Capacitance Prediction Using Multi-cascade Convolutional Neural Network for Efficient Wireless Power Transfer

Meng Wang, Mingshen Li, Qi Luo, *Senior Member*, *IEEE*, and Yanyan Shi

***Abstract*—The efficiency of the wireless power transfer is significantly impacted by misalignment between the transmitting and receiving coils due to impedance mismatching. To tackle this issue, an efficient power transfer solution is proposed, employing a capacitance prediction method based on a multi-cascade convolutional neural network. In the study, the impedance matching characteristic of a magnetic coupling resonant wireless power transfer system with an impedance matching network is analyzed. After that, a neural network-driven approach is introduced to establish a mapping between reflection impedance and the optimal capacitance, and the impedance matching performance of the system is assessed in the presence of coil misalignments. To validate the effectiveness of the proposed approach, tests are conducted and measurements demonstrate a significant improvement in power transfer efficiency.**

***Index Terms*—Multi-cascade convolutional neural network, impedance matching, wireless power transfer (WPT).**

I. Introduction

As an emerging technology for power transmission, magnetic coupling resonant wireless power transfer (MCR-WPT) has shown its great potential in a variety of applications[1]-[5]. In MCR-WPT, misalignment between the transmitting coil and the receiving coil is a known issue that leads to impedance mismatch. As a result, the efficiency of the wireless power transmission is significantly reduced [6].

To enhance transfer efficiency in the case of misalignment between coils, a number of approaches have been proposed. Optimization of the coil structure is considered as one solution. In [7], multiple series connected square coils are designed to form the transmitting coil and a reverse winding of adjacent coils is used to optimize magnetic field. Using this proposed method, it is found that the transmission performance can be effectively improved when the distance between coils varies. In addition, the impedance matching method offers alternative solutions. In [8], a switchable impedance matching network is developed for the transmitting device. By adjusting the matching network, the impedance of the MCR-WPT system can be controlled. Aside from the above approaches, some new methods have been presented recently. In [9], nonlinear components are introduced at transmitting and receiving sides. The maximum power transfer efficiency increases to 51% at the axial distance of 20 mm. In [10], a novel metamaterial slab with negative magnetic permeability is used to enhance magnetic coupling between coils. The results show that transfer efficiency is improved under coil misalignment. It should be noted that it is difficult to obtain the optimal design of a coil when the transfer distance between coils varies. With regards to the impedance matching method, additional circuits are required which makes the MCR-WPT system very complicated [11]. The performance of power transfer is constrained by amplitude-frequency coupling characteristic of nonlinear components [12]. The introduction of metamaterial slabs restricts the system's flexibility [13]. Therefore, it is highly desirable to develop a novel method to cope with the problem caused by coil misalignment.

In this study, a novel capacitance prediction method based on a multi-cascade convolutional neural network is proposed to improve transfer efficiency of wireless power transfer. The MCR-WPT system is constructed with an inverse Γ-type matching network. Based on the circuit model, the characteristic of the impedance matching is analyzed. Then the proposed capacitance prediction method for impedance matching is presented. It predicts the optimal capacitance of the capacitor in the impedance matching network in the case of coil misalignment.

II. Analysis of Impedance Matching for MCR-WPT System

The schematic of the MCR-WPT system with an impedance matching network is shown in Fig. 1.

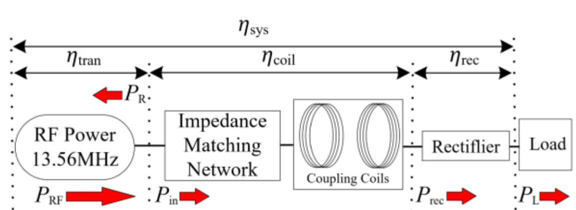

Fig. 1. The schematic of the MCR-WPT system.

Power is emitted from a RF generator and P_R is the reflected power. After passing through the matching network, the coupling coils and the rectifier, the power is finally delivered to the load. Therefore, transfer efficiency η_{sys} of the MCR-WPT system can be expressed as [14].

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$$\eta_{\text{sys}} = \frac{P_{\text{L}}}{P_{\text{RF}}} = \frac{P_{\text{in}}}{P_{\text{RF}}} \cdot \frac{P_{\text{rec}}}{P_{\text{in}}} \cdot \frac{P_{\text{L}}}{P_{\text{rec}}} = \eta_{\text{tran}} \cdot \eta_{\text{coil}} \cdot \eta_{\text{rec}} \tag{1}$$

where P_{L} is the power received by the load, P_{RF} is the power emitted from the RF generator, P_{in} is the power delivered to the impedance matching network, P_{rec} is the power received by the rectifier, η_{tran}, η_{coil} and η_{rec} represent the efficiency. Additionally, η_{tran} can be expressed as

$$\eta_{\text{tran}} = 1 - |S_{11}|^2 \tag{2}$$

where S_{11} is the reflection coefficient.

According to (2), η_{tran} increases as $|S_{11}|$ decreases. Thus, η_{tran} can be improved by decreasing $|S_{11}|$. S_{11} is formulated as [15]

$$S_{11} = \frac{Z_{\text{in}} - R_{\text{s}}}{Z_{\text{in}} + R_{\text{s}}} \tag{3}$$

where Z_{in} is the equivalent input impedance of the system and R_{s} is the resistance of the source.

Substituting (3) into (2), it can be obtained that

$$\eta_{\text{tran}} = 1 - \left| \frac{Z_{\text{in}} - R_{\text{s}}}{Z_{\text{in}} + R_{\text{s}}} \right|^2 = \frac{4Z_{\text{in}}R_{\text{s}}}{(Z_{\text{in}} + R_{\text{s}})^2} \tag{4}$$

Taking the first-order derivative of (4), the value of Z_{in} when η_{tran} is the maximum is calculated as

$$Z_{\text{in}} = R_{\text{s}} \tag{5}$$

Thus, the optimal transfer performance is achieved when Z_{in} is equal to R_{s} where η_{tran} can be maximized.

In this work, an inverse Γ-type matching network with a variable capacitor is used for compensating the impedance mismatching under the misalignment between coils. With this matching network, constant load current can be obtained. The simplified equivalent circuit of the MCR-WPT system is depicted in Fig. 2. V_{s} is the peak voltage of the source, C_1 and C_2 are two capacitors for resonance, L_1 and L_2 are respectively the self-inductance of the transmitting coil and the receiving coil, L is the inductor, C is the variable capacitor, R_{L} is the resistance of the load, U denotes the voltage on the capacitor C, I is the current through the transmitting coil.

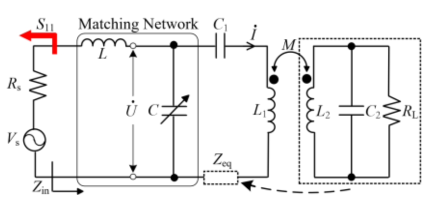

Fig. 2. The simplified equivalent circuit of the proposed MCR-WPT system with an adjustable capacitor.

The reflected impedance Z_{eq} is described by

$$Z_{\text{eq}} = \frac{\dot{U}}{\dot{I}} - j(\omega L_1 - \frac{1}{\omega C_1}) \tag{6}$$

Also, it can be expressed as

$$Z_{\text{eq}} = \frac{M^2(R_{\text{L}} - j\omega L_2)}{L_2^2} \tag{7}$$

where M is the mutual inductance. Then, the input impedance Z_{in} can be written as

$$Z_{\text{in}} = \frac{(\omega^2 CL - 1)(j\omega C_1 \cdot Z_{\text{eq}} - \omega^2 C_1 L_1 + 1) + \omega^2 C_1 L}{\omega(\omega CC_1 \cdot Z_{\text{eq}} + j\omega^2 CC_1 L_1 - C - C_1)} \tag{8}$$

It is known that mutual inductance varies when there is misalignment between coils. Consequently, the reflected impedance Z_{eq} changes. Affected by Z_{eq}, Z_{in} varies leading to impedance mismatch and transfer efficiency degradation. From Fig. 2, it is observed that Z_{in} is related to the variable capacitor C. Therefore, the system can return to the matching state by adjusting the variable capacitor in the matching network. Using this method, the reflection coefficient S_{11} is minimized and the transmission performance can be enhanced when the position of coils changes. Fig. 3 depicts the variation of reflection coefficient against the capacitance of the variable capacitor for three different values of reflected impedance. It is seen that the amplitude of S_{11} is reduced by optimising the value of the variable capacitance. The capacitance which corresponds to the minimum S_{11} is considered as the optimal capacitance C_{opt} where the impedance is well matched.

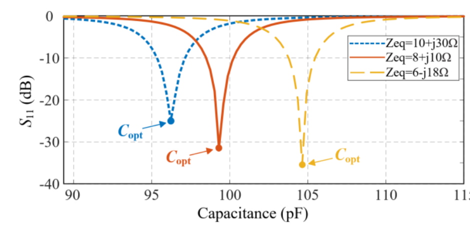

Fig. 3. The variation of reflection coefficient against the capacitance of the variable capacitor.

III. Neural Network-Based Prediction Method for Impedance Matching

From the above discussion, it is found that impedance mismatch can be avoided by adjusting the capacitance of the variable capacitor to the optimal value. In this section, a novel method based on a multi-cascade convolutional neural network is proposed to predict the optimal capacitance.

A. Proposed Impedance Matching Method

The proposed impedance matching method is based on a multi-cascade convolutional neural network. Its basic structure is shown in Fig. 4 which consists of the convolutional layer and the fully connected layer. Multiple convolutions are used to ensure that features of the data are better extracted.

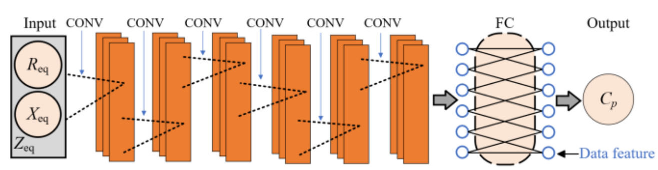

Fig. 4. Structure of the proposed impedance matching method.

The input of the network is the reflected impedance Z_{eq} which is decomposed into the real part R_{eq} and the imaginary part X_{eq}. The convolutional layer can extract local features of the input data by utilizing the convolutional kernels and the bias b [16]. The convolutional kernels are equivalent to weight matrices, and the output of the convolutional layer is given by

$$y_{i,j} = f(\sum_{i,j}^{n} w_{i,j} \cdot x_{i,j} + b_{i,j}) \tag{9}$$

where $y_{i,j}$ is the output of the convolutional layer in row i and column j, $w_{i,j}$, $x_{i,j}$, and $b_{i,j}$ are the convolutional kernel, input data and bias in row i and column j, respectively, $g(z)$ is the activation function expressed by:

$$g(z)=\left(1+e^{-z}\right)^{-1} \tag{10}$$

The data output from the convolutional layer is passed to the next convolutional layer for further extraction. The output of the last convolutional layer serves as the input of the fully connected layer. After data features have been extracted, the output of the network is the optimal capacitance C_{opt}.

B. Neural Network Training and Performance Evaluation

To establish the mapping relationship between the reflected impedance and the predicted capacitance, training of the neural network is required. For the matching network, the inductance of the inductor is 2.5 μH and the original capacitance of the capacitor is 117.7pF. The self-inductance of the coils L_1 and L_2 is 8.5 μH. To resonate at 13.56 MHz, compensation capacitance C_1 and C_2 are calculated as 25 pF and 16.2 pF, respectively. To train the neural network, a large number of training datasets is needed. In the training, R_{eq} varies within the range of 2 Ω to 50 Ω with a step of 2 Ω and X_{eq} changes within the range of -j50 Ω to +j50 Ω with a step of +2j Ω. Then different combinations of R_{eq} and X_{eq} are used as the input of the network. Based on the above parameters, the reflection coefficient S_{11} can be determined and the corresponding optimal capacitance of the capacitor in the matching network is obtained. There are a total of 1275 groups of data. 1250 groups are designated as the training set and 25 groups of data are used as the test set.

To assess how the predicted capacitance C_{p} deviates from the optimal value. The root mean square error (RMSE) is employed as a metric which is defined as

$$\mathrm{RMSE}=\sqrt{\frac{\sum_{i=1}^{N}\left(C_{\mathrm{opt}}-C_{\mathrm{p}}\right)^2}{N}} \tag{11}$$

where N is the number of misalignments, i is the data index.

Fig. 5 compares the predictive error of the conventional structure and the proposed structure. For both the training set and the test set, the RMSE has been largely reduced. The predictive error of the training set decreases from 0.0784 to 0.0299 and the predictive error of the test set drops from 0.0822 to 0.0282. Thus, the proposed network has better performance in the prediction.

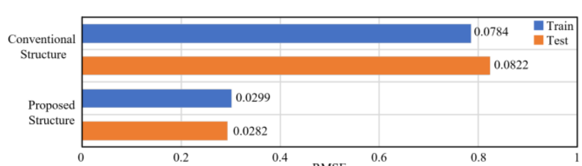

Fig. 5. Comparisons of predictive error of the conventional structure and the proposed structure.

Once the network has been trained, the proposed method can be used to predict the optimal capacitance when the position of coils changes. To validate the generalization capability, three types of coil misalignments are analyzed as shown in Fig. 6(a). The gray coil represents the initial position with d=30 mm, l=0 mm and a=0°. O_1 and O_2 are the center of two coils respectively. Case A, Case B and Case C denote the cases of axial, radial and angular misalignments separately. For Case A, the axial misalignment is denoted by d varying in the range of [10 mm, 50 mm] with a step of 10 mm. For Case B, the radial misalignment is denoted by l and varies in the range of [15 mm, 75 mm] with a step of 15 mm. For Case C, the angular misalignment is denoted by α varying in the range of [10°, 50°] with a step of 10°. The reflected impedance is input to the trained neural network and the capacitance is predicted. A comparison between the predicted capacitance and the optimal capacitance is shown in Fig. 6(b). Besides, the corresponding relative error is calculated. The predicted capacitance is almost identical to the optimal capacitance. The maximum and the minimum relative error are 0.60% and 0.10% respectively. For all the misalignments, RMSE is 0.0323. The result indicates that high prediction accuracy can be obtained when the proposed method is used.

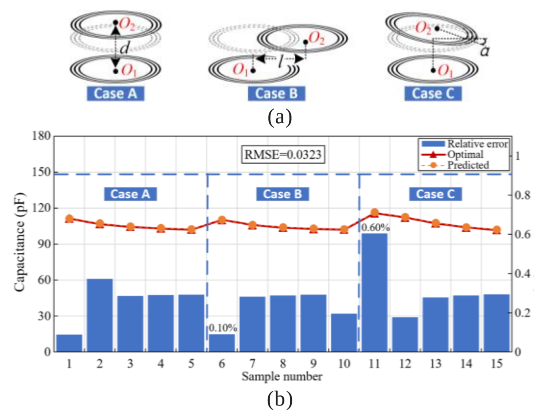

Fig. 6. Illustration of coil misalignments and comparison between predicted and optimal values. (a) Illustration of coil misalignments; (b) comparison between predicted and optimal values.

From the above discussion, it is concluded that the reflected impedance Z_{eq} when misalignment occurs can be calculated from (6) once the voltage U and current I have been measured. Then, the reflected impedance Z_{eq} is divided into a real part and an imaginary part. With the real part and the imaginary part performing as the input of the proposed network, the optimal capacitance is predicted. Finally, adjust the capacitance C in the circuit according to the predicted value. This is the whole procedure of the proposed method.

C. Impedance Matching Analysis

With the proposed method, the capacitance of the capacitor in the matching network for impedance matching is predicted. For impedance matching analysis, the Smith chart and the curve of S_{11} are depicted in Fig. 7. In the analysis, the axial misalignment with d=70 mm, the radial misalignment with l=75 mm and the angular misalignment with α=40º have been considered. The reflected impedance of the receiving side is connected in series with L_1 and C_1 of the transmitting side. Then impedance matching can be implemented with the matching network. In Fig. 7, the path of the curve represents variation of the reflected impedance. Compared with the input impedance under mismatched conditions, the input impedance after matching is closer to the target impedance. From the amplitude-frequency curve, it is found that amplitude of S_{11} significantly decreases when compared with the mismatch condition. Reflected power loss can be largely reduced.

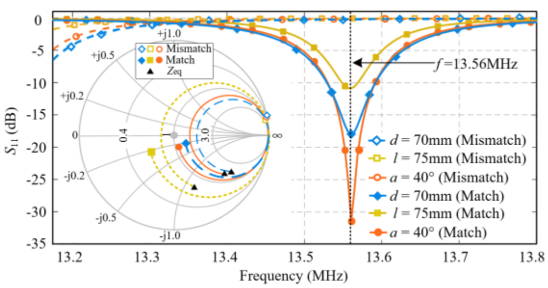

Fig. 7. Amplitude-frequency curve and Smith chart for the MCR-WPT system without and with impedance matching.

IV. Experimental Verification

In this section, an experiment is carried out to validate the performance of the proposed method when there is coil misalignment. The experimental platform of the MCR-WPT system is illustrated in Fig. 8. The transmitting and receiving coils are circular flat coils with an inner diameter of 90 mm. The number of turns is 7 and the wire diameter is 3 mm.

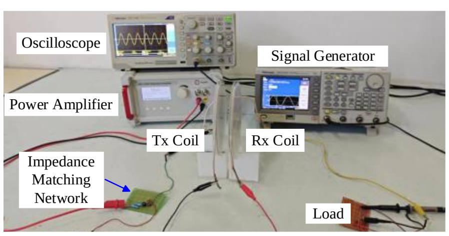

Fig. 8. Experimental platform of the MCR-WPT system.

The performance of the proposed method is estimated under axial, radial and angular misalignments of coils respectively. Fig. 9 shows transfer efficiency of the system when the impedance is matched and mismatched. As given in Fig. 9, transfer efficiency is 91.2% when there is no misalignment (d=30 mm, l=0 mm, α=0°). Generally, transfer efficiency declines with the increase of misalignment. Compared with the results under the mismatch condition, there is a noticeable increase in transfer efficiency if the impedance is matched. In Fig. 9(a), transfer efficiency is only 14.7% when d=60 mm while it increases to 67.4% after impedance matching. Fig. 9(b) compares transfer efficiency when there is radial misalignment. The efficiency is 34.3% when l=45 mm. The efficiency reaches 78.5% after impedance matching. Fig. 9(c) shows the efficiency when the angular misalignment varies. Similarly, transfer efficiency decreases when α=30° which is only 9.7%. In contrast, transfer efficiency is 62.7% in the matched condition. To conclude, transfer efficiency can be effectively improved in the cases of coil misalignment with the proposed method.

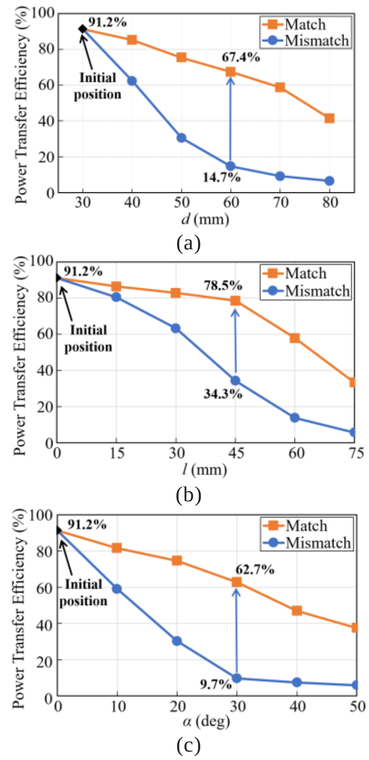

Fig. 9. Comparison of transfer efficiency before and after matching under three kinds of misalignments between coils. (a) Axial misalignment; (b) Radial misalignment; (c) Angular misalignment.

Table I tabulates the comparison between this work and related works. In [17], a multilayer coil technology with two rectangular assistant coils stacked on a circular primary coil is proposed. In [18], the ferrite core is used at the transmitting and receiving sides for impedance matching. Comparatively, the maximum efficiency enhancement of the WPT based on the proposed method is higher than other approaches and extra coils are not required.

TABLE I
Comparison With Other Approaches

Ref.	Operating frequency	Number of coils	Coil size/ diameter	Maximum efficiency↑
[8]	600kHz	2	14cm	51%
[17]	145kHz	6	4.5cm	46.1%
[18]	257kHz	2	62×33cm	42%
This work	13.56MHz	2	13.2cm	53%

V. Conclusion

In this letter, a capacitance prediction method using multi-cascade convolutional neural network is proposed for efficient power transfer in MCR-WPT. The reflected impedance is used as the input of the network and the output is the predicted optimal capacitance for impedance matching. With the proposed method, the results show that transfer efficiency can be largely improved when coil misalignments occur. For accurate prediction, it should be noted that a great deal of simulation work should be conducted to obtain the training dataset which consumes time. This is the limitation of the proposed method.

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