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Optimal Excitation of Multi-transmitter Wireless Power Transfer System without Receiver Sensors

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Abstract—The optimal excitation of multi-transmitter wireless power transfer systems is dependent on the position of the receiver (Rx). To maximize the output power and efficiency, the transmitter (Tx) coils closer to the Rx should have higher currents compared to the ones farther away. This paper presents a simple approach to determine the optimal excitation of individual Tx without using any measurement at the Rx side. The Tx coils are arranged to be uncoupled from adjacent Tx coils. In this configuration, the optimal current distribution in each Tx coil is a function of the mutual inductances of each Tx-Rx coil pair, which can be evaluated by analyzing the voltage measurements at Tx coils. The proposed approach is experimentally verified using a laboratory prototype.

Index Terms—Wireless power transfer, Multiple transmitter, Coupling estimation

I. INTRODUCTION

Wireless Power Transfer (WPT) technology has become an exciting topic for both industry and academia in recent years. WPT is beneficial for many applications including consumer electronics applications, medical implants, and electric vehicle charging. Multi-transmitter WPT, where multiple power transmitters (Tx) are used to energize single or multiple receivers (Rx), can be useful to extend the mobility of the Rx, as is schematically illustrated in Fig. 1. For example, multiple Tx can be positioned in a planar, pad-like arrangement to charge electric vehicles [1], [2], mobile devices [3] or medical implants [4]. In a typical multi-Tx WPT, all the Tx coils are connected to the same power source and excited simultaneously [4]. However, such simultaneous and homogeneous activation may not be optimal because the power contribution from each Tx to the Rx depends on the mutual coupling between each Tx-Rx pairs. Tx coils with strong coupling to the receiver transfer more power than the Tx coils with weak coupling. Therefore, coil currents in each Tx should be optimized depending on the mutual coupling between Tx-Rx pairs [5]. Depending on the mutual inductances between each Tx-Rx pair, the optimal current distribution in each Tx coil can be determined. As such, in a multi-Tx WPT system, the detection of Rx location is crucial for the optimal excitation of the Tx.

Several approaches have been proposed in the literature to estimate the mutual inductance between Tx and Rx coils. The straightforward way is to use an additional sensing mechanism to detect the presence of Rx, for example, a proximity sensor, which will increase the cost and complexity due to the requirement of an additional sensing circuitry. Several

mutual inductance estimation methods have been proposed to use the voltage and current measurements from both Tx and Rx sides [6], [7], and to introduce additional detection coils at both Tx and Rx sides [8]. Such methods require a wireless communication link between Tx and Rx to transfer Rx side measurements to the Tx side. There have been few approaches to detect the presence of Rx and the mutual inductance by using only Tx side measurements in a single-Tx WPT system [9]–[11]. For example, [9] proposes to estimate coupling by analyzing the input impedance seen by the Tx. However, the variation in input impedance is very minimal for weak coupling. Therefore, it can only be effective when the coupling is strong. The study [10] estimates the Rx side parameter by a curve fitting technique which fits the measured voltage and current at the Tx side to the equivalent circuit model. A frequency domain analysis of the Tx current is proposed in [11]. However, both curve fitting technique and frequency domain analysis require a substantial computational power, and therefore they are not very effective in multi-Tx WPT. Sharp coupling variations in multi-Tx WPT can be detected by analyzing the change in the phase angle between the Tx current and the supply voltage, however, such approach can only be useful in detecting the edge of a Tx array [12]. Different from the existing approaches, this paper proposes a simple technique to determine the optimal current distribution in Tx coils by estimating the mutual inductance ratios between each Tx-Rx pairs with only Tx-side measurements.

This paper is organized as follows. Section II presents theoretical analysis of multi-Tx WPT systems, and introduces the mutual inductance estimation approach for optimal excitation. The experimental results are given in Section III followed by conclusions in Section IV.

II. ANALYSIS OF MULTI-TX WPT SYSTEMS

A. Multi-transmitter WPT system

We analyze multi-Tx WPT systems using the equivalent circuit method. The equivalent circuit of an n -Tx WPT system is shown in Fig. 2, where n is the number of Tx coils that are

Fig. 1. Schematic of a multi-transmitter WPT pad.

powered simultaneously or individually. The system equation of such an n -Tx WPT can be written as

$$[V]_{(n+1) \times 1} = [Z]_{(n+1) \times (n+1)} [I]_{(n+1) \times 1}, \quad (1)$$

where

$$[V]_{(n+1) \times 1} = [V_1 \ V_2 \ \cdots \ V_n \ V_r]^T, \\ [I]_{(n+1) \times 1} = [I_1 \ I_2 \ \cdots \ I_n \ I_r]^T,$$

are the voltages and currents at Tx (with subscripts 1, 2, ..., n) and Rx coils (with subscript r). They are related by the impedance matrix $[Z]_{(n+1) \times (n+1)}$ in which the elements have the values

$$[Z]_{kl} = \begin{cases} Z_k = R_k + jX_k, & k = l \neq n+1 \\ Z_{n+1} = R_r + jX_r, & k = l = n+1 \\ X_{kl} = X_{lk} = j\omega M_{kl}, & k \neq l. \end{cases} \quad (2)$$

The diagonal terms Z_k are the self-impedances of the n Tx ($k = 1, 2, \dots, n$) and Rx ($k = n+1$ or r) coils, which consist of the parasitic resistance R_k and the reactance $X_k = \omega L_k - 1/\omega C_k$ (L_k and C_k represent the inductance and capacitance of each coil, respectively). R_L is the equivalent load resistance at Rx. The off-diagonal terms representing the mutual couplings, however, are nearly purely reactive, and M_{kl} ($= M_{lk}$) is the mutual inductance between the k^{th} coil and l^{th} coil. ω is the operational angular frequency of the power source.

By expanding the last row of the system (1) and assuming that $V_r = I_r R_L$, we can obtain the Rx current I_r as

$$I_r = \left(\sum_{k=1}^n j\omega M_{kr} I_k \right) / (R_r + R_L + jX_r). \quad (3)$$

The output power at the receiver is

$$P_{\text{out}} = |I_r|^2 R_L, \quad (4)$$

and the efficiency of the wireless link equals

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{|I_r|^2 R_L}{\sum_{k=1}^n |I_k|^2 R_k + |I_r|^2 (R_r + R_L)}. \quad (5)$$

To maximize the output power and efficiency, we should maximize the magnitude of the Rx current while reducing the parasitic losses within the coils. It is obvious from Eq. (3) that we should operate at the resonance frequency of the Rx, so that $X_r = 0$, and we should maximize the summation of the $M_{kr} I_k$ product. On the other hand, from Eq. (5) we conclude that we should also minimize the summation of the $|I_k|^2 R_k$ product. To this end, as the parasitic resistances R_k are approximately the same for all the coils, currents I_k in each Tx should be optimized according to the mutual inductances between each Tx-Rx pair.

We define the currents in each Tx coil as

$$\begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} = \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{bmatrix} I_0, \quad (6)$$

Fig. 2. The equivalent circuit of multi-transmitter WPT system.

where $\alpha_{1,2,\dots,n}$ are current distribution coefficients (CDC) that determine the currents in each Tx relative to the nominal current I_0 . The nominal current I_0 will be determined depending on the power requirement. For optimal power transfer from multi-Tx to Rx, the optimal current coefficients can be derived as [5]

$$\alpha_k = M_{kr} / \sqrt{\sum_{l=1}^n M_{lr}^2} = 1 / \sqrt{\sum_{l=1}^n \left(\frac{M_{lr}}{M_{kr}} \right)^2}. \quad (7)$$

It is clear that the most crucial parameter to determine the optimal current distribution is the mutual inductance ratios between each Tx-Rx pair. Therefore, instead of focusing on finding the absolute value of the mutual inductance, the estimation of the mutual inductance ratios is enough for achieving an efficient power transfer from multi-Tx.

B. Estimation of the mutual inductance ratio

To avoid unwanted couplings between Tx when Rx is absent, we design the set of Tx coils so that the adjacent Tx coils are not coupled. For example, Fig. 3 shows the coupling variation between two planar circular spiral coils with respect to the displacement between them. We can then put all the adjacent Tx coils to the places with the distance equal to the zero-coupling displacement [Fig. 3]. In addition, with this configuration, the coupling between non-adjacent coils will also be negligibly small due to the large distance. In this case the impedance matrix $[Z]_{kl}$ is simplified to

$$[Z]_{kl} = \begin{bmatrix} Z_1 & 0 & \cdots & 0 & j\omega M_{1r} \\ 0 & Z_2 & \cdots & 0 & j\omega M_{2r} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & Z_n & j\omega M_{nr} \\ j\omega M_{r1} & j\omega M_{r2} & \cdots & j\omega M_{rn} & Z_r \end{bmatrix}. \quad (8)$$

When we activate one Tx coil (by connecting it to a power source), there will not be any induced voltage across any other Tx coil if there is no Rx coil. On the other hand, when an Rx device is present, there will be induced voltages across the inactive Tx coils due to couplings M_{kr} from the Rx coil. By analyzing the induced voltages, we can evaluate the mutual inductance ratios.

Fig. 3. Coupling coefficient variation between two co-planar spiral coils with respect to the lateral displacement d .

Let us now assume that the m^{th} Tx coil is connected to a power source and there is an Rx present. Then as all the other Tx's (marked by k) are open and there is no current through them, i.e., $I_k = 0$. However, there is voltage induced in them and the voltage measured across the k^{th} Tx coil, V_{km} , can be obtained from Eqs. (1) and (8) as

$$V_{km} = j\omega M_{kr} I_{rm}, \quad (9)$$

where I_{rm} is the Rx current when m^{th} Tx is active. If we assume that the operation frequency is identical to the resonance frequency of the Rx, I_{rm} can be evaluated as

$$I_{rm} = -\frac{j\omega M_{mr} I_m}{R_r + R_L}, \quad (10)$$

where I_m is the current in the m^{th} Tx coil. If we measure induced voltages across two different Tx coils, e.g., k^{th} and l^{th} Tx coils, when the m^{th} Tx is active, we can easily find the mutual inductance ratio from Eq. (9):

$$\frac{M_{lr}}{M_{kr}} = \frac{V_{lm}}{V_{km}}. \quad (11)$$

We can repeat the measurement procedure by connecting the source to each Tx coil in the Tx pad, and evaluate all the mutual inductance ratios. In fact, the same ratio can be evaluated using different measurements, which can be used for the verification purposes. Once the mutual inductance ratios are known, the optimal CDC can be easily calculated using Eq. (7).

We can also notice from Eqs. (9) and (10) that the induced voltage V_{km} is proportional to the product of the mutual inductance between the m^{th} Tx and Rx and the k^{th} Tx and Rx, i.e., to $M_{mr}M_{kr}$. Therefore, by analyzing the profile of the mutual inductance ratios and the products, the approximate position of Rx can be estimated. For example, Fig. 4 shows an example multi-Tx WPT setup, and the CDC for four Rx positions are illustrated in Fig. 4(b). Transfer distance of 15 mm is used for the calculations, and the theoretical mutual inductances are calculated using the circular loop approximation as presented in [13]. It can be seen that the Rx position can be easily and reliably estimated from the CDC. For instance, positions P1 and P4 are aligned to a single Tx,

Fig. 4. (a) An arrangement of a multi-Tx WPT pad. Four Rx positions P1, P2, P3, and P4 are analyzed, (b) current distribution coefficients (CDC) with respect to each Tx when the Rx is positioned at four reference positions P1, P2, P3, and P4.

and we can easily see a peak CDC for respective Tx coils. Similarly, P2 is in between two Tx's, and the distances from P3 to the three closest Tx's are the same, which can easily be understood by observing the CDC profile [Fig. 4(b)].

Furthermore, in case of multiple Rx's, the proposed approach can still be used as long as Rx's are not too close to each other. In such cases, we should analyze the profile of the mutual inductance ratios to isolate multiple Rx's. In principle, the proposed Rx positioning approach can be used with any transfer distance, however, measurement sensitivity can be affected when the transfer distance is very large due to the very small mutual inductances.

III. EXPERIMENTAL RESULTS

The proposed mutual inductance estimation approach is experimentally verified using a laboratory prototype of a 3-Tx WPT system. The parameters of the coils and the WPT setup are given in Table I. The experimental setup is shown in Fig. 5 and the arrangement of the Tx coils is illustrated in the inset. The position of the Rx coil is varied along the x -axis (inset of Fig. 5). For a given Rx position, each Tx is connected to an RF power amplifier and the induced voltages across the other two Tx coils are measured using an oscilloscope. Next, the measured voltages are used to estimate the mutual inductance ratios using Eq. (11). Finally, the optimal CDC, $\alpha_{1,2,3}$ are evaluated using Eq. (7). The measurement results are compared with the theoretical calculations in Fig. 6. It is obvious that the measurement results are in a very good agreement with the theoretical calculations. Measurements can be easily automated using a digital controller, but this is outside the scope of this paper. Different configurations of Tx coil arrangements and the performance characteristics will be discussed in detail in the full paper.

IV. CONCLUSION

In this paper, we have proposed and demonstrated a simple method for determination of the optimal excitation of multi-transmitter (Tx) WPT systems without any measurements from the receiver (Rx) side. The optimal Tx current distribution has been defined using the mutual inductance ratios between each Tx-Rx pair. The Tx coils are positioned to be uncoupled from adjacent Tx coils, so that the interactions between Tx coils are

TABLE I
THE PARAMETERS OF THE EXPERIMENTAL PROTOTYPE.

Coil Design	
Parameter	Value
Outer diameter	100 mm
Turns separation	4 mm
Number of turns	10
WPT setup	
Parameter	Value
Coil Inductance	6 μ H
Load	1 Ω
Operating frequency	3.58 MHz
Transfer distance	15 mm

Fig. 5. The experimental setup and the arrangement of the three Tx coils (inset).

Fig. 6. Experimental results: the optimal current distribution coefficient (CDC) variation with respect to Rx position in the x -direction.

kept minimal in the absence of receivers. The individual Tx coils are activated one-by-one and the induced voltage across the inactive Tx coils is measured. When the Rx is absent, the induced voltages across inactive Tx coils are close to zero due to the minimal coupling between the Tx's. On the other hand, when the receiver is present, the inactive Tx coils are coupled through the Rx, inducing voltage across them. By analyzing

the induced voltages, we estimate the mutual inductance ratios, and find the optimal current distribution in the Tx coils. The theoretical analysis is experimentally verified in a laboratory prototype. The proposed concept is not limited to the position detection of receivers in WPT systems. In general, it can be developed as a sensor to detect positions of any magnetically coupled intrusions.

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