Sensitivity Comparison of Parameter Identification Methods in Inductive Wireless Power Transfer Systems

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ABSTRACT

Inductive wireless power transfer (IWPT) systems without any feedback from the secondary-side rely on estimated parameters solely from the primary-side of the system to ensure efficient power transfer. Conventionally, there exist numerous parameter identification methods. However, the evaluation of system performance under measurement errors and parameter tolerances is insufficiently conducted. Due to changes that occur from component variations of values during system operation, the identified parameters are influenced as a result and erroneous estimations may be obtained. This article, therefore, focuses on the comparison of system performance given the sensitivity analysis of the identified parameters. An algorithm selection guide according to system application is deduced. Simulation verification illustrating the variation analyses of the parameters are carried out and presented.

Keywords: Inductive wireless power transfer, parameter estimation, sensitivity analysis.

I. INTRODUCTION

Crucial to the design and optimization of the IWPT systems is the accurate identification of system parameters, which can be influenced by various factors such as coil alignment and load variations. Two broadly classified approaches are considered here for primary-side parameter identification. One of them is analytical approach that is based on simplified circuit models without modification to the system assuming certain operating system parameters, which allows for straightforward parameter extraction such as the equivalent load resistance, R_e, and the mutual inductance, M, through mathematical derivations [1]. While computationally efficient, their accuracy is often limited by assumptions, and hence susceptible to error translations. The second approach to look into involves modification of the IWPT system for the estimation of unknown parameters through secondary-side termination conditions such as short-circuiting or open circuiting [2]. Although this approach provides lesser exposure to errors, it is time-consuming and requires additional components, such as switch for termination purposes, making them less practical for certain applications due to interruption of system operation.

The investigation in this paper aims to provide a selection guide for IWPT system engineers and researchers based on a comparative study on the impacts of the sensitivity of the above highlighted analytical approach and modification approach.

II. SENSITIVITY ANALYSIS OF IDENTIFIED PARAMETERS

Fig. 1 shows a schematic for a series-series-compensated IWPT system illustrating primary-side identified parameters which will be used for reference in this comparative analysis. The key parameter estimation equations that have been proposed in their respective articles will be utilized to carry out the analysis.

The work in [1] presents a method for estimating R_e and M. Through analysis and derivation of the system quantities, the

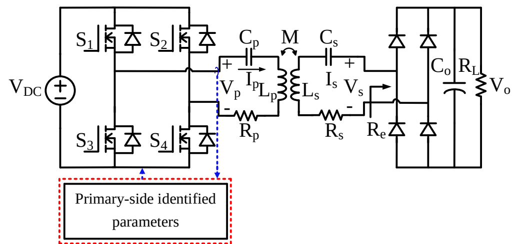

Fig. 1. Primary-side identification of IWPT system.

aforementioned parameters are given as

$$R_e=\frac{\left(R_{\mathrm{in}}-R_{\mathrm{p}}\right)\left(1-\frac{\omega_{os}^2}{\omega^2}\right)\omega L_{\mathrm{s}}}{\left(1-\frac{\omega_{op}^2}{\omega^2}\right)\omega L_{\mathrm{p}}-X_{\mathrm{in}}}-R_{\mathrm{s}} \tag{1}$$

$$M=\sqrt{\frac{\left(R_{in}-R_p\right)\left(\left(R_s+R_e\right)^2+\left(1-\frac{\omega_{os}^2}{\omega^2}\right)^2\omega^2 L_s^2\right)}{\omega^2\left(R_s+R_e\right)}}\,. \tag{2}$$

As the components in the system are not constant during operation, further sensitivity analysis should be performed to this identification approach to investigate its outcome in the case of these parameter tolerances following the normalized derivative-based local method as

$$S_{R_e}^{M}=-\frac{\mathrm{R_e}\left(\mathrm{c}-\frac{\left(\mathrm{R_{in}}-\mathrm{R_p}\right)\left(2\mathrm{R_e}+2\mathrm{R_s}\right)}{\omega^2\left(\mathrm{R_e}+\mathrm{R_s}\right)}\right)}{2\mathrm{b}} \tag{3}$$

$$S_{R_{in}}^{R_e}=-\frac{\omega\mathrm{L_s}\mathrm{R_{in}}\left(\frac{\omega_{\mathrm{os}}^2}{\omega^2}-1\right)}{\mathrm{X_{in}}+\omega\mathrm{L_p}\left(\frac{\omega_{\mathrm{op}}^2}{\omega^2}-1\right)\left(\mathrm{R_s}-\frac{\omega\mathrm{L_s}\left(\mathrm{R_{in}}-\mathrm{R_p}\right)\left(\frac{\omega_{\mathrm{os}}^2}{\omega^2}-1\right)}{\mathrm{X_{in}}+\omega\mathrm{L_p}\left(\frac{\omega_{\mathrm{op}}^2}{\omega^2}-1\right)}\right)} \tag{4}$$

$$S_{L_s}^{R_e}=-\frac{\omega\mathrm{L_s}\left(\mathrm{R_{in}}-\mathrm{R_p}\right)\left(\frac{\omega_{\mathrm{os}}^2}{\omega^2}-1\right)}{\mathrm{a}},\ S_{Lp}^{R_e}=\frac{\omega^2\mathrm{L_p}\mathrm{L_s}\left(\mathrm{R_{in}}-\mathrm{R_p}\right)\left(\frac{\omega_{\mathrm{op}}^2}{\omega^2}-1\right)\left(\frac{\omega_{\mathrm{os}}^2}{\omega^2}-1\right)}{\mathrm{a}} \tag{5}$$

where

$$\mathrm{a}=\left(\mathrm{X_{in}}+\omega\mathrm{Lp}\left(\frac{\omega_{\mathrm{op}}^2}{\omega^2}-1\right)\right)\left(\mathrm{R_s}-\frac{\omega\mathrm{L_s}\left(\mathrm{R_{in}}-\mathrm{R_p}\right)\left(\frac{\omega_{\mathrm{os}}^2}{\omega^2}-1\right)}{\mathrm{X_{in}}+\omega\mathrm{L_p}\left(\frac{\omega_{\mathrm{op}}^2}{\omega^2}-1\right)}\right) \tag{6}$$

$$\mathrm{b}=\frac{\left(\mathrm{R_{in}}-\mathrm{R_p}\right)\left(\left(\mathrm{R_e}+\mathrm{R_s}\right)^2+\omega\mathrm{L_s}^2\left(\frac{\omega_{\mathrm{os}}^2}{\omega^2}-1\right)^2\right)}{\omega^2\left(\mathrm{R_e}+\mathrm{R_s}\right)^2}\,. \tag{7}$$

Analyzing the derived sensitivity equations, major deductions are observed as follows: it is seen that secondary-side coupler inductance L_s has much influence on the identified R_e. This influence is more pronounced when the frequency ratio *(ω^2_{os}/ω^2)* is large, implying that away from resonance, the influence of L_s is stronger. Also, the interactions of L_p and L_s are prominent in this case as long as the frequency ratio does not equal unity. The sensitivity relative to M is seen to be majorly influenced by the resistive and reactive components of the system.

For identification that follows load termination, the work in

Tabel 1. Simulation specifications values.

L_P	696 μH	L_S	696 μH	f_P	99 kHz
C_P	3.64 pF	C_S	3.64 pF	f_S	99 kHz

Table 2. Summary of parameter sensitivity of both approaches.

Analytical	Dependency	Modification	Dependency
$S^{R_e}_{L_p}$	-1.05274	$S^{R_e}_{M}$	2
$S^{R_e}_{L_S}$	1.03788	$S^{M}_{R_p}$	3.12e-06
$S^{R_e}_{R_{in}}$	1.07631	$S^{M}_{C_p}$	-1.35e-17
$S^{M}_{R_e}$	0.48173	$S^{M}_{L_p}$	0.99997

[2] discusses steady-state parameter estimation. Circuit is first open-circuited then short-circuited by help of additional switch components to facilitate these conditions. Parameters M and R_e are obtained with the following equations:

$$M = \frac{V_{sref}}{\omega V_P}\sqrt{\left(\omega L_P - \frac{C_P}{\omega}\right)^2 + R_P^{\,2}} \tag{8}$$

$$R_e = \frac{C_s}{\omega} - L_s - R_s - \frac{(\omega M)^2}{R_p + \omega L_p - \frac{V_p}{I_p} - \frac{C_p}{\omega}} \tag{9}$$

where V_{Sref} is a known reference voltage. During a frequency sweep, the secondary-side voltage is compared to the reference voltage and the condition is changed from open circuit to short circuit when they are equal. Corresponding sensitivity analysis to understand how component tolerances would influence the estimated parameters is as shown

$$S^M_{R_p} = \frac{R_p^{\,2}}{\left(\omega L_p - \frac{C_p}{\omega}\right)^2 + R_p^{\,2}},\ S^M_{L_p} = \frac{\omega L_p\left(\omega L_p - \frac{C_p}{\omega}\right)}{\left(\omega L_p - \frac{C_p}{\omega}\right)^2 + R_p^{\,2}},\ S^M_{C_p} = -\frac{C_p\left(\omega L_p - \frac{C_p}{\omega}\right)^2}{\omega\left(\left(\omega L_p - \frac{C_p}{\omega}\right)^2 + R_p^{\,2}\right)} \tag{10}$$

$$S^{R_e}_M = \frac{(\omega M)^2}{\left(R_s + \omega L_s - \frac{C_s}{\omega} + \frac{(\omega M)^2}{R_p + \omega L_p - \frac{V_p}{I_p} - \frac{C_p}{\omega}}\right)\left(R_p + \omega L_p - \frac{V_p}{I_p} - \frac{C_p}{\omega}\right)}. \tag{11}$$

In the case of this analysis, the sensitivity of the estimated parameters to R_p appears to have proportional influence but it is limited by the denominator quantity as well. Furthermore, how the L_p and C_p impact the output parameters is dependent on the frequency term. M quadratically impacts R_e assuming that the other terms have relatively small deviations.

III. Simulation Comparison and Discussion

The values in Table 1 are used in powersim (PSIM) software to simulate the theoretical analyses in Section II. Table 2 summarizes the sensitivity of the identified parameters at normalized resonant frequency showing their different respective dependencies. For the analytical approach, L_S exhibits the most sensitivity, as is observed in Section II, especially for R_e identification, and M is influenced most by the estimated R_e. In Fig. 3, deviations of R_e due to 10 % changes of the input quantities are shown. Increase in R_e in turn influences light load condition in the system, hence the power delivery is reduced. Similarly, as shown in Fig. 4 M is most volatile to changes in both positive and negative tolerances of R_s.

The illustration for the modification approach also shown in Table 2 depicts R_e being the most sensitive parameter. However, the changes observed are smaller, as compared to the analysis approach, thus the effects are generally not as sensitive. This can be attributed to the limiting denominator term in the analysis. In Fig. 4, R_p has the least impact as M deviates by a small margin. Also, a 10 % change in L_p value results in highly varying M values, thus imposing an effect on the resonance of the coupler.

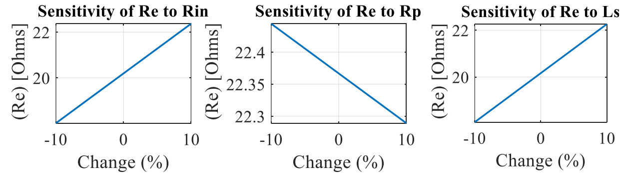

Fig. 2. Deviations of R_e respective to percentage change of input quantities in of analysis approach.

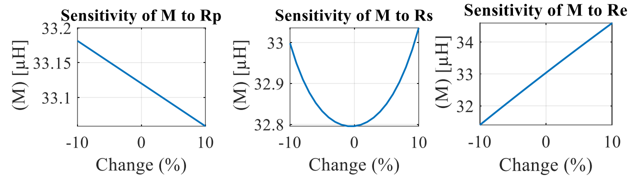

Fig. 3. Deviations of M respective to percentage change of input quantities in of analysis approach.

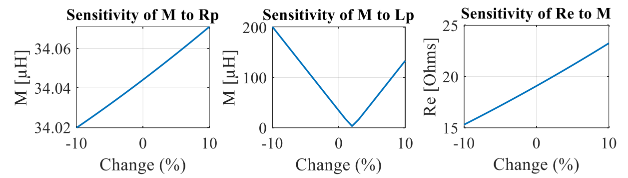

Fig. 4. Deviations of M and R_e respective to percentage change of input quantities of the modification approach.

The system is designed for 258 W with 20 Ω R_e. Comparatively, analytical approach is quite reduced to 234 W due to R_e fluctuation to 18 Ω as even though M is not affected as much while modification approach has 294 W as deviations in M majorly influence the system with variation of R_e at 23 Ω as is the case from sensitivity.

IV. Conclusion

A comparative sensitivity analysis is carried out that analyzes analytical approach and modification approach. The influence on the identified parameters and on the system performance is assessed. An algorithm selection guide following the deductions from these analyses can be made as follows:

a) For a stationary pickup system, a modification approach of estimation is recommended as accuracy is improved due to impedance of the load being matched with that of the source with good performance. However, the termination operation interrupts the power transfer for this purpose, hence a moving pick-up would be largely affected by this process.

b) An analytical approach is recommended for both stationary and moving pick-up receiver cases because not only is it less resource-intensive but also capable of quick recalibration in dynamic environments such as vehicular systems. However, system nonlinearities and noise should be taken into account.

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