Effective Load Identification for Inductive Wireless Power Transfer Systems Utilizing Kalman Filter Approach

Andrew-Ngini Mwangi*, Ngoc-Thao Pham**, and Sung-Jin Choi***
Department of Electrical, Electronic, and Computer Engineering, University of Ulsan, South Korea
*nginiandrew79@gmail.com, **ptnthao1776@gmail.com, and ***sjchoi@ulsan.ac.kr

ABSTRACT

Inductive wireless power transfer (IWPT) systems require accurate load estimation to maintain efficient power delivery under varying operating conditions. Existing load estimation techniques often suffer from calibration and calculation burdens. To address this limitation, this paper presents an effective load estimation strategy for IWPT systems by combining analytical estimator and predictions of the Kalman filter estimator. By modelling the IWPT dynamics under a fixed mutual inductance, load resistance is obtained analytically then the load voltage tracking is implemented by the Kalman filter. Hence, reliability of the IWPT system is maintained, as the identification accuracy is upheld during abrupt load changes. Simulation verification is presented to verify the discussed two-step identification approach.

I. INTRODUCTION

An essential challenge in IWPT systems is that the secondary-side load parameters, are hard-to-measure quantities when communication is eliminated [1]. In practical IWPT system implementation, there is bound to be parameter drifts owing to factors such as manufacturing tolerances of capacitors, inductors as well as dynamic load changes. Even though it is presumed that the mutual inductance is a known constant due to Guided Positioning in accordance with Qi wireless charging standards [2], factors such as neighbouring magnetic materials deteriorates the mutual inductance value.

Considering the aforementioned instances, a two-step identification is presented. Analytical identification carried out prior is to estimate equivalent load resistance, R_{eq}. However, this approach alone cannot handle dynamic changes. Kalman filter then uses the estimated R_{eq} to build a dynamic model and continuously estimate the secondary-side output parameters, under noise and system uncertainties. This is because Kalman estimator is a recursive model that is able to handle measurement noise and model noise in a system during dynamic changes through prediction and update phases [3].

II. TWO-STEP IDENTIFICATION APPROACH

The series-series (SS) compensation has been widely used in IWPT systems due to its analytical simplicity. Hence, it is also utilized here. Fig. 1 illustrates the two-step identification of an SS-compensated IWPT system presented in this paper.

A. Analytical Identification of Load Resistance

From Fig. 1, the equivalent input impedance seen from the primary side is found as

$$Z_{in} = R_p + j\omega L_p + 1/j\omega C_p + \frac{(\omega M)^2}{R_p + j\omega L_p + 1/j\omega C_p}. \tag{1}$$

The real and imaginary parts are given as

$$R_{in} = R_p + \frac{\omega^2 M^2 (R_{eq} + R_s)}{(R_{eq} + R_s)^2 + (\omega L_s - 1/\omega C_s)^2} \tag{2}$$

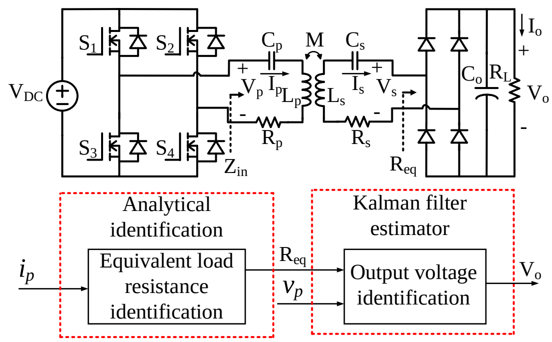

Fig. 1. Two-step identification of an SS-compensated IWPT system.

and

$$X_{in} = \omega L_p - \frac{1}{\omega C_p} - \frac{(\omega L_s - 1/\omega C_s)\omega^2 M^2}{(R_{eq} + R_s)^2 + (\omega L_s - 1/\omega C_s)^2}. \tag{3}$$

(2) and (3) are simplified by equating same denominator terms on the right-hand side to obtain (4)

$$\frac{\omega^2 M^2 (R_{eq} + R_s)}{R_{in} - R_p} = -\frac{(\omega L_s - 1/\omega C_s)\omega^2 M^2}{X_{in} - \omega L_p + 1/\omega C_p} \tag{4}$$

and thus, equivalent load resistance can be estimated as

$$R_{eq} = -\frac{(R_{in} - R_p)(\omega L_s - 1/\omega C_s)}{X_{in} - \omega L_p + 1/\omega C_s} - R_s. \tag{5}$$

This is adjusted to the load resistance R_L by the power balance for the lossless full bridge rectifier as $R_L = (\pi^2/8)R_{eq}$.

B. Kalman Filter Implementation

Having identified the equivalent load resistance, the output voltage is next be estimated. To implement the Kalman filter approach, a state-space representation of the system is first established. The state variables are $x_1=i_p$, $x_2=i_s$, $x_3=v_{cp}$ and $x_4=v_{cs}$, while $u=v_p$ and $y=x_2=i_s$ are assigned as input and output vectors, respectively. From Fig. 2, which illustrates a magnetically coupled IWPT system with mutual inductance modelled as current-controlled voltage sources, state equations are obtained as shown

$$u = x_3 + R_p x_1 + L_p \dot{x}_1 + M\dot{x}_2 \tag{6}$$

$$M\dot{x}_1 = R_{eq} x_2 + L_s \dot{x}_2 + R_s x_2 + x_4 \tag{7}$$

$$\dot{x}_3 = 1/C_p x_1 \tag{8}$$

$$\dot{x}_4 = 1/C_s x_2. \tag{9}$$

Solving the state-space equations results in state transition matrix A, input matrix B, output matrix C and direct transition matrix D,

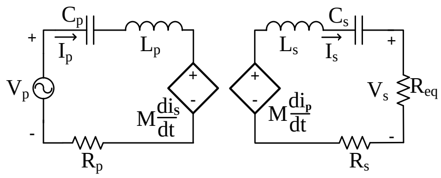

Fig. 2. Schematic of a magnetically coupled IWPT system.

that model the dynamic behaviour of the IWPT system. They are obtained as

$$A=\begin{bmatrix} (-R_pL_s)/L_i & M(R_s+R_{eq})L_i & -L_s/L_i & M/L_i \\ (R_pM)/L_i & -L_p(R_s+R_{eq})L_i & M/L_i & -L_p/L_i \\ 1/C_p & 0 & 0 & 0 \\ 0 & 1/C_s & 0 & 0 \end{bmatrix} \quad (10)$$

$$B=\begin{bmatrix} L_s/L_i & -M/L_i & 0 & 0 \end{bmatrix}^T, C=\begin{bmatrix} 0 & 1 & 0 & 0 \end{bmatrix}, D=\begin{bmatrix} 0 \end{bmatrix}$$

where L_i= L_p L_s -M and the Kalman filter estimator can now be utilized as

$$\mathbf{x}_k = A\mathbf{x}_{k-1} + Bu_{k-1} + w_{k-1} \quad (11)$$

$$\mathbf{z}_k = H\mathbf{x}_k + v_k \quad (12)$$

where $\mathbf{x}_k$ is the four-by-one state vector of the parameter to be estimated which in this case is $\mathbf{x}_k$=[x_1 x_2 x_3 x_4]^T, $\mathbf{z}_k$ is the one-by-one measurement vector, H=[0 1 0 0] is the measurement matrix C from the state-space model, w_k is the process noise and v_k is the measurement noise. Since i_s and R_{eq} have been identified, the voltage v_s can then be obtained through the relation $v_s= i_s{\cdot}R_{eq}$. This ac voltage is then rectified by the lossless full bridge rectifier as V_o=(2V_{s1})/π, where V_o is the output dc voltage and V_{s1} is the amplitude of the secondary side ac current.

III. Simulation Verification

Simulation of a SS-compensated IWPT system is conducted to verify the two-step identification approach utilizing the specification parameters in Table 1. A disturbance is introduced for the load resistance parameter value to observe the performance of the two-step identification.

From Fig. 3 (a), it can be observed that the analytically identified load resistance shows an error of within 0.5% at nominal load and steady-state error of 7.1% after the load step change. This is compared to conventional estimation that also shows increased error of 8.8% at increased load resistance values as noted in [4]. Fig. 3 (b) illustrates the Kalman filter estimate for output voltage achieves steady-state errors of 1.8% and 4.6% before and after the load step change, respectively, while a 7.9% error deviation is observed for the conventional identification. The limitation of analytical approach to dynamic change is illustrated. Transient fluctuation in current estimation remains within 2% of the actual value after energy in resonant elements is quickly delivered to the load as can be seen in the spike during load step change in Fig. 3 (c).

Overall, the proposed two-step estimation approach improves performance for load parameter identification in dynamic conditions since the Kalman estimator adaptively filters noise and tracks dynamic changes with minimized error.

Partial derivative-based normalized sensitivity analysis, as demonstrated in Fig. 3 (d), shows how R_{eq} in (5) is affected by parameter variations. This analysis reveals that R_{eq} is most sensitive to R_p (+1.82), L_p (–1.19), and L_s (+1.19), due to their direct roles in reflected impedance in the system. R_p dominates as it affects power loss as it is proportionally correlated. L_p and L_s influence the resonant behaviour and coupling efficiency, leading to equal but opposite sensitivities. R_s (–0.91) and R_{in}

Table 1. Simulation parameters

L_p	155.4 µH	C_s	16.07 nF
L_s	156.56 µH	f_o	101.1 kHz
M	41.547 µH	f_{sw}	101.1 kHz
C_p	15.92 nF	R_L	20 Ω

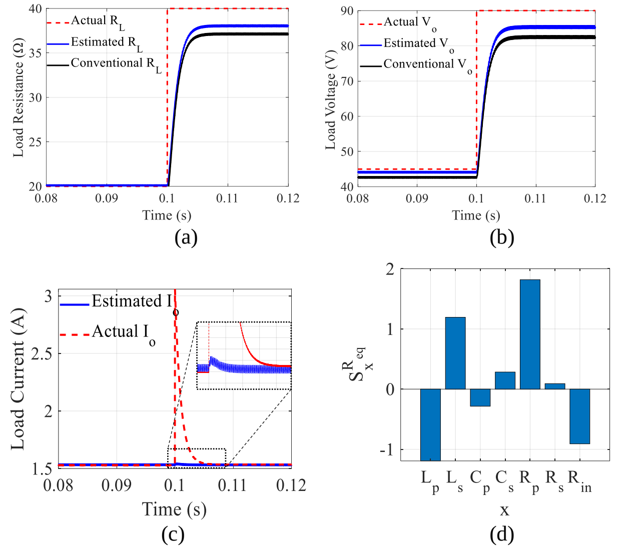

Fig. 3. (a) Load resistance estimation. (b) Output voltage estimation. (c) Output current estimation. (d) Sensitivity analysis relative to R_{eq}.

(+0.91) moderately affect R_{eq} via the load path. C_p and C_s (±0.28) show minimal impact due to resonance tuning.

IV. Conclusion

A two-step identification approach of analytical and Kalman filter estimators has been presented. Practical implementation challenging factors of the IWPT systems have been considered to investigate the dynamicity of the presented two-step approach to effectively identify the load parameters with system uncertainties. The provided simulation verification demonstrates identification errors of 7.1% and 4.6% for analytical and Kalman estimators, respectively, under system disturbance. Future work will focus on extending the two-step identification framework from simulation into a hardware implementation to validate the system performance under real world practical constraints.

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