Range-adaptive Impedance Matching of Wireless Power Transfer System Using a Machine Learning Strategy Based on Neural Networks

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***Abstract*— This work describes the implementation of a machine learning (ML) strategy based on the neural network for real-time range-adaptive automatic impedance matching of Wireless Power Transfer (WPT) applications. This approach for the effective prediction of the optimal parameters of the tunable matching network and classification range-adaptive transmitter coils (Tx) is introduced in this paper aiming to achieve an effective automatic impedance matching over a wide range of relative distances. We propose a WPT system consisting of a tunable matching circuit and 3 Tx coils which have different radius controlled by trained neural network models. The feedforward neural network algorithm was trained using 220 data and classifier's in pattern recognition accuracy were characterized. The proposed approach achieves a Power transfer efficiency (PTE) around 90% for ranges within 10 to 25cm, is reported.**

***Keywords*— Impedance matching, machine learning, neural network, pattern recognition, resonant coupling, wireless power transfer.**

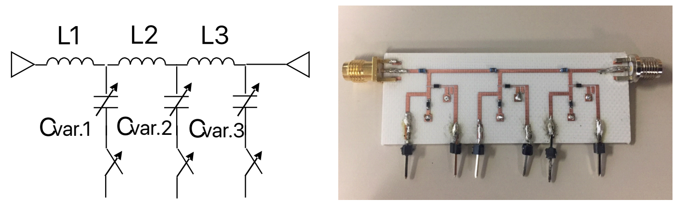
I. Introduction

The impedance matching of a wireless power transfer (WPT) system using magnetic resonance coupling (MRC) has become a critical challenge in order to maintain a reasonable Power transfer efficiency (PTE) for time-varying configurations. Several approaches of impedance matching have been proposed [1], [2] and [3] regarding the distance between the receiver (Rx) and transmitter (Tx) as PTE varies significantly with distance. However, these are limited in the effective ranges as a consequence of their unexpected variation of the transfer distance or load impedance. Here, we propose an alternative approach that takes advantage of a novel method based on a feedforward neural network combined with pattern recognition techniques, thus addressing the shortcomings of the aforementioned impedance matching approaches while retaining high PTE. As a proof-of-concept, one receiver coil, three selective transmitter coils and a matching circuit with tunable capacitors are first designed and measured. Then, a machine learning approach utilizing neural network algorithms that can construct the mapping relationship is presented to improve the capability of the WPT system.

II. WPT application

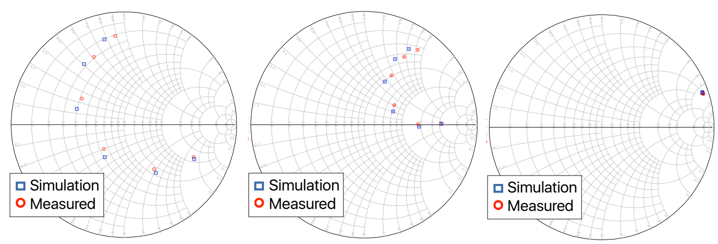
A. Matching Circuit Design

A matching circuit topology consisting 3 consecutive L-type series inductor and shunt capacitor with p-i-n diode switch was used in [3]. The simplified schematic of this matching circuit is shown in Fig.1-(a), and a fabricated prototype is shown in Fig. 1-(b). To overcome the limited capability of this static topology to provide an acceptable PTE over a wide range of transmitter-receiver distances, one variable capacitor from Murata electronics is employed in this paper enabling superior characteristic of matching circuit compared with previous work and allows for the on-demand value tuning utilizing the results from the proposed machine learning approach. These tunable capacitors typically achieve capacitanve values that can vary by applying voltage to their elctrodes in the rance of 30pF-60pF (0-3V) and 100pF-200pF (0-5V). As experimental verification of the variability of the capacitance values is shown in Fig. 2. With this proposed method, a wide range of impedance coverage can be realized though the variation of the input impedance Z_{in}. For the inductance values of $L1$, $L2$, and $L3$, 1432nH, 610nH and 1484nH were optimized corresponding to the values of capacitance's tunable ranges.



(a) (b)

Fig. 1. (a) Simplified schematic of the matching circuit. (b) Prototype of the matching circuit.



(a) (b) (c)

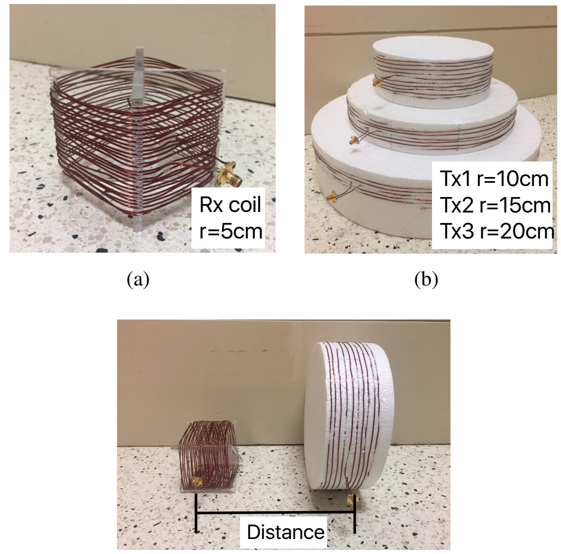
Fig. 2. Simulated and Measured capacitance variability of (a) Cvar.1 (b) Cvar.2 (c) Cvar.3.

Table 1. Parameters of the Rx and Tx Coils for the Proposed WPT System

	Rx	Tx1	Tx2	Tx3
Self-resonance Frequency (MHz)	13.56			
Copper Wire Radius (mm)	0.5			
Radius (cm)	5	10	15	20
Number of turns	27	10	6	4.5
Pitch (mm)	2	5		

B. Selective Transmitter coils

A multi transmitter coils topology is employed to reduce the variation in the input impedance of the WPT system with respect to the distance. In order to maximize the coil-to-coil efficiency, it was found that the optimal radius of Tx is approximately equal to the distance of coil-to-coil in [4] reporting the analytically derived equation $r_{Tx} = d$, when $r_{Rx} << r_{Tx}$. Based on their analysis, the overall geometrical design for Rx and Tx coils is controlled by the key parameters summarized in TableI. In order to confirm the effectiveness of this approach, several open type helical coils with different radius were designed on CST studio 2016 using the integral solver. The extracted S-parameters from the simulations will serve a standard dataset for the neural network training presented in next section. A phorograph of the fabricated Rx and 3 Tx coils are shown in Fig. 3.



(a) (b)

(c)

Fig. 3. (a) Fabricated Rx coil. (b) Fabricated 3 Tx coils. (c) Distance between Rx and Tx1.

III. Machine learning approach

Neural networks represent powerful machine learning-based techniqeus used to solve many problems apart from other machine learning algorithms that make use of architecture inspired by the neurons in the human brain. There networks turn out to be well-suited to modeling high-level abstractions across a wide array of disciplines and industries.

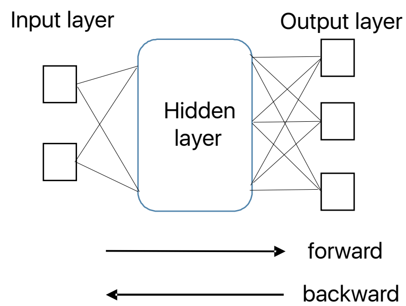


Fig. 4. The schematic of the feedforward neural network with backpropagation.

A. Feedforward neural network with backpropagation

The feedforward neural network, also called deep feedforward network is one of the deep learning models. To approximate some function $f(x)$ through the feedforward neural network, when x is input, the feedforward neural network defines a mapping function $y = f(x;\theta)$ and determines the parameters θ which gives the best function approximation results [5]. Also, the backpropagation method provides a neural network with a set of input values for which the correct output value is known beforehand and then it is added in a feedforward neural network. In this network as shown in Fig. 4, the informtion moves in both directions from the input layer where each input has an associated weight factor(w), though the hidden layers are usually used for improving mapping ability to the output layers. In this work, we propose a WPT scheme with three cascading L-type impedance matching network based on a feedforward neural network which is similar approach used in [6]. They developed a mapping relationship between the impedance of the equivalent load ($Z_{eq} = R_{eq} + jX_{eq}$) and then the matched capacitors connected with each switch, capacitor set composed of (C_1, C_2, C_3) in consideration of each switching status as well. The dataset for training to produce a function of the network consists of the distribution of $|S11|$ matched by the neural network within a range of 0 to 20Ω for R_{eq} and -50 to 50 for X_{eq} with 1 interval in total 220 data.

B. Neural Network Pattern Recognision

Additionally, we proposed the advanced approach using a shallow neural network to classify patterns. Normally, only feedforward networks are used for pattern recognition. Through classification, an automated system declares that the inputted object belongs to a particular category. 220 set of output parameters, which represents capacitance value, (C_1, C_2, C_3) from above trained model acts as an input to select proper transmitter coils among T_{x1}, T_{x2}, T_{x3}, then trained classifier can recognize the three categories associated with each input parameters with 90.18% accuracy.

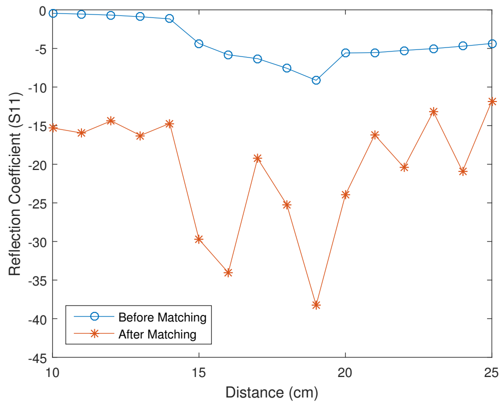


Fig. 5. Comparison of reflection coefficicent (S11) before matching and after matching at distance 10-25cm.

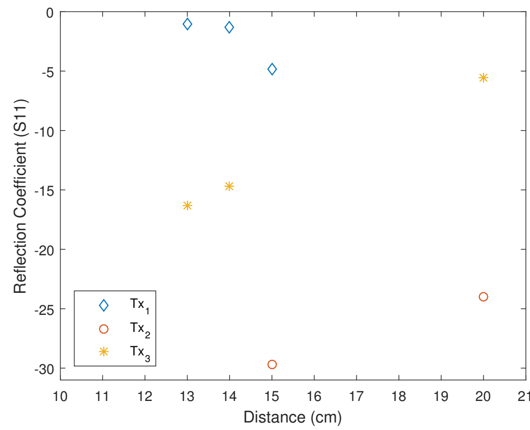


Fig. 6. Transmitter selectivity.

IV. Implementation and Performance Evaluation

To predict the capacitance values and classify the type of transmitter, a training process using the feedforward neural network and pattern recognition was implemented. The trained feedforward neural network model and classifier are built by the process of previous section. Firstly, the initial impedance assumed according to the coil-to-coil distance such as of Rx-Tx1 at 10-14cm, Rx-Tx2 at 15-19cm and Rx-Tx3 at 20-25cm. Before matching, the initial input impedance of Rx-Tx at 13.56MHz were measured by a vector network analyzer and plotted in Fig. 5. After matching through the trained neural network model and classifier, the input impedance matching is improved over the entire separation distance range and were also plotted in Fig. 5. Especially at distances 13, 14, 15 and 20cm, the capacitance values extracted from the trained neural network model were classified to the transmitter coil with different radius which results in significant improvement by switching, shown in Fig. 6. To verify and validate the proposed approach, Fig. 7 shows calculated PTE at each distance in the range of 10 to 25cm compared with using only one specific Tx coil and with selective Tx coils under the condition of the similar matching approach in [4]. By utilizing the selective Tx coils, the PTE was more stable and able to avoid the sudden drop at a certain range as shown in Fig. 7. Moreover, the proposed approach achieves a PTE around 90% for ranges within 10 to 25cm.

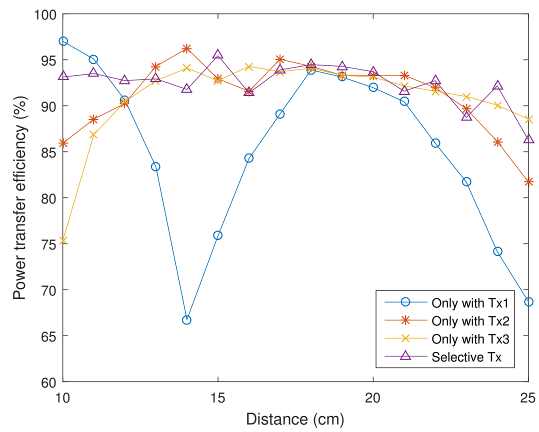


Fig. 7. The PTE without the selective Tx versus with the selective Tx.

V. Conclusion

In this paper, range-adaptive impedance matching of WPT system utilizing neural network algorithms was demonstrated. The implementation of the feedforward neural network and pattern recognition techniques for real-time range-adaptive automatic impedance matching of WPT applications can, not only, predict the capacitance value of the matching circuit under a specific environment, but can also select one of Tx coils which maximize Rx-Tx power transfer efficiency up to 95%. In addition, the proposed model is scalable and generalizable to contexts such as misalignment of Rx-Tx coils and a wide range of operation distances. The work reported here could greatly enhance the state-of-the-art real-time range-adaptive automatic impedance matching techniques.

References

[1] T. C. Beh, M. Kato, T. Imura, S. Oh, and Y. Hori, "Automated impedance matching system for robust wireless power transfer via magnetic resonance coupling," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 9, pp. 3689–3698, 2013.

[2] B. Park and J. Lee, "Adaptive impedance matching of wireless power transmission using multi-loop feed with single operating frequency," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 5, pp. 2851–2856, 2014.

[3] J. Bito, S. Jeong, and M. M. Tentzeris, "A real-time electrically controlled active matching circuit utilizing genetic algorithms for wireless power transfer to biomedical implants," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 2, pp. 365–374, 2016.

[4] H. Qiu, Y. Narusue, Y. Kawahara, T. Sakurai, and M. Takamiya, "Digital coil: Transmitter coil with programmable radius for wireless powering robust against distance variation," in *2018 IEEE Wireless Power Transfer Conference (WPTC)*, June 2018, pp. 1–4.

[5] K.-I. Funahashi, "On the approximate realization of continuous mappings by neural networks," *Neural Networks*, vol. 2, no. 3, pp. 183 – 192, 1989.

[6] Y. Li, W. Dong, Q. Yang, J. Zhao, L. Liu, and S. Feng, "An automatic impedance matching method based on the feedforward-backpropagation neural network for a wpt system," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 5, pp. 3963–3972, May 2019.