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Optimal Matching Reactance Design and Validation in Wireless Power Transfer System for Electric Vehicle Based on SAE J2954-RP

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***Abstract*—Wireless power transfer (WPT) is foreseen as a suitable technology to provide charging without cables to electric vehicles. The charging requires a specific charging profile for different type of battery. In addition, the loading condition of the charging circuit could change drastically as following the charging profile. Due to the dependencies on loading condition, the transmission efficiency of a WPT system could degrade during the charging process. Nevertheless, the sensitivity of efficiency to loading condition could be reduced with proper design of compensation network, e.g., LCC. In this paper, a SPICE-simulation based optimization flow is demonstrated for matching reactance optimization for a WPT system following the Society of Automotive Engineers (SAE) J2954 recommended practice (RP). Based on the method we proposed, it is possible to obtain the optimal reactance value for multiple loading conditions regarding transfer efficiency. The proposed method and result are verified by experimental measurements.**

***Index Terms*—Wireless power transfer; electric vehicles; reactance optimization; SAE J2954**

I. Introduction

The wireless power transfer (WPT) technology has drawn much attention as it brings mobility and flexibility in charging for electric vehicles (EVs). In recent years, general EVs have been well developed and commercialized. A recommended practice (RP) for the EV-WPT systems was also proposed by the Society of Automotive Engineers (SAE) [1].

Referring to the SAE J2954-RP, the WPT system for EVs consists of a transmitter (e.g., inverter), a pair of magnetic coupling coils, a receiver (e.g., rectifier) and the battery pack, as shown in Fig. 1. It is worth noting that the batteries are fragile and prone to overheat during charging. Unrestricted charging at a high current could generate large heat dissipation and ruin the battery pack eventually. As a result, charging profiles must be followed to ensure safety and long life without compromising performance [2].

However, the changing voltage and current relation during the charging process will introduce a drastic change in loading condition. Besides, the overall voltage of battery pack could be 280 V, 350 V and 420 V as legislated in SAE J2954. The power transfer efficiency (PTE) could be easily affected by the loading condition as coils with high quality factor are deployed in developed WPT systems. As a result, maintain high PTE for all types of battery packs could be challenging.

To reduce the influence of time-varying input impedance of a battery pack, an impedance converter could be used. As demonstrated in Fig. 1, an optional impedance converter (e.g., dc-dc converter) could be installed at the receiver side to minimize the influence of impedance variation. However, the converter could decrease the system efficiency while increasing the complexity. Extra losses could be generated by the extra impedance converter either. As an alternative to the battery management dc-dc converter, the charging efficiency could be optimized with selecting proper matching components in the compensation networks. As demonstrated in Fig. 1, topologies of the compensation networks at both transmitter and receiver sides are already specified by the SAE J2954-RP. Nevertheless, only the reactance ranges of X_{GA} and X_{VA} are given in the RP document, which provides flexibility to improve the efficiency under different loading conditions.

In this paper, a WPT system prototype and the corresponding circuit simulation model are built. The purpose of the prototype is to evaluate the electric performance under different loading conditions. Meanwhile, the prototype is used as the reference for simulation validation. The simulation-based matching reactance optimization method is then proposed. In addition to the optimization, the simulation model could be used as basis for further advanced component tuning methods.

II. Description of Prototype and Simulation Model of a WPT System

1) Inverter and Rectifier: As shown in Fig. 1, the inverter and the rectifier are required for the WPT system. For the experimental prototype, high voltage IGBTs (model: IHW50N65R5) were used in a H-bridge arrangement. The rectifier was built with silicon carbide schotty diode FFSH2065A. In the simulation, the SPICE models of both IGBT and diode were extracted according to their datasheets.

2) Operation Frequency: Operation frequency of the system could be slightly tuned to compensate for various operation conditions. However, the switching frequency must be within 81.38 kHz and 90 kHz for emission considerations

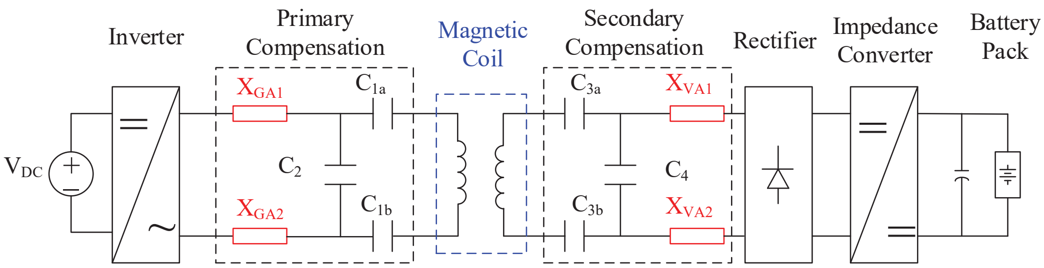

Fig. 1. General schematic diagram of WPT system complaint with SAE J2954-RP.

according to [1]. To avoid introducing frequency related error into measurements and simulations, the frequency was configured as 85 kHz, which is the nominal one defined in the SAE J2954-RP.

3) Magnetic Coupling Coils: To guarantee the PTE of overall system, which is from DC input source to battery pack, the magnetic coupling coils are critical. The coils used in the system was built referring to the J2954, and details of the coil configuration are discussed in [3]. Diagram of the magnetic coils is illustrated in Fig. 2. Both ground assembly (GA) and vehicle assembly (VA) coils were made with 1000 strands of AWG 36 Litz wire. The GA and VA coils were wound with 8 and 9 turns, respectively. The distance between GA and VA coils was configured as the nominal magnetic gap, i.e., 142 mm.

The electrical parameters of magnetic coupling coils were obtained with measurements by LCR meter (Model: TH2827C) and kelvin test fixture (Model: Agilent 16048G) at 85 kHz, and the corresponding parameters are shown in Table I.

TABLE I
MEASURED ELECTRICAL PARAMETERS OF MAGNETIC COUPLING COILS AT 85KHZ

Parameter		Value
ESR	Tx coil	41.9 mΩ
	Rx coil	53.7 mΩ
Inductance	Tx coil	42.68 μH
	Rx coil	43.04 μH
Coupling coefficient		0.182

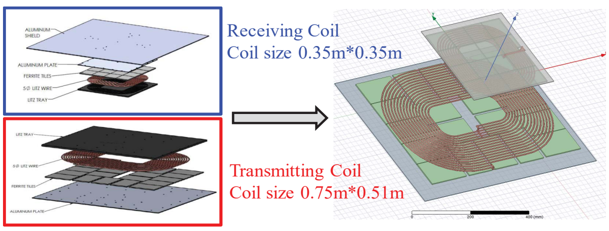

Fig. 2. Diagram of magnetic coils referring to J2954 class WPT2/Z2.

4) Matching Components: Even though the equivalent series resistances (ESR) of matching components are not specified by the standard, the ESRs should be as small as possible to minimize the loss. The metallized polypropylene film capacitors were then used due to their low ESRs. In addition, inductors were made with Litz wire and low loss ferrite cores (TDK N95).

Fig. 1 and Table II show the block diagram of the matching network and its circuital parameters, respectively.

TABLE II
MEASURED ELECTRICAL PARAMETERS OF MATCHING COMPONENTS AT 85 KHZ

Parameter		Value	Parameter		Value
ESR	C_{1a}	5. 5mΩ	ESR	C_{3a}	6.1 mΩ
	C_{1b}	4.7 mΩ		C_{3b}	5.7 mΩ
	C_2	4.3 mΩ		C_4	5.2 mΩ
Capacitance	C_{1a}	268.8 nF	Capacitance	C_{3a}	250.5 nF
	C_{1b}	268.9 nF		C_{3b}	249.5 nF
	C_2	274 nF		C_4	166.8 nF

5) Battery Pack: Three reference battery voltages are listed in J2954-RP (280 V, 350 V and 420 V) and all those battery packs were simulated to demonstrate the proposed optimization method. Besides, an 0.15Ω series connected resistor was used to model the internal loss generated during charging, as suggested by the standard.

6) Output Power: In this manuscript, the investigation was performed for a Class 2 WPT system, whose input apparent power is legislated as 7.7 kVA. Due to the lack of power factor correction (PFC) circuit, the target output power was set as 6.6 kW (assume corrected power factor is 95% and the efficiency of PFC block is 90%). Besides, proportional-integral controllers were deployed in both prototype and simulation model to the maintain constant output power under all input and loading conditions. It is worth noting that, both duty cycle and frequency of gate driving signal are constant value, the tuning is achieved by adjusting input voltage level only.

III. SPICE SIMULATION BASED MATCHING REACTANCE OPTIMIZATION METHOD

As we have mentioned, the reactance ranges other than exact values of X_{GA} and X_{VA} are specified to accommodate different battery packs. In this section, a SPICE simulation-based reactance optimization method and the its constraints are discussed.

A. Proposed Simulation Based Optimization Method

Due to the non-linear natures of IGBTs and diodes, PTE of the WPT system could not be accurately estimated by analytical equations. Therefore, the commercial SPICE software (ANSYS Simplorer) was used for the optimization problem. In addition, in-house codes (Matlab) were built to communicate with SPICE software and post-process the raw time domain simulation results. Besides, in the optimization process, we assume matching components used in GA and VA sides are identical, i.e., $X_{GA1} = X_{GA2}$ and $X_{VA1} = X_{VA2}$.

The optimization formulation is as follows:

$$\max \quad PTE(X_{GA}, X_{VA}) \tag{1}$$
$$\text{subject to} \quad 4\ \Omega \le X_{GA} \le 16\ \Omega \tag{2}$$
$$-6\ \Omega \le X_{VA} \le 7\ \Omega \tag{3}$$
$$380\ V < V_{in} < 500\ V \tag{4}$$
$$P_{out} = 6.6\ kW \tag{5}$$
$$\angle(Z^1_{inverter}) > 0.1\ rad \tag{6}$$

The PTE maximization of overall system was selected as an objective function. (2) and (3) are ranges of X_{GA} and X_{VA} respectively, (4) defines the range of input voltage of inverter at GA side. Those parameters are well-defined in the J2954-RP.

To maximize the PTE of overall system, the switching loss in the inverter should be considered [4]. According to reference [5], the zero voltage switching is the most efficiency control method. As the result, the output voltage waveform of inverter V should lead its current waveform I. Therefore, the input impedance $Z_{inverter}$ is defined as

$$Z_{inverter} = \frac{V^1_{inverter}}{I^1_{inverter}}, \tag{7}$$

where $V^1_{inverter}$ and $I^1_{inverter}$ are fundamental terms of Fourier expansion of above-mentioned voltage and current waveforms.

B. Optimization Results

After applying all the previous optimization constraints into the simulation, X_{GA} and X_{VA} values which guarantee the PTE larger than 90% are obtained and demonstrated in Fig. 3.

It should be noted that the optimal matching components were obtained by applying same constraints for all three types of battery packs (280 V, 350 V and 420 V). The maximum efficiency is achieved at $X_{GA} = 13.5\ \Omega$ and $X_{VA} = 5\ \Omega$. The simulated optimal efficiency is 93.5%.

Due to the ZVS constraint shown in (6), the X_{VA} has to be a non-negative value, i.e., the matching component X_{VA} could not be a capacitor.

IV. Experimental Validation

To validate the simulation model and the optimization proposal, the simulation results were compared with the measurement ones. The impedance of X_{GA} and X_{VA} at 85kHz were determined based on the previous optimization results. The electric parameters of them are illustrated in Table III.

In the experiment, a dc E-load (model: Maynuo M9718B) was used to mimic the battery. Also, the load resistance was swept from 20 Ω ∼ 30 Ω to mimic the battery pack. Besides, the input voltage was swept from 50 V ∼ 150 V, where the maximum output power was only up to 1.54 kW due to the limited output power of power supply (model: TDK GEN500-10).

Fig. 4 plots the comparison of measured and simulated PTEs of overall system under different input and loading conditions. They have similar trends under all operation conditions. Moreover, the errors between measurement and simulation are less than 1.5%. The good correlation between measurements and simulations validated the simulation model as well as the

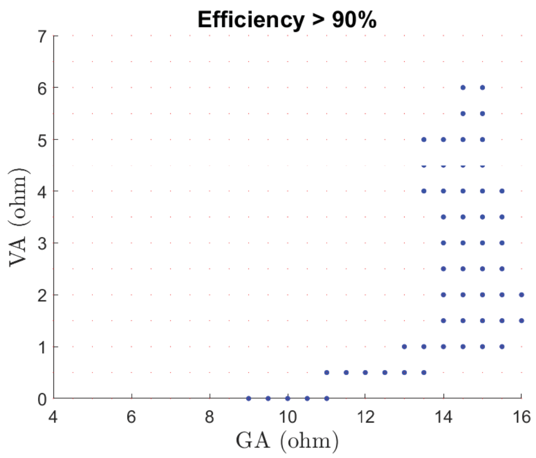

Fig. 3. Values of X_{GA} and X_{VA} guarantee PTE > 90%. Both step sizes are 0.5Ω.

TABLE III
MEASURED ELECTRICAL PARAMETERS OF MATCHING COMPONENTS AT 85 KHZ

Parameter		Value	Parameter		Value
Reactance	X_{GA1}	13.87 Ω	ESR	X_{GA1}	18.8 mΩ
	X_{GA2}	13.12 Ω		X_{GA2}	16.5 mΩ
	X_{VA1}	5.1 Ω		X_{VA1}	9.8 mΩ
	X_{VA2}	5.23 Ω		X_{VA2}	6.3 mΩ

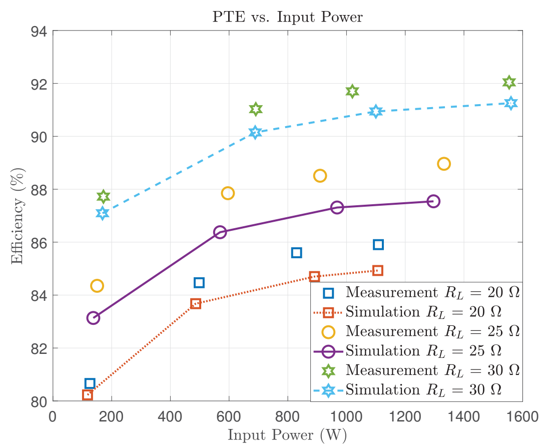

Fig. 4. Comparison of measured and simulated PTEs under different input and loading conditions.

proposed method.

V. Conclusion

In this paper, a circuit simulation based optimization method was proposed to maximize PTE of a WPT system for EV. In addition to the SPICE model, a prototype of WPT system was built for validation of simulation model. The maximum measured efficiency is $\sim 92\%$, which is well matched with simulated result. The good correlation between simulations and measurements proves the effectiveness of proposed method.

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