Heuristic Passive and Active Matching Circuit Design Method for Wireless Power Transfer for Moving Objects

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***Abstract*—In this paper, a novel matching circuit design method utilizing a genetic algorithm and measured S-parameters of randomly moved coils is discussed. From the analytical comparison of different matching circuit topology, the superiority of active matching circuit is suggested, and potentially there is 21.4 % improvement in wireless power transfer efficiency by using 4 cell active matching circuit, which can create 16 different impedance values. Also, the matching circuit design simulation can be simplified by choosing representative impedance values of coils utilizing K-means clustering and use these values as targets. This drastically reduce the time for the matching circuit design simulation, especially for the matching circuit with larger number of cells.**

***Index Terms*—Wireless power transfer, impedance matching, genetic algorithms, real-time system, wearable**

I. Introduction

These days, wireless power transfer (WPT) technology has attracted a lot of attention from industry and research community in order to realize a highly demanded truly cableless power supply system. One of the most important applications of this technology is the medical field, especially for wearable/implantable devices. Also, recently, the demand of wireless charging system for vehicles and UAVs is increasing because of their short cruising distance. There are several types of WPT systems relying on different operation principles. Among them, resonant coupling, especially the magnetic resonant coupling method, utilizing resonating coils, is one of the strongest candidates because of its relatively large operation distance and high maximum power transfer efficiency. However, associated with the fundamental operation principle of this method, the WPT efficiency degrades because of the transmitter (Tx) and the receiver (Rx) coil separation distance variations. This could be a critical issue for WPT for the moving objects such as human bodies and UAVs. In the literature, it has been reported that this problem can be potentially solved by utilizing an active matching system even under misaligned conditions in addition to the coil separation distance change [1], [2]. However, in more realistic situations, the impedance of the Tx-Rx coil network continuously changes because of movement of coils. In this paper, a novel matching circuit design method utilizing a genetic algorithm and clustering which can maximize the performance of the fixed value passive matching circuit and the active matching circuit, which is composed of a combination of inductors, capacitors and p-i-n diodes, is analytically discussed the based on the measured coil S-parameters under the moving conditions.

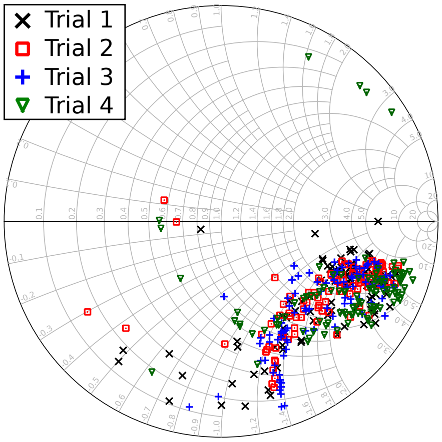

Fig. 1. Measured input impedances of Tx-Rx coil network under random movements in Trial 1 to Trail 4.

II. Characterization of Tx-Rx Coil Impedance under Moving Condition

In order to characterize the effect of the movements of the Tx-Rx coils for the coil input impedance, the S-parameters of the Tx-Rx coils were periodically measured using a vector network analyzer(VNA), ZVA8 from Rohde & Schwarz, which was controlled by using LabVIEW. As a proof-of-concept and without loss of generality, 10 cm diameter open helical coils whose resonance frequency is 13.6 MHz were used for both Tx and Rx coil, and the S-parameters were measured 100 times with the time interval of 250 ms by moving the coils randomly within the coil center to center distance in the range of about 10 to 20 cm. During the measurement, the coils are placed on sponges to avoid the interaction with hands, and the sponges were moved with the hands. The same experiment was repeated four times, and the measured Tx-Rx coil network input impedance at each trial are shown in Fig. 1. As can be recognized from the figure, the input impedance of the coils varies in a quite wide range, but there is a clear tendency in the distribution of impedance values. In Fig. 2, the distribution of power transfer efficiency, $|S_{21}| \times 100$ (%), of 400 measurements and arithmetic mean of them are depicted. The average power transfer efficiency without any matching circuit is about 60.8 %.

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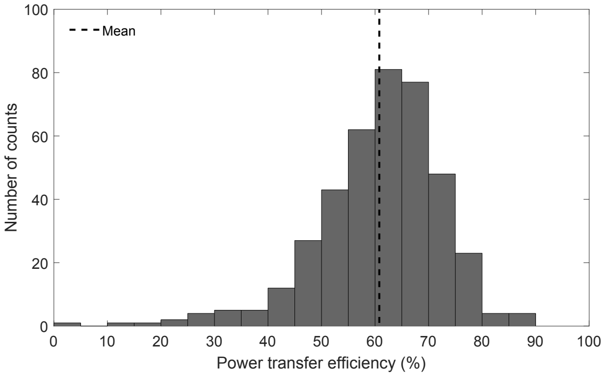


Fig. 2. Distribution and arithmetic mean of measured power transfer efficiency in Trial 1 to Trail 4.

III. MATCHING CIRCUIT DESIGN USING GENETIC ALGORITHM

Genetic algorithm (GA) is a heuristic searching method which can be applied for many engineering problems. This method is suitable to solve the problems which have a combination of discrete values as an answer. For easy and quick implementation of GA, MATLAB Global Optimization Toolbox was utilized. For this research, first, the fixed value passive matching circuit topology which can maximize the power transfer efficiency for the moving coils is discussed. Next, the GA based matching circuit design process is extended to the active matching circuit design.

In general, a cascaded two-port networks can be expressed as a multiplication of each transmission (ABCD) matrix. The ABCD matrix of each sample can be obtained from the measured S-parameters of the Tx-Rx coil network by converting the S matrix to the ABCD matrix. Once the ABCD matrix of the matching circuit is determined by choosing the lumped component values in the matching circuit, the S-matrix of a cascade of the matching circuit and the coils can be computed from the total transmission matrix [3]. Assuming that there are M samples of S-parameters of the coil network, the probability of choosing i-th sample is $\frac{1}{M}$. In this research, the power transfer efficiency (η) is defined as the expected value of $|S_{21}|$ as described in equation (1). For active matching circuit, there are more than two matching circuit configurations, so the maximum $|S_{21}|$ value among all the possible $|S_{21}|$ values for i-th sample is chosen. Fitting function for this GA simulation is defined as F in equation (1), and the matching circuit component values which can minimize the value of F are selected.

$$F = 100 - \eta \quad where \quad \eta = \sum_{i=1}^{M} |S_{21}|^{i}_{Max} \; P_i \times 100 \ (\%) \quad (1)$$

A. Fixed Value Passive Matching Circuit

In order to determine the optimal fixed value passive matching circuit topology, two Pi matching circuits, one has a series inductor with two parallel capacitors, and another one has a series capacitor with two parallel inductors are defined. The two Pi matching circuits are depicted in Fig. 3. For both inductors and capacitors, 29 consecutive commonly used circuit values, which cover a lumped element value range of more than 1000:1 for the operation frequency of 13.6 MHz were considered. Also, the parallel components are allowed to be open, which virtually can create L matching circuit. The circuit component values which minimizes the fitness function for each circuit topology are shown in Table I.

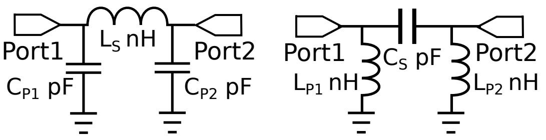


Fig. 3. Pi matching circuit topology with a series inductor and a series capacitor.

TABLE I
CIRCUIT COMPONENT VALUES FOR OPTIMIZED FIXED PI MATCHING CIRCUIT TOPOLOGY

Series L		Series C	
L_S	1000 nH	C_S	10.0 pF
C_{P1}	0 pF	L_{P1}	1000 nH
C_{P2}	39 pF	L_{P2}	720 nH

B. Active Matching Circuit

In this research, a discrete value impedance matching circuit with p-i-n diode switches is adopted because of its fast switching speed, small feature size and robustness [3]. The matching circuit topology is based on the cascading of an unit cell consisting of an L-type series inductor and shunt capacitor as shown in Fig. 4. For the ease of fabrication and simplicity avoiding additional capacitors for dc block in the bias circuit. N cells of matching circuit can create 2^N different impedance values. For both inductors and capacitors, 29 consecutive component values, which are the same as the case of fixed value passive matching circuit, were used. In this case, the inductance values are allowed to be 0. The circuit component values which minimizes the fitness function for each number of cell are shown in Table II.

In Table III, the figure of merit of each matching circuit topology is summarized. The improvement is the difference of power transfer efficiency from the case without matching circuit. The error represents the number of data points whose power transfer efficiency is lower than the case without matching circuit. As can be easily recognized from the table, the active matching circuit is more effective to improve the power transfer efficiency compared to the fixed value matching circuit. As the number of cell increases, the efficiency

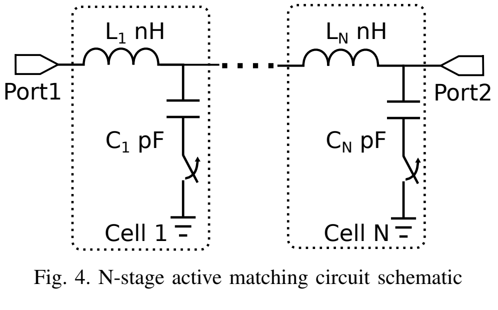


Fig. 4. N-stage active matching circuit schematic

increases following the decrease of error rate. From this simulation, it can be said that 3 cells or 4 cells are enough to optimally improve the power transfer efficiency because the improvement saturates. As a comparison, the power transfer efficiency using the previously designed 6 cell active matching circuit is 72.2 % [2]. This implies that a higher power transfer efficiency can be achieved even with smaller number of cells compared to the previously designed matching circuit.

TABLE II
CIRCUIT COMPONENT VALUES FOR OPTIMIZED ACTIVE MATCHING CIRCUITS WITH DIFFERENT NUMBER OF CELLS

	Inductors (nH)				Capacitors (pF)			
	L_1	L_2	L_3	L_4	C_1	C_2	C_3	C_4
1 cell	1000	-	-	-	47	-	-	-
2 cell	330	820	-	-	390	47	-	-
3 cell	330	330	820	-	150	330	39	-
4 cell	330	470	0	820	180	330	82	33

TABLE III
FIGURE OF MERIT OF EACH MATCHING CIRCUIT TOPOLOGY

	No MC	Ser L	Ser C	1 C	2 C	3 C	4 C
Efficiency (%)	61.5	76.4	76.4	78.3	80.8	82.2	82.9
Improvement (%)	-	14.9	14.9	16.8	19.3	20.7	21.4
Error (%)	-	15	13	10	4	1	1

In order to confirm if the designed matching circuits based on the measurement data in Trial 1 can also work for other set of sampled data, the power transfer efficiencies for each trial is computed and summarized in Table IV. The degradation is maximum decrease of efficiency when the set of samples obtained in Trial 2 to Trial 4 are used to compute the power transfer efficiency compared to the no matching circuit condition in each trial. From the table, it can be said that there is no significant performance degradation even with data from different trial.

TABLE IV
POWER TRANSFER EFFICIENCY COMPARISON WITH MEASURED S-PARAMETERS IN TRIAL1 TO TRIAL4

	No MC	Ser L	Ser C	1 C	2 C	3 C	4 C
Eff (Trial1) (%)	61.5	76.4	76.4	78.2	80.8	82.2	82.9
Eff (Trial2) (%)	60.1	73.6	73.6	75.4	76.8	78.1	78.5
Eff (Trial3) (%)	59.9	72.8	72.9	75.4	77.4	78.3	79.2
Eff (Trial4) (%)	61.6	79.2	79.1	80.6	82.9	85.6	86.2
Degradation (%)	-	2.0	1.9	1.4	2.6	2.7	2.9

IV. K-MEANS CLUSTERING

Since there is a clear trend in the distribution of coil impedance values, it is potentially possible to reduce the time for GA simulation by selecting the representative impedance values as targets instead of using all sampled data. Also, the fitness function calculation which includes many S to ABCD matrix conversions is not really efficient. In order to choose a much smaller but almost equally efficient subset of coil impedance values, we employed the k-means clustering method, which is commonly used for the data mining from big data, utilizing MATLAB. At the beginning of the data mining, we have set automatically generated 100 replicates as starting points in order to increase the accuracy of the clustering [4].

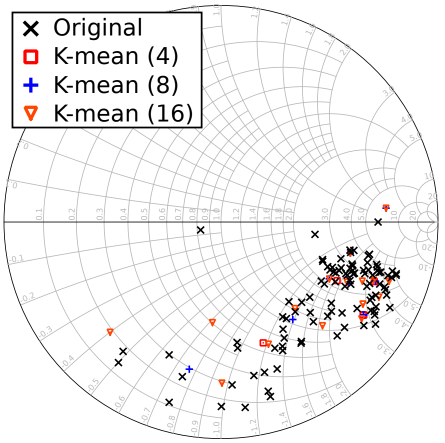


Fig. 5. Measured 100 input impedances of Tx-Rx coil network under random movements in Trial 1 and representative impedance values selected by using K-means clustering.

For the proof-of-concept of clustering data mining method, 4, 8 and 16 representative coil input impedance values are chosen by using the measured S_{11} values in Trial 1. In Fig. 5, 100 sampled impedance values, 4, 8 and 16 clustered impedance values are plotted. Since the power transfer to the load can be maximize when input impedance of the matching circuit from port 2 (Z_{22}) is the complex conjugate of the coil impedance (Z_C), the sum of reflection coefficient between i-th clustered coil impedance and Z_{22} is introduced as a new fitness function (G) as described in equation (2).

$$G = \sum_{i=1}^{L} |\Gamma|^{i}_{Min} \quad where\ \Gamma = \frac{Z^*_{Ci} - Z_{22}}{Z^*_{Ci} + Z_{22}} \tag{2}$$

In Table V, the power transfer efficiency for each matching circuit topology using clustered data as target impedance in GA simulation is summarized. From the table, it can be said that there are some cases that the clustered data do not work as proper targets, especially for series inductor Pi matching circuit case, and degrade the performance of matching as the number of cluster decreases. However, in most cases, the clustering of impedance value does not have significant effect on the matching circuit design performance.

TABLE V
POWER TRANSFER EFFICIENCY COMPARISON WITH EACH MATCHING CIRCUIT DESIGNED BY USING 100 SAMPLED DATA AND REPRESENTATIVE IMPEDANCE VALUES

	No MC	Ser L	Ser C	1 C	2 C	3 C	4 C
Eff (100) (%)	61.5	76.4	76.4	78.3	80.8	82.2	82.9
Eff (K-4) (%)	-	35.5	75.2	78.3	79.6	81.6	82.0
Eff (K-8) (%)	-	62.6	76.0	78.0	79.5	81.7	82.5
Eff (K-16) (%)	-	62.6	75.8	77.6	79.5	81.6	82.3

V. MEASUREMENT RESULTS

Based on the matching circuit design using GA on MATLAB, the prototype of 1 cell active matching circuit was fabricated as shown Fig. 6. The series inductor and parallel capacitor in the L matching network are Coilcraft 0603HL and Taiyo Yuden UMK105CG series, respectively. Also, the

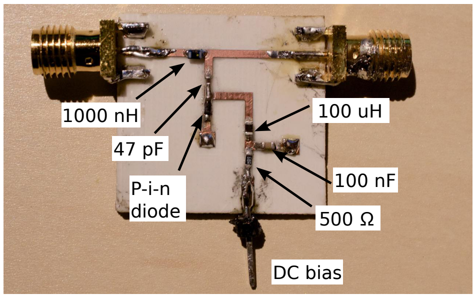


Fig. 6. Prototype of 1 cell active matching circuit.

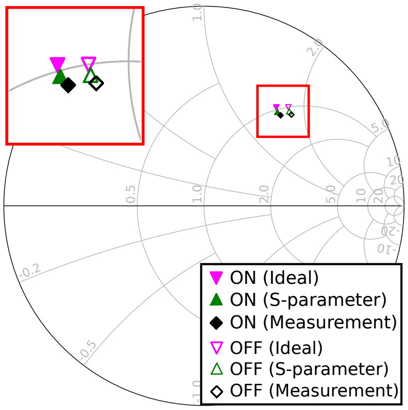
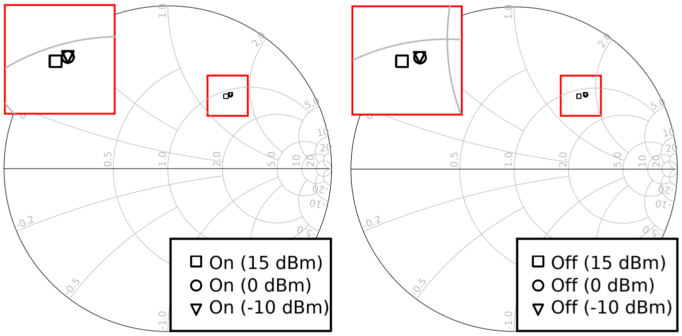


Fig. 7. Measured and simulated input impedances of 1 cell active matching circuit at on and off conditions.

p-i-n diode is Skyworks SMP1340. The bias circuit is the same design as previously reported results [5].

The two port S-parameters of the 1 cell matching circuit at on and off states were measured using the VNA with input power of 0 dBm at 13.6 MHz. The bias voltage at on condition is 5.5 V from Arduino Uno module. The S_{11} at on and off states are depicted in Fig. 7. As a comparison, ADS simulation results of matching circuit with ideal inductor, capacitor and switch, and with S-parameters of inductor and capacitor and non-ideal p-i-n diode model provided by manufacturers are also depicted in the same figure. As can be seen from the figure, there are slight differences between simulation results with ideal components and measurement results. The simulation results with S-parameters and non-ideal diode model are close to the measurement results, which implies that GA matching design process can be improved by integrating S-parameters of each lumped component instead of using ideal values.

The S_{11} of the matching circuit at on and off states are measure with different input power level. the The output power from the VNA was calibrated using the power sensor, NRP-Z211 from Rohde & Schwarz, at 15 dBm which is the maximum output power from the VNA at 13.6 MHz. The measurement results with input power of 15, 0 and -10 dBm are depicted in Fig. 8 (a) and (b). It can be easily recognized from figures that there are slight differences in input impedance values in the case of input power of 15 dBm compared to the other input power level. The variation can be larger if input power is higher.



(a)

(b)

Fig. 8. Measured input impedance of 1 cell active matching circuit with different input power level at (a) on and (b) off conditions.

VI. CONCLUSION

In this paper, a novel matching circuit design method utilizing the genetic algorithm based on the measured S-parameters of randomly moved coils was discussed. From the analytical comparison of different matching circuit topology, the superiority of active matching circuit is suggested, and potentially there is 21.4 % improvement in wireless power transfer efficiency by using 4 cell active matching circuit. Also, the matching circuit design simulation can be simplified by choosing only representative impedance values as targets utilizing K-means clustering. The matching circuit design time can be reduced to less than 20 min from 2 to 7 h by introducing the K-means clustering and the new fitting function without significant effects on the matching circuit performance. From the measurements of 1 cell active matching circuit input impedance, it is suggested that it is possible to improve the accuracy of the matching circuit design by integrating S-parameters of each lumped component in the matching design process.

VII. ACKNOWLEDGMENT

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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 Trans. Ind. Electron.*, vol. 60, no. 9, pp. 3689–3698, Sept. 2013.

[2] 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 Trans. Microw. Theory Techn.*, vol. 64, no. 2, pp. 365–374, Feb 2016.

[3] C. Sanchez-Perez, J. de Mingo, P. L. Carro, and P. Garcia-Ducar, “Design and Applications of a 300- 800 MHz Tunable Matching Network,” *IEEE Trans. Emerg. Sel. Topics Circuits Syst.*, vol. 3, no. 4, pp. 531–540, Dec. 2013.

[4] D. Arthur and S. Vassilvitskii, “K-means++: The Advantages of Careful Seeding,” in *Proceedings of the Eighteenth Annual ACM-SIAM Symposium on Discrete Algorithms*, 2007, pp. 1027–1035.

[5] J. Bito and M. M. Tentzeris, “Bias Circuit Design for a Real-time Electrically Controlled Active Matching Circuit utilizing p-i-n Diode Switches for Wireless Power Transfer,” in *2016 IEEE Antennas and Propag. Society Int. Symp.*, Fajardo, Puerto Rico, Jun-Jul. 2016.