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Amadou Bayaghiou Diallo, Mohamed Bensetti, Christian Vollaire, Lionel Pichon, Arnaud Breard. Scale Reduction for Modeling and Prototyping of Inductive Power Transfer System for EV applications. IEEE Transactions on Magnetics, 2023, 59 (5), pp.8600404. 10.1109/TMAG.2023.3239564 . hal-03998693

HAL Id: hal-03998693

<https://hal.science/hal-03998693v1>

Submitted on 21 Feb 2023

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Scale Reduction for Modeling and Prototyping of Inductive Power Transfer System for EV applications

Amadou Bayaghiou Diallo^{1,2}, Mohamed Bensetti², Christian Vollaire¹, Lionel Pichon², and Arnaud Breard¹

¹Univ Lyon, Ecole Centrale de Lyon, INSA Lyon, Univ Claude Bernard Lyon 1, CNRS, Ampère, UMR5005, 69130 Ecully

²GeePs – Group of electrical engineering - Paris, UMR CNRS 8507, CentraleSupélec, Université Paris-Saclay, Sorbonne Université, 3 & 11 rue Joliot-Curie, Plateau de Moulon 91192 Gif-sur-Yvette, France

In this paper, the scale reduction method is applied to an induction power transfer (IPT) system for electric vehicle charging for its rapid and low cost prototyping. In addition, a co-simulation method is proposed which is based on the coupling between a circuit analysis and a finite element (FE) analysis. Then, it is proposed to combine the scale reduction method with the co-simulation method to consider at the same time the nonlinearities due to the power electronic converter and the magnetic material characteristics of the system. Finally, a 1 kW experimental IPT system is proposed to validate both methods.

Index Terms—FE methods, Inductive power transfer, Scale reduction method, Magnetic field radiation, Co-simulation.

I. INTRODUCTION

THE massive development of electric vehicles (EVs) is a major ecological imperative to replace conventional vehicles that use combustion engines. These vehicles use batteries instead of fossil fuel on board to store the electrical energy needed to propel the vehicle. Large capacity, high power battery packs are generally required for EVs to operate over reasonable distances. However, it is not easy to realize reliable and competitive batteries for EVs in the 1 kW to 10 kW range due to the requirements of cost, safety level, power densities, long cycle life, volume and weight, which should all be satisfied simultaneously. Currently marketed lithium-ion batteries for EVs are recognized as the most competitive solution, but the power densities of lithium-ion batteries are less than 100 Wh/kg [1], [2]. On the other hand, gasoline has an energy density of about 12,000 Wh/kg [3], which implies that EVs are not sufficiently attractive compared to conventional vehicles until now.

In addition, long recharge times of EV batteries make them unattractive to many consumers. Therefore, the study of charging types is important for the optimal deployment of EVs. Plug-in charging, which involves connecting the electric vehicle to an energy source through an electric cable, poses some limitations to the use of the EV during its operation. To address these issues, there is a desire to replace conductive charging with inductive power transfer (IPT) charging systems. The IPT charging system has many advantages such as the elimination of cables and charging stations, it requires less maintenance and can take fewer batteries on board for a dynamic charging system. However, the IPT system has some disadvantages, such as the problem of misalignment between the primary coil and the secondary coil and electromagnetic radiation in the surrounding environment.

In general, the modeling of an IPT system needs to be verified by small-scale laboratory experiments. So, it is necessary to verify the limit of validity of this small prototype with a

power rating that is several orders of magnitude lower than the final application. In the literature, there are few publications on the downscaling method applied to IPT systems. A set of assumptions have mainly allowed the geometric scaling of the coils and the equivalent circuit parameters [4]–[6].

It is therefore important to further study this approach for IPT systems and the main contributions in this paper are : (i) The study of the scale reduction approach for IPT systems under new assumptions, the identification of the limit of validity and the impact of this approach on the electromagnetic field in the frequency and time domain by numerical simulation, (ii) the validation of the proposed approach in a co-simulation scenario in the time domain to take into account at the same time the non-linearities due to the power electronics and the magnetic materials of the coupler, (iii) the verification of the effectiveness of the scale reduction and co-simulation methods by means of numerical simulations and experimental results.

This paper is structured as follows: Section II discusses scale reduction method and the coupling between finite element model and circuit model, Section III presents experimental and numerical results, and Section IV concludes the paper.

II. PROPOSED METHODS

A. Inductive Power Transfer system modeling

With the first harmonic approximation in steady state [7], [8], the magnetic coupler in the IPT system can be modeled by an equivalent circuit as illustrated in (Fig. 1). The capacitors connected in series with the transmitting and receiving coils allow to compensate the reactive energy of the leakage inductance which is high due to the air gap between the coils. R_L being the equivalent resistance of the load and ω_s the angular switching frequency, the voltage V_1 and total impedance Z_T seen from the primary side are expressed as follows :

$$V_1 = R_1 I_1 - jM\omega_s I_2 \quad (1)$$

$$Z_T = R_1 + \frac{M^2 \omega_s^2}{R_2 + R_L} \quad (2)$$

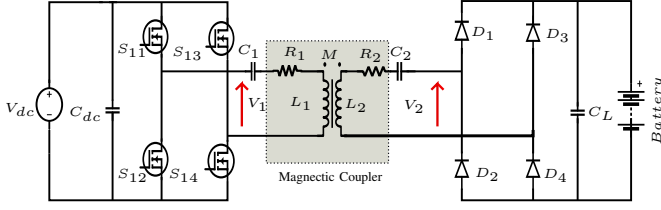


Fig. 1. Simplified electrical diagram of an IPT system. $L_{1,2}(M)$: Self (mutual) inductance, R_1, R_2 : Ohmic resistance of coils.

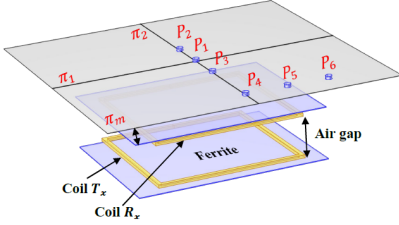


Fig. 2. 3D view of the magnetic coupler model. π_1, π_2 are the Symmetry planes, π_m is the measurement plane at 580 mm of the R_x ferrite. ($P_1 - P_6$) are the measurement points of the magnetic field.

TABLE I
CHARACTERISTICS OF THE COILS AND FERRITES

Parameters	Dimensions	Parameters	Values
Ferrites	500 × 600 × 2 mm	Section of a turn	20 mm ²
Coils	442 × 442 × 10 mm	Coil	Litz wire

B. Scale Reduction Method

Scale reduction method is a very common numerical technique in various engineering fields. Its objective is to reduce the size of the prototype for a given engineering large problem. Let λ be a generic linear dimension of the real system and λ' the corresponding dimension of the scaled down system. The scaling factor is defined by $\beta = \lambda'/\lambda$. This factor is applied to all geometric and electrical quantities of the system under these assumptions: (1) no magnetic saturation in the system, (2) constant number of turns of the coil, (3) no ohmic losses in the coils, (4) uniform and constant current density and (5) constant working frequency. From Table I, the thickness of the ferrite is 2 mm, which is quite small, so for the scale models, it will also be assumed that this thickness remains content regardless of the scale factor.

Starting with the induced electrical field due to a thin wire loop, we can calculate the mutual and self-inductance for two thin wires loops (Γ_1, Γ_2) in a homogeneous medium [9].

$$L_{ij} = \frac{\mu_0}{4\pi} \oint_{\Gamma_1} \oint_{\Gamma_2} \frac{dl_1 \cdot dl_2}{r} \quad (3)$$

Where μ_0 is the vacuum permeability, dl_1 and dl_2 represent the elementary lengths and r the distance between them. So the self-inductance and mutual inductance are proportional to $L_{ij} \propto \beta$. In the same way, the cross-section is proportional to

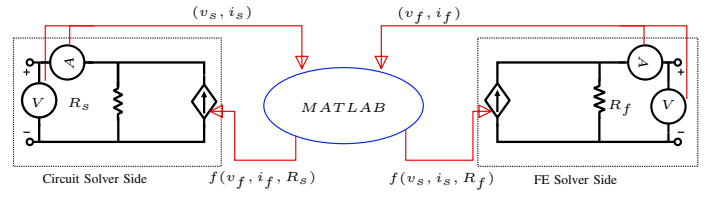


Fig. 3. The interface variables for the coupling between the FE solver and the circuit solver.

TABLE II
IPT DESIGN PARAMETERS

Parameters	Numerical	Measure
$L_1(L_2)$ μH	63.56(63.56)	61.92(62.8)
$R_1(R_2)$ $m\Omega$	9(9)	70(85)
$C_1(C_2)$ nF	-	66(66)

$S \propto \beta^2$ and under the assumption of uniform and constant current density distribution, the coil resistances are proportional to $1/\beta$. Given the expression $LC\omega_s^2 = 1$ at resonance, the series compensation capacitors are proportional to $C \propto 1/\beta$ with ω_s a constant. For electrical quantities, assuming a constant current density, the current is given by $I = JS$ and expressed by $I \propto \beta^2$. From equation (1), without ohmic losses, the voltage is given by $V \propto \beta^3$. By applying Ohm's law, the total impedance seen at the primary is defined by $Z_T \propto \beta$. The resistance of the load is deduced from the equation (2) with $R_1 = R_2 = 0$ by $R_L \propto \beta$. Finally, thanks to Ampere's theorem, the magnetic field can be expressed by $B \propto \beta$.

C. FE-Circuit Solvers co-simulation

In steady state, the magnetic coupler is modeled by an equivalent circuit for one operating point and the nonlinearities due to the magnetic material and the magnetic losses are not considered [10]. It is then important to combine both the physics-based FE solvers for the magnetic coupler and the circuit solvers for the power electronics and its control in time domain to consider all nonlinearities. The main limitations of a coupling between a FE solver and a circuit solver in time domain are the poorness of the FE solvers to solve power electronics with very small time step and the computation time.

In this work, the COMSOL software is considered to model the magnetic coupler and the Simulink Simscape library to simulate the power electronics and its control. To consider non-linearities, the two models are coupled together using the LiveLink tool for MATLAB [11]. This tool provides a direct connection to MATLAB while running COMSOL. The details of the coupling between the two tools are shown in Fig. 3. In each simulation tool, a Norton equivalent circuit is added that represents the missing system. As already presented in detail in [12] for circuit/circuit coupling, a waveform relaxation method is used to solve the coupled system.

III. VERIFICATION AND RESULTS

The experimental setup used to validate the IPT system is composed of a DC/AC inverter, a DC voltage source of 40

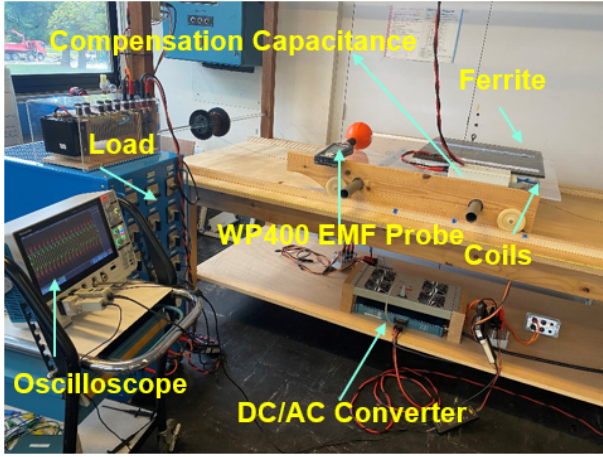
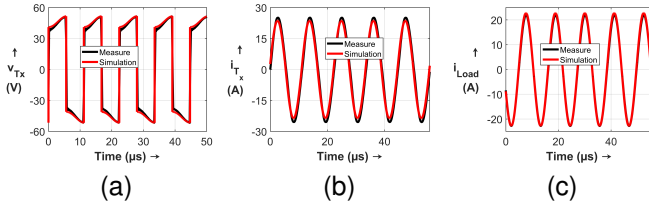


Fig. 4. The Setup of the IPT system.

Fig. 5. Experimental results. a) The inverter output voltage. b) Current in the transmitting T_x . c) Current in the receiving coils R_x .TABLE III
MAGNETIC FIELD, MEASUREMENT VS SIMULATION

Points	Numerical (μT)	Measure (μT)	Error (%)
P_1	66.88	63.70	4.99
P_2	65.59	63.90	2.64
P_3	61.75	65.80	6.16
P_4	21.74	22.10	1.63
P_5	20.45	22.70	9.91
P_6	15.68	16.68	6.00

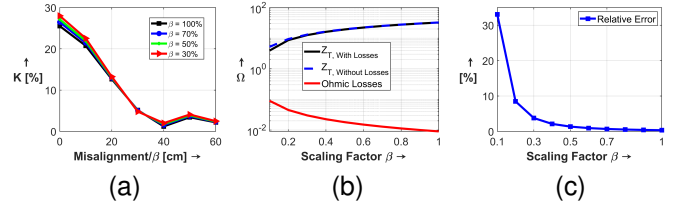
Volts, a variable resistive load, a 1 kW magnetic coupler. The magnetic coupler is composed of two coils of 6 turns on two layers and for the ferrites of dimensions 500×600 mm, 20×24 small ferrites of dimensions $25 \times 25 \times 2$ mm are used of N27 magnetic material from TDK glued together on epoxy which is neutral to the magnetic field. All design parameters are given in Table I. The measurement of currents and voltages are performed with a Tektronik 3 series oscilloscope and current and voltage probes. For the magnetic field, a WP400 EMF probe from WAVECONTROL with a bandwidth of 1 Hz-400 kHz is used.

A. Experimental Validation of the IPT System

To validate the magnetic coupler, we directly connected a resistive load of 2.5Ω to the receiver coil without the rectifier in Fig. 1, the resonant frequency in this configuration is 89 kHz. Table 2 shows the parameter of the magnetic coupler, the error between the numerical calculation and the measurement of the self-inductance is less than 5%. Fig. 5 shows a comparison

TABLE IV
COMPUTATION TIME FOR COMPUTING COUPLING COEFFICIENT IN FIG.6

-	$\beta = 100\%$	$\beta = 70\%$	$\beta = 50\%$	$\beta = 30\%$
Mesh Elements	373401	81372	77759	73381
Time	33min	7min45s	6min27s	6min18s

Fig. 6. Scaling down results. a) The coupling coefficient for different scaling factors. b) The total impedance Z_T with(without) losses. c) The relative error between Z_T with and without losses.

between the currents and voltages obtained by simulation and measurement. In general, a very good agreement is observed despite some deviations that are due to not taking into account all the short connection cables. In addition, a measurement of the magnetic field at different points ($P_1 - P_6$) is done and compared to the magnetic field obtained by a frequency analysis of the 3D FE model using the measured current. Table III shows the relative deviation between the measurement and the model which is less than 10% for the six measurement points. Finally, all these comparisons show that the proposed FE model is relevant to represent the physical behavior of the IPT system.

B. Validation of the Scale Reduction Method

The high potential of the scale reduction method is demonstrated for the different scales (100%–30%) considered in this work. In fact, misalignment of transmitter and receiver coils is one of the main problems in IPT system for EV's [13]. So, Fig. 6a shows the coupling coefficient for different scale factors and for different misalignment between the centers of the coils where 0 mm means perfect coils alignment. The β factor on the x-axis allows to scale the coupling coefficient curves on the same graph. The relative error on the coupling coefficient is less than 5% between the full scale model and the reduced models. By comparing this error with the performances obtained in the Table IV, it is clearly demonstrated the interest of this method. Table IV shows also the performance of model reduction on the computation time on an Intel(R) Core (TM) i7- 8665U CPU@1.90 2.11 GHz laptop for the different reduced models. The computation of the reduced model $\beta = 50\%$ is 4.7 times faster than the full model $\beta = 100\%$.

According to the expression of the coil resistances established in Subsection II.B, as the scale factor decreases, the value of these resistances increase and become significant compare to the impedance of the other elements. The difference between the total impedance with and without losses is shown in Fig. 6b. It can be seen that the behavior with losses is similar to the one without losses as long as the scaling factor

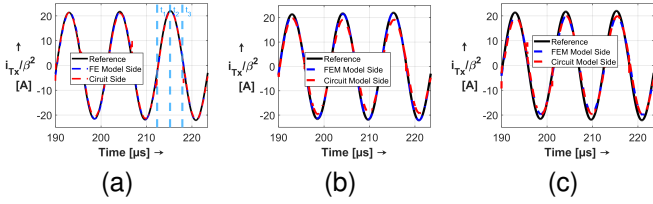


Fig. 7. Co-simulation results, current in the transmitting coil T_x . a) $\beta = 100\%$, b) $\beta = 50\%$, c) $\beta = 30\%$.

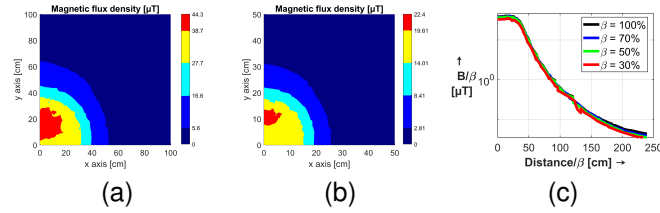


Fig. 8. Co-simulation results, Magnetic flux density distribution at time t_2 . a) $\beta = 100\%$. b) $\beta = 50\%$. c) The Magnetic flux density at time t_2 for $\beta = 100\%$, 70%, 50%, 30%.

remains above 30% otherwise the relative error is greater than 5% below this value (Fig. 6c). This defines the limit of validity of this method for our operating point, but obviously, this limit can change depending on the load, the frequency and also the coupling between the transmitting and receiving coils.

C. Validation of the FE-Circuit Solvers Co-simulation

To validate the co-simulation, the FE model of the magnetic coupler and circuit model of the power electronic were run on an Intel(R) Core (TM) i7- 8665U CPU@1.90 2.11 GHz laptop. To relax the constraint on the FE solver, its maximum time step is fixed at $0.2 \mu\text{s}$ against $0.02 \mu\text{s}$ for the circuit solver. The model being symmetrical with respect to the π_1 and π_2 planes (Fig. 2), the quarter of the 3D FE model was considered for the co-simulation. Fig. 7 shows the waveforms of the currents in the transmitter coil T_x for different scaling factors, the current is divided by β^2 to return to the full scale. Overall a good correlation can be observed compared the reference which has already been validated in subsection III.A. It can be noticed that the differences between the reference and the co-simulation increase when β decreases. This is due to the ohmic losses which increase when β decreases.

Finally, it is clearly demonstrated the influence of the scale reduction method on the ohmic losses which have a direct impact on the current and thus on the distribution of the magnetic field (Fig. 8c). Fig. 8a-8b show the magnetic flux density distribution in the π_m plane (Fig. 2) at time $t_2 = 215.2 \mu\text{s}$. The relative error on the maximum field between the full model and the reduced models is less than 2% for $\beta = 50\%$.

IV. CONCLUSION

In conclusion, we have shown that under certain realistic assumptions, the scale reduction method is perfectly applicable for IPT system, a method that allows to make a fast and cheap prototyping and then to extrapolate the results to the

real scale for the study of the system characteristics. In addition, we proposed to combine this down-scaling method with a co-simulation method to consider at the same time the nonlinearities due to the power electronic converter and the magnetic characteristics of the magnetic coupler. The co-simulation platform is developed using two software tools based on circuits and finite element (FE) analysis. A 1 kW experimental setup has been proposed to validate both methods. The different results and discussions show the effectiveness of these methods and the possibility to study an IPT system at a reduced power scale and then to extend it by extrapolation to a much larger power scale.

ACKNOWLEDGMENT

This research program is funded by the French National Research Agency (ANR): ECOCES project (Electromagnetic compatibility Co-simulation Of Complex Electrical Systems), ANR-19-CE05-0016-05.

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