Article

Adaptive Impedance Matching Scheme for Magnetic MIMO Wireless Power Transfer System

Ziyang Lu ¹ , Yubin Zhao ¹ and Dunge Liu ^{2,*}

¹ School of Microelectronics Science and Technology, Sun Yat-sen University, Zhuhai 519082, China; luzy3@mail2.sysu.edu.cn (Z.L.); zhaoyb23@mail.sysu.edu.cn (Y.Z.)

² State Key Laboratory of Space-Ground Integrated Information Technology, Space Star Technology Co., Ltd., Beijing 100041, China

* Correspondence: zkylunge@163.com

Abstract: In coupled magnetic resonance (CMR) wireless energy transfer systems, the energy transfer power is low and the power transfer efficiency changes with the coil position. One reason for this reduction in power and efficiency is the impedance mismatching (IM) between the Tx and Rx coils; achieving impedance matching for multiple-input multiple-output (MIMO) CMR IM wireless power transmission (WPT) is quite complex due to the uncertainty in the number of coils and the interaction between coils. In this paper, we provide an analytical model of MIMO CMR which fully formulates the complex relationship between multiple Tx and Rx channels. Then, we design an impedance matching network (IMN) for MIMO CMR and derive an optimal IM solution. Based on this solution, we also develop an adaptive impedance matching scheme to control IMN, based on an automatic analysis of MIMO CMR system; the resulting control scheme achieves optimal values for transmission power and efficiency through IMN and coil selection. The simulation results indicate that the scheme is able to automatically adjust the impedance matching network according to the changes of the relative positions between Tx and Rx coils to achieve high energy transfer power and efficiency.

Keywords: multi-coil; wireless power transmission; coupled magnetic resonance; adaptive impedance matching

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1. Introduction

With the prevalence of electronic devices in daily life, the limitations of wired energy transmission have become increasingly apparent. Wireless power transfer (WPT) has gained widespread popularity as it reduces reliance on wired connections. WPT can be divided into three main categories: magnetic induction [1], coupled magnetic resonance [2] and microwave radiation [3]. Among them, CMR offers unique advantages, as it has higher transfer distance and power transfer efficiency [4,5]. In [6], Karalis et al. demonstrated that CMR can achieve 40% wireless power transfer efficiency (PET) at a distance of 2m. Thus, CMR technology has a variety of potential applications, e.g., sensors, wearable mobile devices [7] and electronic vehicles [8].

However, energy distance and efficiency are still in need of further improvement. Single Tx and Rx CMR not only has low energy transfer distance and efficiency, but the application range is also limited. Recently, multiple-input multiple-output (MIMO) has been proposed. Based on the number of coils, CMR can be divided into single-input single-output (SISO), single-input multiple-output (SIMO), multiple-input single-output (MISO) and MIMO. Jadidian et al. proposed the idea of MIMO CMR systems, which attracted significant attention within the field [4]. Nguyen et al. investigated the effect of MIMO WPT system on the transmitting power [9], while Aoki et al. have calculated the maximum transmitting efficiency of MIMO WPT [10]. In addition Lang et al. proposed that MIMO can transfer higher power than SISO or SIMO [11]. Compared to the other

CMR models, MIMO is able to carry multiple users at the same time while achieving high energy transfer power.

Impedance mismatch is the main problem for CMR. Input impedance of the system varies with the position between the Tx and Rx coils. The input impedance of the system directly affects the variation of the reflection coefficient and thus the efficiency and energy transfer power [12]. Therefore, the impedance mismatch in CMR is a problem worth focusing on. Researchers have begun looking for ways to solve the impedance mismatch problem.

Impedance mismatch is not a novel problem. To solve the problem of impedance mismatch, several solutions have been proposed based on impedance mismatching networks (IMNs). Classical IMNs are divided into L-type, π -type and T-type networks [6]. Liu et al. proposed a one-side automated discrete impedance matching network system [13]. Kim et al. propose a impedance matching network for the case of one transmitter coupled to multiple receivers [14]; however, its application scope is small. Lee et al. have proposed an impedance matching analysis method for CMR systems containing multiple repeaters [15], while Li et al. have used a BP neural network to realize impedance match [16]. Jeong et al. have used neural networks and IMN techniques to achieve coil selection that maximises power transfer efficiency [17]. Zhai et al. have achieved impedance matching by changing the operating frequency of the system. [18]. Kin et al. have achieved impedance matching by using automated source frequency tracking [19], but this method shows slow response. Lee et al. have used π -type impedance matching networks for wireless energy transfer [20]. Lu et al. have used printed spiral coils with impedance matching networks for wireless energy transfer [21]. Fujiki et al. have applied impedance matching networks to wireless energy transmission systems with repeaters for the purpose of reducing frequency splitting [22]. Boo et al. have proposed an analysis and impedance matching optimization of a wireless energy transfer system with a rotating coil [23]; however, it can only be used on SISO CMR systems.

Conventional SISO CMR systems are unable to fulfil high-powered energy transmission and flexible user-side combinations requirements. Impedance mismatch is more complex in MIMO. The circuit composition of MIMO is more flexible and the input impedance is affected by multiple coils, which are entangled together, making it complex to calculate the input impedance and analyse the IM for MIMO. IM in MIMO has yet to be fully investigated.

In this paper, we solve the problem of constructing a complex IM model for MIMO CMR system. The main contributes of this paper are as follows:

- We propose an analytical model which thoroughly addresses the complexity of the MIMO CMR system. The MIMO CMR system model can simulate and calculate the current and voltage values of the MIMO CMR system before and after impedance matching.
- Based on the MIMO CMR system model, we design an impedance matching network (IMN) and derive an optimal impedance matching (IM) solution.
- We also propose an adaptive impedance matching scheme for magnetic MIMO wireless power transfer system. The scheme, which is based on an analytical model of MIMO CMR system, achieves optimal values for transmission power and efficiency through IMN and coil selection. Our proposed scheme is able to automatically adjust the impedance matching network according to the change in relative position between the Tx and Rx coils to achieve high energy transfer power and efficiency. The simulation results indicate that a MIMO CMR system with IMN can achieve higher energy transfer power and efficiency than a MIMO CMR system without IMN.

In the rest of the paper, we analyze the MIMO CMR system in Section 2. Based on this, the problem simulation of power transfer efficiency and MIMO-IM is presented in Section 3. We design a IMN for MIMO CMR system and derive a theoretical approach for achieving MIMO CMR system IM in Section 4. We design an automatic control scheme

for optimal values of transmission power and efficiency through IMN and coil selection in Section 5. The final simulation results are presented in Section 6.

2. System Model

The circuit diagram of a MIMO CMR system is shown in Figure 1. The power source provides AC voltage and the internal resistance is equivalent to $Z_S = R_S$. The Tx consists of a resonant capacitor C_T , a resistance R_T and a Tx coil with inductance L_T . Similarly, the receiver consists of a Rx coil with a resonant capacitor C_R , the resistance R_R and the inductance L_R of the Rx coil. The input impedance varies with the mutual inductance M , which relates to the position and distance between the transmitting and receiving coils, and results in an impedance mismatch. At the same time, the addition of multiple coils results in coils coupling to each other, making the input impedance Z_{in} analysis more complex.

Figure 1. MIMO CMR system.

Assuming that the current went through the N th transmitter coil is I_N and the current went through the K th receiver coil is I_{LK} . Since the system operates in resonance, based on Kirchhoff's voltage law (KVL), we have expressions of every circuit:

Tx:

$$\left\{ \begin{array}{l} V_1 = I_1 R_{T1} + I_1 R_S + \sum_{i \neq 1}^N j\omega M_{T_1 T_i} I_i - \sum_{i=1}^K j\omega M_{T_1 R_i} I_{Li} \\ \vdots \\ V_N = I_N R_{TN} + I_N R_S + \sum_{i \neq N}^N j\omega M_{T_N T_i} I_i - \sum_{i=1}^K j\omega M_{T_N R_i} I_{Li} \end{array} \right. \quad (1)$$

Rx:

$$\left\{ \begin{array}{l} \sum_{i=1}^N j\omega M_{T_i R_1} I_i - \sum_{i \neq 1}^K j\omega M_{R_i R_1} I_{Li} = I_{L1} (R_{L1} + R_{R1}) \\ \vdots \\ \sum_{i=1}^N j\omega M_{T_i R_K} I_i - \sum_{i \neq K}^K j\omega M_{R_i R_K} I_{Li} = I_{LK} (R_{LK} + R_{RK}) \end{array} \right. \quad (2)$$

where M was mutual inductance, V was voltage of source and I was current. Equation (1) is expression of Tx circuits and Equation (2) is expression of Rx circuits. By changing Equations (1) and (2) into matrix form, we can obtain Equations (3) and (4).

Tx:

$$\mathbf{V} = \begin{bmatrix} R_{T1} + R_S & j\omega M_{T_1 T_2} & \cdots & j\omega M_{T_1 T_N} \\ j\omega M_{T_2 T_1} & R_{T2} + R_S & \cdots & j\omega M_{T_2 T_N} \\ \vdots & \vdots & \ddots & \vdots \\ j\omega M_{T_N T_1} & j\omega M_{T_N T_2} & \cdots & R_{TN} + R_S \end{bmatrix} \times \mathbf{I} - \begin{bmatrix} j\omega M_{T_1 R_1} & \cdots & j\omega M_{T_1 R_K} \\ j\omega M_{T_2 R_1} & \cdots & j\omega M_{T_2 R_K} \\ \vdots & \ddots & \vdots \\ j\omega M_{T_N R_1} & \cdots & j\omega M_{T_N R_K} \end{bmatrix} \times \mathbf{I_L} \quad (3)$$

Rx:

$$\begin{bmatrix} j\omega M_{T_1 R_1} & j\omega M_{T_2 R_1} & \cdots & j\omega M_{T_N R_1} \\ \vdots & \vdots & \ddots & \vdots \\ j\omega M_{T_1 R_K} & j\omega M_{T_2 R_K} & \cdots & j\omega M_{T_N R_K} \end{bmatrix} \times \mathbf{I} \\ = \begin{bmatrix} (R_{L1} + R_{R1}) & \cdots & j\omega M_{R_K R_1} \\ \vdots & \ddots & \vdots \\ j\omega M_{R_1 R_K} & \cdots & (R_{LK} + R_{RK}) \end{bmatrix} \times \mathbf{I_L} \quad (4)$$

where Tx voltage vector was $\mathbf{V} = [V_1 \ V_2 \ \cdots \ V_N]^T$, Tx current vector was $\mathbf{I} = [I_1 \ I_2 \ \cdots \ I_N]^T$ and Rx current vector was $\mathbf{I_L} = [I_{L1} \ I_{L2} \ \cdots \ I_{LK}]^T$. Substituting Equation (4) into Equation (3) and simplifying it we get Equation (5)

$$\mathbf{I} = (\mathbf{T_{z1}} - \mathbf{T_{z2}}\mathbf{T_{z3}}^{-1}\mathbf{T_{z4}})^{-1} \mathbf{V} \quad (5)$$

where matrix $\mathbf{T_{z1}}$, $\mathbf{T_{z2}}$, $\mathbf{T_{z3}}$ and $\mathbf{T_{z4}}$ are the matrices used to simplify the operation, which include all information of the system as showed below.

$$\left\{ \begin{array}{l} \mathbf{T_{z1}} = \begin{bmatrix} R_{T1} + R_S & j\omega M_{T_1 T_2} & \cdots & j\omega M_{T_1 T_N} \\ j\omega M_{T_2 T_1} & R_{T2} + R_S & \cdots & j\omega M_{T_2 T_N} \\ \vdots & \vdots & \ddots & \vdots \\ j\omega M_{T_N T_1} & j\omega M_{T_N T_2} & \cdots & R_{TN} + R_S \end{bmatrix} \\ \mathbf{T_{z2}} = \begin{bmatrix} j\omega M_{T_1 R_1} & \cdots & j\omega M_{T_1 R_K} \\ j\omega M_{T_2 R_1} & \cdots & j\omega M_{T_2 R_K} \\ \vdots & \ddots & \vdots \\ j\omega M_{T_N R_1} & \cdots & j\omega M_{T_N R_K} \end{bmatrix} \\ \mathbf{T_{z3}} = \begin{bmatrix} (R_{L1} + R_{R1}) & \cdots & j\omega M_{R_K R_1} \\ \vdots & \ddots & \vdots \\ j\omega M_{R_1 R_K} & \cdots & (R_{LK} + R_{RK}) \end{bmatrix} \\ \mathbf{T_{z4}} = \begin{bmatrix} j\omega M_{T_1 R_1} & j\omega M_{T_2 R_1} & \cdots & j\omega M_{T_N R_1} \\ \vdots & \vdots & \ddots & \vdots \\ j\omega M_{T_1 R_K} & j\omega M_{T_2 R_K} & \cdots & j\omega M_{T_N R_K} \end{bmatrix} \end{array} \right. \quad (6)$$

The total impedance can be obtained by dividing the supply voltage V by the current I obtained from Equation (5). The total impedance minus the internal resistance of the supply R_S can obtain the input impedance Z_{in} . The expression of input impedance Z_{in} is shown in Equation (7).

$$Z_{in} = \frac{V}{I} - R_S \quad (7)$$

where voltage V and current I follows Equation (5) according by the mutual inductance M . Therefore, when the coil position is changed, the mutual inductance M changes, which in turn changes the input impedance Z_{in} .

3. Problem Formulation

3.1. Power Transfer Efficiency

Power transfer efficiency of the CMR system η_{sys} is very important. Figure 2 shows the equivalent circuit diagram of the CMR system. The energy from the AC source is transferred to the load resistor through the mutual inductance M_{TR} between the Tx coil and the Rx coil. The power from AC source P_S , the input power P_{in} , the output power P_{out} and the load received power P_{load} are shown in Figure 2. The power transfer efficiency is obtained from Equation (8).

$$\eta_{sys} = \eta_{match} \eta_{trans} \eta_{rec} = \frac{P_{in}}{P_S} \times \frac{P_{out}}{P_{in}} \times \frac{P_{load}}{P_{out}} = \frac{P_{load}}{P_S} \quad (8)$$

where η_{match} , η_{trans} and η_{rec} are the matching system efficiency, transmission system efficiency and receiving efficiency, respectively. The expression of matching system efficiency η_{match} is illustrated in Equation (9).

$$\eta_{match} = 1 - |S_{11}|^2 = \frac{4Z_{in}R_S}{(Z_{in} + R_S)^2} = \left(1 - \frac{IR_S}{V}\right) \frac{4IR_S}{V} \quad (9)$$

where S_{11} is the S parameter of the matching network; Z_{in} is the input impedance; V is the Tx voltage; I is the Tx current; R_S is the internal resistance of the power supply. From Equation (9), when $Z_{in} = R_S$, the optimal value of $S_{11} = 0$, and the maximum value of η_{match} can be obtained the matching system efficiency $\eta_{match} = 1$. When $Z_{in} \neq R_S$, $S_{11} \neq 0$, the matching system efficiency η_{match} is not optimal, $\eta_{match} < 1$, and the power transfer efficiency of the WPT system η_{sys} cannot reach the maximum value. Thus, the major problem of our paper is to adjust Z_{in} to achieve maximum η_{sys} .

Figure 2. Equivalent circuit diagram of the CMR system.

3.2. Impedance Matching

To solve impedance mismatching problem, the IMN is used. Compared with other types of networks, L-type network is simple in structure and have a considerable range of variation. However, L-type IMN cannot be used in high-frequency areas. This disadvantage is neglected because the MIMO CMR system model we constructed is not in the high-

frequency area. We apply L-type IMN in the MIMO CMR system. The L-type impedance matching network can be subdivided into two types: the L-type IMN and the reverse L-type IMN, which is demonstrated in Figure 3. Because there are branches in the L-type IMN circuit, and the branches will make the coil current different from the power source current, it is quite complicated to analyze the energy transfer after adding IMN. The L-type IMN and the reverse L-type IMN are used in different situations. L-type IMN is used when Tx coil closed to Rx coil. Reverse L-type IMN is used frequently when Tx coil stay away from Rx coil.

Figure 3. L-type IMN and reverse L-type IMN.

When $\Re(Z_{TX}) > R_S$, an L-type IMN is used, and in order to achieve impedance matching ($Z_{in} = R_S$), the component parameters in the IMN should satisfy Equation (10).

$$R_S = \frac{1}{jB + \frac{1}{Z_{TX}}} + jX \quad (10)$$

where Z_{TX} represents the equivalent impedance on the right side of the IMN; R_{TX} and X_{TX} represent the real and imaginary parts of Z_{TX} . By separating the real and imaginary parts of Equation (10), we obtain the component parameters X and B of the L-type IMN, where B is included in X .

$$X = \frac{1}{B} + \frac{R_S X_{TX}}{R_{TX}} - \frac{R_S}{B R_{TX}} \quad (11)$$

$$B = \frac{X_{TX} \pm \sqrt{R_{TX}/R_S} \sqrt{R_{TX}^2 + X_{TX}^2 - R_S R_{TX}}}{R_{TX}^2 + X_{TX}^2} \quad (12)$$

Conversely, when $\Re(Z_{TX}) < R_S$, a reverse L-type IMN is a better choice, and the component parameters in the IMN are, thus, varied and satisfy Equation (13).

$$\frac{1}{R_S} = \frac{1}{jX + R_{TX} + jX_{TX}} + jB \quad (13)$$

By separating the real and imaginary parts of Equation (13), we obtain the component parameters X and B of the reverse L-type IMN.

$$X = \pm \sqrt{R_{TX}(R_S - R_L)} - X_{TX} \quad (14)$$

$$B = \pm \frac{\sqrt{(R_S - R_{TX})/R_{TX}}}{R_S} \quad (15)$$

From Equation (10) to Equation (15), it can be seen that the component parameters X and B of IMN are influenced by the equivalent impedance Z_{Tx} on the right side of IMN, and when Z_{Tx} changes, X and B change as well.

3.3. MIMO System Impedance Matching Network

From Equation (10) to Equation (15), it can be seen that the values of component parameters X and B are only affected by their respective equivalent impedance Z_{Tx} and not by the other coils. Therefore, the IMN of each transmitter can be analyzed independently. The analysis and calculation of impedance matching networks are relatively independent. Therefore, the IMN of each Tx coil behaves as two types, each corresponding to the L-type impedance matching network and the reverse L-type impedance matching network proposed in the previous section.

To reduce the space of the IMN, we use the IMN model shown in Figure 4, which consists of two inductance matrices and one capacitance matrix. As shown in Figure 4, by controlling single-pole multiple-throw switches, the inductance matrix and capacitance matrix are combined with each other to be able to form different impedance matching networks. By pre-simulation shown in Section 5, at a coil distance of 0.001 m to 0.5 m, the component of capacitor matrix B range from 40 pF to 15 nF, the component of inductor matrix X_L range from 270 nH to 12 μ H, and the component of inductor matrix X_{RL} range from 29 nH to 550 nH. All of the components are cheap and easy to get. From the application point of view, the use of simple and inexpensive components to achieve optimal transmission efficient and transmission energy is feasible and effective. In order to achieve impedance matching, the component parameters of the IMN should satisfy Equation (16).

$$R_S = jX_L + \frac{1}{jB + \frac{1}{jX_{RL} + Z_{TX}}} \quad (16)$$

Equation (16) shows that at $\Re(Z_{Tx}) > R_S$, the IMN behaves as a L-type IMN by shorting X_{RL} , i.e., $X_{RL} = 0$. The IMN component parameters are expressed in Equation (17).

$$\begin{cases} X_L = \frac{1}{B} + \frac{R_S X_{TX}}{R_{TX}} - \frac{R_S}{B R_{TX}} \\ X_{RL} = 0 \\ B = \frac{X_{TX} \pm \sqrt{R_{TX}/R_S} \sqrt{R_{TX}^2 + X_{TX}^2 - R_S R_{TX}}}{R_{TX}^2 + X_{TX}^2} \end{cases} \quad (17)$$

Similarly, when $\Re(Z_{Tx}) < R_S$, the IMN behaves as a reverse L-type IMN by shorting X_L , i.e., $X_L = 0$. The IMN component parameters are expressed in Equation (18).

$$\begin{cases} X_L = 0 \\ X_{RL} = \pm \sqrt{R_{TX}(R_S - R_L)} - X_{TX} \\ B = \pm \frac{\sqrt{(R_S - R_{TX})/R_{TX}}}{R_S} \end{cases} \quad (18)$$

As shown in Equations (17) and (18), we can obtain the L-type IMN by shorting X_{RL} . Similarly, we can obtain the reverse L-type IMN by shorting X_L . In order to analyze the effect of IMN on the power transfer efficiency of the MIMO CMR system. We choose the IMN component parameters X_L , X_{RL} and B to maximize the transfer efficiency η_{sys} .

$$(X_L, X_{RL}, B) = \arg \max \eta_{sys}$$

$$s.t. \quad \Re(Z_{Tx}) > 0.$$

where $\Re(Z_{Tx}) > 0$ means that the Tx coils must only transfer energy. If the appropriate, X_L , X_{RL} and B are selected according to Equations (17) and (18), input impedance $Z_{in} = R_S$ can be obtained, and thus the power transfer efficiency of the WPT system η_{sys} reaches the highest value. Therefore, we only need to analyze the calculation of the impedance matching network to obtain the general equation for the L-type IMN and the reverse L-type IMN.

Figure 4. Pseudo-T-type impedance matching network.

4. Optimal MIMO Impedance Matching Solution

The coupling of multiple coils can make the calculation of impedance matching very complex. A brief circuit diagram of MIMO CMR system impedance matching is shown in Figure 5. From the diagram we can see that each transmitting coil is equipped with an impedance matching network, and each impedance matching network is analyzed and calculated independently of the other impedance matching networks. The power source I and the transmitter coil current I' are shown in Figure 5.

Figure 5. Impedance matching networks for MIMO CMR system.

The impedance matching of the MIMO system can be achieved by using the IMN of Figure 4 in the MIMO system of Figure 5. Take the l th Tx for instance, where $l \in \{1 \cdots N\}$. Based on KVL, the expression of the l th Tx is shown in Equation (19).

The l th Tx:

$$\begin{cases} V_l = I_l R_S + jX_{Ll} I_l + \frac{I_l}{jB_l} - \frac{I'_l}{jB_l} \\ \frac{I_l}{jB_l} = \frac{I'_l}{jB_l} + I'_l R_{Tl} + jX_{RLl} I'_l + \sum_{i \neq l}^N j\omega M_{T_l T_i} I'_i - \sum_{i=1}^K j\omega M_{T_l R_i} I_{Li} \end{cases} \quad (19)$$

where V_l is the voltage of the voltage source; I_l is the current flowing through the voltage source; I'_l is the Tx coil current; X_{Ll} , X_{RLl} , and B_l are all component parameters of IMN; M_{TR} is the mutual inductance between Tx and Rx; M_{TT} is the mutual inductance between Tx and Tx; R_S is the internal resistance of the voltage source; and R_T is the resistance of the Tx coil.

Take the p th Rx for instance, where $p \in \{1 \cdots K\}$. Based on KVL, the expression of current and voltage relationship for the p th Rx is shown in Equation (19). It shows that Tx coil is influenced by other Tx coils and Rx coils.

The p th Rx:

$$\sum_{i=1}^N j\omega M_{T_i R_p} I'_i - \sum_{i \neq p}^K j\omega M_{R_p R_i} I_{Li} = I_{Lp} (R_{Lp} + R_{Rp}) \quad (20)$$

where I_{Lp} is the current flowing through the Rx coil; I'_p is the current flowing through the Tx coil; M_{TR} is the mutual inductance between Tx and Rx; M_{RR} is the mutual inductance between Rx and Rx; R_{Lp} is the load resistance; and R_{Rp} is the resistance of the Rx coil. Equation (20) present that Rx coil is influenced by other Tx coils and Rx coils.

By changing Equations (19) and (20) into matrix form, we can obtain Equations (21) and (22).

$$\mathbf{T_x: I'} = \begin{bmatrix} G_1 & 0 & \cdots & 0 \\ 0 & G_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & G_N \end{bmatrix} \mathbf{I} - \begin{bmatrix} jB_1 & 0 & \cdots & 0 \\ 0 & jB_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & jB_N \end{bmatrix} \mathbf{V} \quad (21)$$

$$\mathbf{R_x: \begin{bmatrix} \mathbf{I} \\ \mathbf{I_L} \end{bmatrix}} = \begin{bmatrix} D_1 & -S_1 M_{T_1 T_2} & \cdots & -S_1 M_{T_1 T_N} & S_1 M_{T_1 R_1} & \cdots & S_1 M_{T_1 R_K} \\ -S_2 M_{T_2 T_1} & D_2 & \cdots & -S_2 M_{T_2 T_N} & S_2 M_{T_2 R_1} & \cdots & S_2 M_{T_2 R_K} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \cdots & \vdots \\ -S_N M_{T_N T_2} & -S_N M_{T_N T_2} & \cdots & D_N & S_N M_{T_N R_1} & \cdots & S_N M_{T_N R_K} \\ F_1 M_{T_1 R_1} & F_1 M_{T_2 R_1} & \cdots & F_1 M_{T_N R_1} & 0 & \cdots & -F_1 M_{R_1 R_K} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ F_K M_{T_1 R_K} & F_K M_{T_2 R_K} & \cdots & F_K M_{T_N R_K} & -F_K M_{R_K R_1} & \cdots & 0 \end{bmatrix} \times \begin{bmatrix} \mathbf{I'} \\ \mathbf{I_L} \end{bmatrix} \quad (22)$$

where Tx current vector $\mathbf{I'} = [I'_1 \ I'_2 \ \cdots \ I'_N]^T$, the voltage source current vector $\mathbf{I} = [I_1 \ I_2 \ \cdots \ I_N]^T$, Tx voltage vector $\mathbf{V} = [V_1 \ V_2 \ \cdots \ V_N]^T$ and Rx current

vector $\mathbf{I}_L = [I_{L1} \ I_{L2} \ \cdots \ I_{LK}]^T$. Parameters G , D , S and F are used to simplify the operation, which is expressed in Equation (23).

$$\begin{cases} G_i = jB_i R_S - B_i X_{Li} + 1 \\ D_i = 1 - B_i X_{RLi} + jB_i R_{Ti} \\ S_i = B_i \omega \\ F_i = j\omega / (R_{L1} + R_{R1}) \end{cases} \quad (23)$$

Substituting Equation (22) into Equation (21) and simplifying it, we get Rx current vector in Equation (24) and the current vector went through the voltage source in Equation (25).

$$\mathbf{I}_L = \mathbf{T}_1^{-1} \mathbf{T}_2 (\mathbf{T}_3 + \mathbf{T}_4 \mathbf{T}_1^{-1} \mathbf{T}_2)^{-1} \mathbf{T}_5 \mathbf{V} = \mathbf{Y}_1 \mathbf{V} \quad (24)$$

$$\mathbf{I} = \mathbf{T}_6^{-1} [(\mathbf{T}_3 + \mathbf{T}_4 \mathbf{T}_1^{-1} \mathbf{T}_2)^{-1} + \mathbf{E}] \mathbf{T}_5 \mathbf{V} = \mathbf{Y}_2 \mathbf{V} \quad (25)$$

where each current vector is related to the voltage vector by expressions: $\mathbf{Y}_1 = \mathbf{T}_1^{-1} \mathbf{T}_2 (\mathbf{T}_3 + \mathbf{T}_4 \mathbf{T}_1^{-1} \mathbf{T}_2)^{-1} \mathbf{T}_5$, $\mathbf{Y}_2 = \mathbf{T}_6^{-1} [(\mathbf{T}_3 + \mathbf{T}_4 \mathbf{T}_1^{-1} \mathbf{T}_2)^{-1} + \mathbf{E}] \mathbf{T}_5$. Matrix $\mathbf{T}_1$, $\mathbf{T}_2$, $\mathbf{T}_3$, $\mathbf{T}_4$, $\mathbf{T}_5$ and $\mathbf{T}_6$ are used to simplify the operation, which showed in Equation (26). $\mathbf{E}$ is the expression of identity matrix.

$$\begin{aligned} \mathbf{T}_1 &= \begin{bmatrix} 1 & \cdots & F_1 M_{R_1 R_K} \\ \vdots & \ddots & \vdots \\ F_K M_{R_K R_1} & \cdots & 1 \end{bmatrix} \\ \mathbf{T}_2 &= \begin{bmatrix} F_1 M_{T_1 R_1} & F_1 M_{T_2 R_1} & \cdots & F_1 M_{T_N R_1} \\ \vdots & \vdots & \ddots & \vdots \\ F_K M_{T_1 R_K} & F_K M_{T_2 R_K} & \cdots & F_K M_{T_N R_K} \end{bmatrix} \\ \mathbf{T}_3 &= \begin{bmatrix} D_1 G_1 - 1 & -S_1 M_{T_1 T_2} G_1 & \cdots & -S_1 M_{T_1 T_N} G_1 \\ -S_2 M_{T_2 T_1} G_2 & D_2 G_2 - 1 & \cdots & -S_2 M_{T_2 T_N} G_2 \\ \vdots & \vdots & \ddots & \vdots \\ -S_N M_{T_N T_1} G_N & -S_N M_{T_N T_2} G_N & \cdots & D_N G_N - 1 \end{bmatrix} \\ \mathbf{T}_4 &= \begin{bmatrix} (S_1 M_{T_1 R_1}) G_1 & \cdots & (S_1 M_{T_1 R_K}) G_1 \\ (S_2 M_{T_2 R_1}) G_2 & \cdots & (S_2 M_{T_2 R_K}) G_2 \\ \vdots & \ddots & \vdots \\ (S_N M_{T_N R_1}) G_N & \cdots & (S_N M_{T_N R_K}) G_N \end{bmatrix} \\ \mathbf{T}_5 &= \text{diag} \left\{ [jB_1 \ jB_2 \ \cdots \ jB_N]^T \right\} \\ \mathbf{T}_6 &= \text{diag} \left\{ [G_1 \ G_2 \ \cdots \ G_N]^T \right\} \end{aligned} \quad (26)$$

The load received power and power transfer efficiency can be obtained from the relationship between the load current and the voltage of the voltage source shown in Equation (24). The load received power is shown in Equation (27).

$$\begin{aligned} \mathbf{P}_{\text{load}} &= \mathbf{I}_L \circ \overline{\mathbf{I}_L}^T \text{diag}\left\{ \begin{bmatrix} R_{L1} & R_{L2} & \cdots & R_{LK} \end{bmatrix}^T \right\} \\ &= \mathbf{Y}_1 \mathbf{V} \circ (\overline{\mathbf{Y}_1 \mathbf{V}})^T \text{diag}\left\{ \begin{bmatrix} R_{L1} & R_{L2} & \cdots & R_{LK} \end{bmatrix}^T \right\} \end{aligned} \quad (27)$$

where the load received power vector $\mathbf{P}_{\text{load}} = [P_{\text{load}}^1 \ P_{\text{load}}^2 \ \cdots \ P_{\text{load}}^K]^T$. $\overline{\mathbf{I}_L}$ is the Hermite matrix of $\mathbf{I}_L$. R_L is the load resistance of Rx. $\circ$ represent Hadamard product.

Similarly, according to the expression of the relationship between current and voltage in Equation (25), the power supply power can be obtained, as shown in Equation (28).

$$\begin{aligned} \mathbf{P}_S &= \mathbf{I} \circ \overline{\mathbf{I}}^T \text{diag}\left\{ \begin{bmatrix} Z_{in1} & Z_{in2} & \cdots & Z_{inN} \end{bmatrix}^T \right\} \\ &= \mathbf{Y}_2 \mathbf{V} \circ (\overline{\mathbf{Y}_2 \mathbf{V}})^T \text{diag}\left\{ [\text{diag}(\mathbf{Y}_2 \mathbf{V})]^{-1} \mathbf{V} - \begin{bmatrix} R_S^1 & R_S^2 & \cdots & R_S^N \end{bmatrix}^T \right\} \end{aligned} \quad (28)$$

where the load received power vector $\mathbf{P}_S = [P_S^1 \ P_S^2 \ \cdots \ P_S^N]^T$; $\overline{\mathbf{I}}$ is the Hermite matrix of $\mathbf{I}$. Z_{in} is the input impedance of MIMO CMR system. R_S is the internal resistance of the power supply.

Combining Equations (27) and (28), the power transfer efficiency of the WPT system is shown in Equation (29).

$$\eta_{\text{sys}} = \frac{\|\mathbf{P}_{\text{load}}\|_1}{\|\mathbf{P}_S\|_1} \quad (29)$$

The power transfer efficiency of a WPT system is expressed as the ratio of the total load received power to the total power output of the AC source. The total load received power and the total power output were influenced by IMN component parameters X_L , X_{RL} and B . When impedance matching, i.e., $Z_{in} = R_S$, IMN component parameters X_L , X_{RL} and B is obtained. Therefore, the optimal impedance matching solution is obtained. The power transfer efficiency of the WPT system η_{sys} reaches its maximum value.

5. Procedure of Adaptive Impedance Matching Scheme

The adaptive impedance matching scheme can be visually displayed by Figure 6. By cycling the scheme in every T seconds, real-time impedance matching can be achieved. Based on the Tx coil current vector and Tx coil voltage vector, the input impedance can be obtained. If the real part of the input impedance is less than zero, then this transmit coil is disconnected. Based on the real part of the input impedance, values of the impedance matching network are calculated. Micro-controller controls single-pole multiple-throw (SPMT) switches to construct each IMN. Therefore, MIMO CMR system can achieve IM in the period of T seconds.

Algorithms can be used for the simulation of MIMO real-time impedance matching. The algorithm is part of the scheme, and the all scheme is divided into four parts: measuring the coupling inductance M between the calculation coils, Tx impedance measurement, selection of transmitter, IMN type decision and respective component values. The Algorithm 1 shows the detail.

Figure 6. Adaptive impedance matching scheme.

Algorithm 1: MIMO real-time impedance matching.

Input: input M_{TT} , M_{TR} , M_{RR} , R_L , R_S , R_T , R_R , V

Output: output X_{rL} , X_L , B , P_{load} , P_S , η_{sys}

```

1 start
2 Measure:  $M_{TT}$ ,  $M_{TR}$ ,  $M_{RR}$ ,  $R_L$ ,  $R_S$ ,  $R_T$ ,  $R_R$ ,  $V$ 
3 Calculate:  $T_{z1}$ ,  $T_{z2}$ ,  $T_{z3}$  and  $T_{z4}$ 
4  $I = (T_{z1} - T_{z2}T_{z3}^{-1}T_{z4})^{-1}V$ 
5 for  $i = 1$  to number of Tx coils do
6    $Z_{Tx}^i = \frac{V_i}{I_i} - R_S$ 
7   if  $\Re(Z_{Tx}^i) < 0$  then
8     number of Tx coils = number of Tx coils - 1
9     disconnect the  $i^{th}$  Tx coil
10    go to step 2
11  else
12    if  $\Re(Z_{Tx}^i) > R_S$  then
13      Calculate:  $X_L^i$ ,  $B^i$ 
14       $X_{rL}^i = 0$ 
15    else
16      Calculate:  $X_{rL}^i$ ,  $B^i$ 
17       $X_L^i = 0$ 
18    end
19  end
20 end
21 Calculate:  $T_1$ ,  $T_2$ ,  $T_3$ ,  $T_4$ ,  $T_5$ ,  $T_6$ 
22 Calculate:  $P_{load}$ ,  $P_S$ 
23 Calculate:  $\eta_{sys} = \frac{\sum_{i=1}^K P_{load}^i}{\sum_{i=1}^N P_S^i}$ 
24 end
  
```

5.1. Measuring the Coupling Inductance M between the Calculation Coils

The first step is to measure the coupling inductance M between the calculated coils. The coupling inductance M_{TT} between the transmitting coil and the coupling inductance M_{RR} between the receiving coil are measured and analyzed by measurement component. Turning on each Tx coil and Rx coil in sequence, we can obtain the coupling inductance between each Tx coil and Rx coil M_{TR} .

5.2. Tx Impedance Measurement

The second step is to measure and calculate the input impedance. The calculation of the input impedance requires the current went through the transmitter coil and the voltage at the right end of the impedance matching network. The expression of the relationship between current and voltage is shown in Equation (5). Using Ohm's law, we can obtain the input impedance, which is shown in Equation (7). In practice, we can use the AD8302 amplitude & phase measurement monolithic integrated circuit and a micro-controller to form a detection circuit to achieve automatic detection and calculation of the input impedance.

5.3. Selection of Transmitter

The third step is the selection of transmitter Tx. The transmitting coils will be coupled with each other, which will cause corresponding effects. If the transmitting coils are close to each other, the energy transmitted from the transmitting coils may be smaller than the energy received, which causes waste to the energy transmission. For this problem, we adopt the scheme of transmitter Tx selection. Using Equation (7) to obtain the input impedance, if the real part of the input impedance $\Re(Z_{in}) < 0$, micro-controller will disconnect the coil by using swithes until the real part of the input impedance $\Re(Z_{in}) > 0$ for all coils.

5.4. IMN-Type Decision and Respective Component Values

The final step is to determine the type of IMN with the calculation of the values for each component. As a real-time impedance matching network, the value of each component will change every T seconds. According to Equation (16), the equivalent impedance of the right side of the IMN Z_{Tx} can be obtained. When $\Re(Z_{Tx}) > R_S$, shorting X_{RL} , the IMN behaves as an L-type IMN, and the IMN component parameters can be calculated as in Equation (17). Similarly, when $\Re(Z_{Tx}) < R_S$, shorted to X_L , IMN behaves as an reverse L-type IMN, and IMN element parameters can be calculated as in Equation (18). In real applications, this step is implemented within the micro-controller. Micro-controller calculates capacitance values (C) and inductance values (L_L and L_{RL}) for capacitor matrix (B) and inductor matrices (X_L and X_{RL}). The micro-controller will control IMNs by using SMPTs.

6. Simulation and Analysis

6.1. System Set-Up

In this paper, we take a 3-to-3 CMR system as an example. In the 3-to-3 CMR system, there are 3 Tx coils and 3 Rx coils. Each Tx coil connect with IMN and AC power source. Totally, there are 3 transmitters, 3 AC power sources, 3 IMN and 3 receivers in the 3-to-3 CMR system. The power supplies provide the energy for the CMR system; the IMN system achieves impedance matching to improve power transfer efficiency and received power; and the receivers receive the electromagnetic waves and supply energy to the load devices. The critical parameters of the WPT system can be seen in Table 1.

Table 1. Critical parameters of the WPT system.

Parameters	Value
Size of TX coil	7×0.05 m
Equivalent inductance of TX coil	$7.175 \mu\text{H}$
Series capacitor for TX coil	76.8 pF
Size of RX coil	7×0.05 m
Equivalent inductance of RX coil	$7.175 \mu\text{H}$
Series capacitor for RX coil	76.8 pF
Operating frequency of power source	6.78 MHz
Impedance of the power source	50Ω
Voltage of the power source	15 V
Load impedance	50Ω

In the simulation, we lined up coils separately. Figure 7 shows the schematic figure of coil placement. The adjacent Tx coils are spaced 0.2 m apart. The Rx coils are same as Tx coils. The distance of Tx coils and Rx coils was moved from 0.001 m to 0.5 m. To achieve real-time impedance matching, the system calculate and change the IMN per T seconds. In this case, the system can react actively to the distance between each coils.

Figure 7. Schematic figure of coils placement.

6.2. IMN Components

The IMN which consists two inductance matrices and one capacitance matrix. In practical situation, the component matrix represents that B , X_{RL} and X_L will change in a discrete form. For the best performance of the simulated system, we assume that the inductance matrices and capacitance matrix have infinite size and number of components. Therefore B , X_{RL} and X_L will change in continuous form. Figure 8 shows the variation of IMN in different cases. The number and type of IMN will change in each time period, while the micro-controller detects that the $\Re(Z_{Tx})$ less than 0, the micro-controller will disconnect that coil by using a switch. After selecting the coil, the micro-controller calculates the optimal values of capacitor matrix (B) and inductor matrices (X_{RL} and X_L) based on the input impedance Z_{in} . The type of IMN and the variation of component values are listed in Table 2.

Figure 8. Variation of IMN in different cases.

Table 2. Components of the IMN.

Distance	Impedance	IMN Type	B	X_L	X_{RL}	C(nH)	$L_L(\mu F)$	$L_{RL}(\mu F)$
0.001	$5520 - 335i$	L	0.0019	523.9	0	0.28	77.27	0
	$5520 - 599i$	L	0.0019	526.3	0	0.28	77.76	0
	$5520 - 335i$	L	0.0019	523.9	0	0.28	77.27	0
0.1	$6.04 + 2.59i$	Reverse L	0.0539	0	13.7	7.94	0	2.03
	$6.77 + 4.96i$	Reverse L	0.0505	0	12.2	7.44	0	1.79
	$6.04 + 2.59i$	Reverse L	0.0539	0	13.7	7.94	0	2.03
0.2	$0.51 + 3.07i$	Reverse L	0.196	0	1.97	28.9	0	0.15
	$0.22 + 5.39i$	Reverse L	0.2973	0	1.04	43.85	0	0.24
	$0.51 + 3.07i$	Reverse L	0.196	0	1.97	28.9	0	0.15
0.3	$0.084 + 0.382i$	Reverse L	0.4878	0	1.66	71.94	0	0.24
	$0.084 + 0.382i$	Reverse L	0.4878	0	1.66	71.94	0	0.24
0.4	$0.06 + 0.38i$	Reverse L	0.5844	0	1.32	86.19	0	0.19
	$0.06 + 0.38i$	Reverse L	0.5844	0	1.32	86.19	0	0.19
0.5	$0.05 + 0.38i$	Reverse L	0.6153	0	1.24	90.75	0	0.18
	$0.05 + 0.38i$	Reverse L	0.6153	0	1.24	90.75	0	0.18

The capacitance value C of capacitor matrix B can be reached by dividing B by angular frequency ω . Similarly the inductance value L of inductor matrix can be reached by

dividing X by angular frequency ω . The ranges of C , X_L and X_{RL} are commonly used in electronic devices. From the application point of view, the use of simple and inexpensive components to achieve optimal transmission efficient and transmission energy is feasible and effective.

6.3. Result

Table 3 illustrates the received power and power transfer efficiency of 3-to-3 CMR system before and after impedance matching. The third column of Table 3 is compared with the fifth column to obtain Figure 9. Figure 9 shows the power transfer efficiency of the SISO CMR system and the 3-to-3 CMR system before and after impedance matching. Comparing the second column of Table 3 with the fourth column, Figure 10 is obtained. Figure 10 shows the received power comparison between SISO CMR system and 3-to-3 CMR system before and after impedance matching. Divide the received power and power transfer efficiency of Table 3 to get Figure 11.

Figure 9. Power efficiency evaluations.

Figure 10. Received power evaluations.

Figure 11. Source output power evaluations.

Table 3. Comparison of measured results with/without impedance matching.

Distance (m)	Without IMN		With IMN	
	(W)	Efficiency (%)	(W)	Efficiency (%)
0.001	0.04	99.59	1.24	99.89
0.1	0.44	86.84	1.11	98.98
0.2	0.032	9.47	0.96	87.86
0.3	0.003	8.66	0.454	40.36
0.4	0.00076	2.19	0.163	14.51
0.5	0.00025	0.71	0.059	5.24

As shown in Figures 9–11, the power transfer efficiency of the 3-to-3 CMR system was improved after impedance matching, while the power transfer efficiency of the 3-to-3 CMR system decreased without impedance matching. At the distance of 0.05 m, the input impedance Z_{in} equal to internal resistance R_T of power source. Therefore, both power and transfer efficiency reach its maximum. We notice that 3-to-3 MIMO system drops when the distance near 0.24 m. That is because that when the distance between Tx coils and Rx coils at medium and long distances, the coupling between the transmitting coils dominates. It will reflect that received power of Tx coil is greater than the transmitted power. Because of the conflict between received power and transmitted power, we can noticed that received power and transmitted power decrease sharply at the distance of 0.2 m. Consequently, the MIMO real-time impedance matching algorithm automatically disconnects this coil to optimize the system transmission power. By coil selecting, the received power and transmitted power of 3-to-3 MIMO CMR system will increase. The reason for the decrease in energy transmission efficient is that the MIMO system changes from three Tx coils to two Tx coils. The conversion of electromagnetic waves in space into electrical energy is less efficient. Therefore, the energy transfer efficient decreases at 0.24 m in Figure 9. When the distance between the Tx coils and Rx coils equal to 0.236 m, the power transfer efficiency of 3-to-3 MIMO CMR system with IMN is 23.5% higher than SISO CMR system without IMN.

7. Conclusions

In this paper, we focus on the analysis and construction of a MIMO CMR system model. This model can be used to simulate and analyze the state of the MIMO CMR system before and after impedance matching. Based on the MIMO CMR system model, we propose an adaptive impedance matching scheme for magnetic MIMO wireless power transfer system. For every T seconds, IMN will change according to the distance. In this

case, the system can react accurately to the distance between coils. By using MIMO real-time impedance matching algorithm, the proposed scheme is able to improve impedance mismatching problem. The simulation result indicate that MIMO CMR system with IMN and MIMO real-time impedance matching algorithm can achieve higher energy transfer power and efficiency than MIMO CMR systems without IMN.

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