. 3D FEM simulations using the eddy current solver are performed for coil turns ranging from 9.5 to 15.5 turns (1 turn steps) and air gaps from 160 mm to 300 mm (20 mm steps) at a fixed frequency of 85 kHz. The model's tetrahedral mesh includes 1.85 million elements, with 10 convergence passes and 30 % refinement per pass. The eddy current solver, suitable for good conductors with low-frequency fields, handles the "eddy-current" approximation where displacement currents are negligible. The results obtained are discrete values for the self-inductances of the primary coil (L_1), the secondary coil (L_2), the mutual inductance (M), the coupling coefficient (k) and the parasitic resistances of the coils (R_1, R_2) and are exported in a tabular format. This table is imported into MATLAB for curve-fitting and further post-processing.

B. Estimation Process

The results are plotted in MATLAB as singular points for each discrete value of the obtained results and curve-fitting functions are used to define the slope and shape of the curves for self-inductances versus number of turns, and the coupling coefficient versus air gap. These fitted curves are key to the estimation process, allowing predictions within and beyond the simulated range to estimate the power transfer efficiency. A cubic fit is used for air gap versus coupling coefficient due to the nature of the curve's shape, while quadratic fits are sufficient for other plots. The following curve-fitting equations were derived using quadratic and cubic fits. The self-inductance of a coil depends on the number of turns, coil diameter, and coil material. The relationship between coil self-inductances (L_1 and L_2) and the number of turns (n) can be expressed using quadratic fitting functions:

For the primary coil (L_1):

$$L_1 = A_1 n^2 + B_1 n - C_1 \,, \qquad (1)$$

where A_1, B_1, and C_1 are optimized curve-fitting values.

For the secondary coil (L_2):

$$L_2 = A_2 n^2 + B_2 n - C_2 \,, \qquad (2)$$

where A_2, B_2, and C_2 are optimized curve-fitting values.

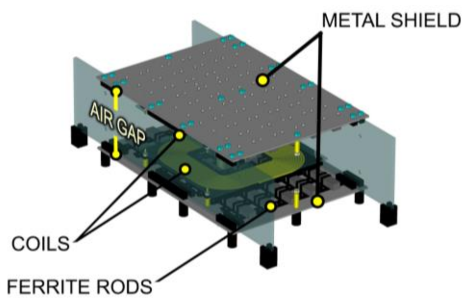

Fig. 4. FEM model of the IPT system

The air gap significantly influences coupling between coils and the relationship between the air gap (x) and coupling coefficient (k), shown in Fig. 3, can be expressed with a cubic fitting function:

$$k = Ax^3 + Bx^2 - Cx + D \,, \qquad (3)$$

where A, B, C, and D are optimized curve-fitting values.

The fitted plot of the coupling coefficient is compared to the measured data in Fig. 3. Also, we summarize the values in Table I. As one can see, the values obtained with the estimation process are in a good agreement with the measured data. The individual Q factors of the primary and secondary coils can be calculated using the self-inductances from (1), (2) an using the equation $Q=\omega L/R$, where ω is the angular frequency, given by $\omega=2\pi f$, where f is the operating frequency (85 kHz in our case), L and R are the self-inductance and resistance of the individual coils respectively. (R is a fixed value at 85 kHz obtained previously via simulation) The geometric mean of the Q factors (Q_{gm}) can then be calculated using: $Q_{gm}=(Q_1 \times Q_2)^{1/2}$.

Finally, the power transfer efficiency can be calculated using the coupling coefficient obtained previously in (3) and by using (4):

$$\eta_{\text{rf-rf}} = \left(\frac{kQ_{g_m}}{\sqrt{1+(kQ_{g_m})^2}} \right)^2 \tag{4}$$

TABLE I. SIMULATED AND MEASURED VALUES OF COUPLING COEFFICIENT FOR DIFFERENT AIR GAPS

Air Gap	**Coupling Coefficient *"k"* (Estimated and Measured)**		
	k (Estimated)	***k (Measured)***	***Error***
160	0.2085	0.2025	2.9%
180	0.1707	-	-
200	0.1465	-	-
220	0.1248	0.1222	2.1%
240	0.1054	-	-
260	0.0910	-	-
280	0.0763	0.0752	1.4%
300	0.0653	-	-

Thus, from Table 1, we can infer that the estimated values and the measured values for the coupling coefficient are closely correlated since the mean of all the errors is only 2.1 %.

IV. CONCLUSION

This paper presents a quick, real-time software package for estimating multiple coupled-coil parameters of an 11-kW wireless charging system for electric vehicles, eliminating the need for running multiple time-consuming FEM simulations. The estimator delivers results in milliseconds, with uncompromised accuracy as shown by comparison with experimental measurements. It paves the way for engineers to assess how air gap and coil turns affect key parameters like self-inductance, mutual inductance, coupling coefficient, ohmic resistance, Q-factor, and power transfer efficiency instantly for a known wireless power transfer system for EV charging. The software also accounts for frequency-related effects and losses associated with ferrite materials and metallic shielding and incorporates curve-scanning functions for instant updating of results. The online version of the software can be utilized through [17] and the offline version is available upon request.

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