Mutual Inductance Estimation of Multiple Input Wireless Power Transfer for Charging Electronic Equipment

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Abstract — The transmission performance of wireless power transfer is highly influenced by the mutual inductance \( M \) between the transmitter and the receiver. This paper proposes a mutual inductance estimation method for the multiple input coils wireless charging system which can be used in low-power portable devices such as mobile phones. The method can estimate \( M \) precisely and reliably without using empirical formulas and additional communication system. It simplifies the estimation process and achieves more accurate values of \( M \) under any conditions. Simulations and experimental results prove the proposed method has a good performance on estimating \( M \) at any circumstance.

1. INTRODUCTION
Wireless power transfer (WPT) is an emerging application area and is rapidly developing because it can make the power charging more flexible and safer than the traditional wired charging. To improve the wireless transmission power, a new type of WPT system is getting more and more attention: The multiple-input / single-output WPT (MISO-WPT) system. Several transmitter coils (Txs) can extend the transmission range and enhance the charging power to the receiver coil (Rx).

The key to charging electronic products using the MISO-WPT system is to accurately estimate the mutual inductance \( M \). The traditional M-estimation method uses empirical formulas based on relative positions between Txs and Rx to estimate \( M \), but such the method is not accurate enough as it is highly influenced by the environmental factors [1-3]. How to obtain the accurate relative position between Txs and Rx is also very difficult. Furthermore, Rx is installed at the bottom of the electronic product, and there are a large number of metal components near it, so the empirical formula is usually invalid. For example, to improve the transmission efficiency, many papers [4, 5] use electromagnetic metamaterials to reduce electromagnetic losses. Metamaterial is a special material with negative permeability, which can amplify the evanescent wave, thereby reducing electromagnetic loss and indirectly interfering \( M \) between Txs and Rx. Therefore, accurately estimating \( M \) becomes a difficulty in achieving effective wireless charging.

To tackle with the issue, some researchers use RF communication devices to send the Rx’s voltage/current information to the Txs side, and then estimate \( M \). [6-8] apply RF devices to transfer all current and voltage information of both Txs and Rx to the controller, and then calculate the \( M \) in the computer. The method must use many sensors which will increase the complexity of the system. [9] gives an excellent idea of estimating \( M \) in several configurations of wireless power transfer system, using information from only one side, either the transmitting side or the receiving side, of the system. But such the method must rely on the RF devices, which both sides of the system should be installed additional communication devices. Hence, such the method makes the system more complicated and
takes up more space, which makes it unsuitable for wireless charging of devices such as mobile phones.

Most modern electronic devices like mobile phones are compact devices. There is no extra space to place complex energy receiving devices. The better design idea should be to simplify the circuit at the Rx side as much as possible and move the circuit to the Tx side as much as possible. Therefore, it is preferable that the mutual inductance can be estimated only on the Tx side.

This paper proposes a M-estimation method and a M-estimation circuit for the MISO-WPT system, which can estimate all mutual inductances between Txs and Rx precisely at one time. The method only relies on the information on the Tx side to estimate $M$ without using any additional communication system and empirical formula. A small number of parameters are used in the M-estimation process to make the results more precise and reliable.

2. THE MISO-WPT SYSTEM

Fig. 1 shows the schematic of proposed MISO-WPT system with n Txs and a Rx. Txs are installed under the desk and Rx is attached to the bottom of the device. Every Tx gets power from the transmission line through a DC-AC$_i$ converter to transmit power for charging Rx. Tx can be disconnected by switching the Single Pole Double Throw Switch (SPDT) $S_i$ from the DC-AC$_i$ to the M-estimation branch. Each M-estimation branch is composed of a resistor $R_i$ and a Hall current sensor which can be used to estimate $M$. Rx is connected to the load circuit which is composed of a bidirectional single-phase AC-DC converter and a bidirectional Buck-Boost converter. Rx is also installed a

![Figure 1. Equivalent circuit for the MISO-WPT system](image)

![Figure 2. The control block for Rx bidirectional AC-DC converter applying the M-estimation mode](image)
The MISO-WPT system can work into two modes: The M-estimation mode and the charging mode. The M-estimation mode can estimate $M$ precisely and the charging mode can charge Rx with a maximum output power. In this paper, we only talk about the M-estimation mode.

The M-estimation mode: Switch SPDT $S_i$ to the M-estimation branch; Rx are driven by the load circuit and the load battery $V_b$ to generate the electromagnetic field for coupling to Txs. In this mode, $R_e$ is connected into the Rx's circuit for preventing Rx from overloading; The transistor Q_B1 is turned off and the Rx controller controls the transistor Q1, Q2, Q3, Q4 and Q_B2 to invert battery's DC voltage $V_b$ back to AC power for driving Rx with a certain current $I_E$. The control block is shown in Fig. 2.

In most cases, the battery voltage $V_B$ is not constant, so it must be converted to a certain value $V_{ref}$ by using the bidirectional Buck-Boost converter before it can be inverted into a set AC current $I_E$.

3. ESTIMATE MUTUAL INDUCTANCES

3.1 The M-estimation method

First, estimate mutual inductance $M_1, ..., M_n$ between Txs and Rx. Normally, we energize Txs to generate magnetic fields. The Rx, brought very close to Txs, would resonate and reflect an equivalent impedance to Txs. The reflected impedance contains the information of mutual inductance which can be computed by using the Kirchhoff’s law. However, such the method cannot be adopted to estimating the mutual inductance in the wireless charging system as Txs and Rx are not always well-coupled. If Txs and Rx are decoupled (for example, Rx is far from Txs), the drive voltage will be fully loaded on Tx’s internal resistance ($Z_i$). The current will be overloaded instantly. Although we can apply small enough voltages on Txs, the magnetic fields they generate will be too weak to estimate the mutual inductance if the distances between Txs and Rx are close.

As Fig. 1 shown, this paper proposes a new method which uses Rx to generate a magnetic field for coupling Txs by switching the MISO-WPT system to the M-estimation mode.

If Txs are nearby, they will experience the electromagnetic field to generate induced current $I_i$ on circuits and then be captured by the Hall current sensors.

Based on Kirchhoff’s law, the system satisfies the equations:

$$
\begin{align*}
\begin{bmatrix} \vec{v}_T \\ \vec{i}_T \end{bmatrix} &= \begin{bmatrix} M_{T1} & M_{T2} \\ M_{T2}^T & R_m \end{bmatrix} \begin{bmatrix} I_E \\ i_T \end{bmatrix} \\
\begin{bmatrix} \vec{v}_T \\ \vec{i}_T \end{bmatrix} &= \begin{bmatrix} Z_R + R_e \end{bmatrix} I_E = M_{T2}^T i_T 
\end{align*}
$$

(1)

Shown in TABLE. I, $M_{T2}$ contains the information of all Txs which can be calculated in advance. So, the mutual inductance between Txs and Rx ($M_{T2}$) can be expressed as:

$$
M_{T2} = \frac{1}{I_E} (R_m + M_{T1}) i_T
$$

(2)

$i_T$ can be detected by Hall current sensors, $M_{T1}$, $R_m$ and $I_E$ are set values. So $M_{T2}$ can be calculated at one time.

This method brings two obvious advantages compared to the method of energizing Txs circuit to couple to Rx:

| Term | Definition |
|------|------------|
| $\vec{v}_T$ | $[V_1, \ldots, V_n]^T$ |
| $\vec{i}_T$ | $[I_1, \ldots, I_n]^T$ |
| $M_{T1}$ | $\begin{bmatrix} Z_1 & j\omega M_{12} & \cdots & j\omega M_{1n} \\ j\omega M_{12} & Z_2 & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ j\omega M_{1n} & \cdots & \cdots & Z_n \end{bmatrix}_{n\times n}$ |
| $M_{T2}$ | $\begin{bmatrix} j\omega M_{1}, \cdots, j\omega M_n \end{bmatrix}^T$ |
| $R_m$ | diag$(R_1, \ldots, R_n)$ |
Save power. Txs are usually loosely installed under the desk in a wider range. If we use Tx coupling to Rx, when the laptop is placed on the table, the system will not know the exact location of the laptop, so all Txs must be activated to "find" Rx. In contrast, this method uses Rx to couple to the sleeping Txs, only some Txs near Rx can be activated and prepare to transmit power.

- Make the estimation more precise and improve the estimation speed. The values of induced current $\vec{I}$ on Txs is small enough, so the coupling between the Txs will not affect the accuracy of mutual inductance estimation much. Moreover, this method can estimate all values at one time, so the M-estimation speed is also fast.

3.2 Calculate the matrix $M_{T_2}$

Once all Txs have been designated and installed completely, the mutual inductance among Txs are constant and the matrix $M_{T_1}$ can be measured in advance.

As Fig. 1 shows, remove Rx out of the MISO-WPT and only consider n Tx. Connect the $i^{th}$ Tx to the AC voltage source and the $k^{th}$ Tx to the M-estimation branch, then leave all other Txs open-circuit. Apply an AC voltage $V_i'$ on $i^{th}$ Tx and then monitor current value of the $k^{th}$ Tx $I_k'$ ($1 \leq k \leq n; k \neq i$).

Similar to the previous analysis, the value of $j \omega M_{ik}$ between the two Txs can be expressed as:

$$
\begin{align*}
V_i' &= I_i'(Z_i + R_i) - j \omega M_{ik} I_k' \\
I_k'(Z_k + R_k) &= j \omega M_{ik} I_i'
\end{align*}
$$

(3)

solve equation (3) we can have:

$$
(j \omega M_{ik})^2 I_k' + j \omega M_{ik} V_i' = I_i'(Z_i + R_i)(Z_k + R_k)
$$

(4)

From the equation (4), the absolute value of $|j \omega M_{ik}|$ between the $i^{th}$ and $k^{th}$ Txs can be calculated. Apply the method to other pairs of Txs, the matrix $M_{T_2}$ will be achieved.

4. EXPERIMENT RESULTS

4.1 The M-estimation test without interference

To validate the proposed M-estimation method, a small MISO-WPT system with 5 Txs and a Rx is established. The picture and the configuration of the system is shown in Fig. 3 and TABLE. II, respectively.

Place Rx at (-0.1, 0.2, 0.05) m as Fig. 3(a) shows. Control the Buck-Boost circuit and the bidirectional AC-DC converter on Rx side to generate a current $I_E$ to drive Rx. Here, $I_E$ is a square wave which the amplitude is 10 A. Then, measure every Tx’s induced current $I_i$. Fig. 4 shows the experimental results of $I_i$ on each Tx. It shows the different relative positions reflect different induced currents, and the different induced currents reflect the different values of mutual inductance between every pair of Tx and Rx.

Amplify the current waveform of Tx3 (shown in Fig. 5). The current curve is complete without major distortion. It proves that the current will not be interfered too much by other Tx, thus ensuring the reliability of the M-estimation method.

Substitute $I_i$ into Eq. (2) for estimating $M$, the results show in TABLE. III. The measured value represents the $M$ measured by the Mutual Inductance Measuring Instrument.
Figure 3. The relative position and the picture of the MISO-WPT system.

Figure 4. The experimental voltage results of each Tx when Rx is at (-0.1, 0.2, 0.05) m.

Figure 5. The current curve of Tx3

TABLE. II Parameters of the system

| Item                          | Value                            |
|-------------------------------|----------------------------------|
| Resonant frequency           | 84.6 KHz                         |
| L and H of coils              | L=680 nF, H=5.2 µH               |
| Diameter of coils             | 0.2 m                            |
| Internal resistances of coils | 0.3 Ω                            |
| Resistor $R_E$                | 10 Ω                             |
| Resistor $R_i$                | 10 Ω                             |
| Equivalent resistance $R_L$  | 20 Ω                             |
| Cross-sectional area of the wire | 2.5 mm$^2$         |

TABLE. III The estimated M v.s. the measured M when Rx is at 3 different positions ($\times 10^{-6}$H).

| Positions | Item     | Tx1 | Tx2 | Tx3 | Tx4 | Tx5 |
|-----------|----------|-----|-----|-----|-----|-----|
| (-0.1, 0.2, 0.5) m | Estimated value | 0.14 | 0.07 | 0.1 | 0.38 | 0.61 |
|           | Measured value     | 0.14 | 0.08 | 0.12 | 0.40 | 0.62 |
| (0, 0.5) m    | Estimated value    | 0.28 | 0.28 | 0.28 | 0.28 | 0.95 |
|           | Measured value     | 0.30 | 0.30 | 0.30 | 0.30 | 0.95 |
| (0.5, 0.5) m  | Estimated value    | 0.46 | 0.45 | 0.07 | 0.07 | 0.55 |
|           | Measured value     | 0.47 | 0.47 | 0.08 | 0.07 | 0.56 |
TABLE. III indicates that the error between the estimated value and the measured value is very tiny, which shows the M-estimation method can estimate the mutual inductance precisely at any relative positions.

4.2 The M-estimation test with the interference

The most important advantage of the proposed method is to estimate $M$ precisely under any circumstance. In this section, we will testify if the proposed method can precisely estimate the mutual inductance when it is interfered by metal components.

![Figure 6. The relative position of the system.](image)

![Figure 7. The picture of the experiment.](image)

A MISO-WPT system with 2 Tx and a Rx is built and the configuration of the coil is the same as the previous system. Between Tx and Rx, 3 metamaterial slabs are added to interfere $M$ (The metamaterial can enhance the coupling to improve the transmission power [10]). The relative position and the picture of the system are shown in Fig. 6 and Fig. 7.

![Figure 8. The value measured by different method with different rotation angle $\alpha$.](image)
Metamaterial slabs are always parallel to Txs and Rx. In the test, rotate Txs to change $M$. To simplify the test, the deflection angle $\alpha$ of the two Txs are always the same. Fig. 8 shows the mutual inductance values under different M-estimation methods with various $\alpha$ (0º ~ 90º).

As Fig. 8 indicates that the $M$ estimated by the proposed method are closest to the values measured by the Mutual Inductance Measuring Instrument. However, the value estimated by the empirical formula [2] exists the large error. This is because empirical formula cannot fully consider the environment interference (metamaterial slabs) around the system.

Measure the value of $M$ again using the instrument after removing metamaterials. We can find the values of $M$ measured by three methods are very close. It proofs the proposed method can estimate $M$ at any circumstance.

5. CONCLUSION
This paper proposes a M-estimation method for the MISO-WPT system. It can estimate $M$ in a simple and accurate way instead of using empirical formulas to roughly estimate or relying on additional RF devices between Txs and Rx. By using Rx to generate magnetic field for coupling Txs, not only the risk of overload on Txs is avoided but also improves estimation accuracy. The tests also prove the proposed method can precisely estimate $M$ at any circumstance.

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