Design of Maximum Efficiency Tracking Control Scheme for Closed-Loop Wireless Power Charging System Employing Series Resonant Tank

Tae-Dong Yeo, DukSoo Kwon, Seung-Tae Khang, and Jong-Won Yu, *Member, IEEE*

***Abstract*—This paper presents a maximum efficiency tracking control scheme for a closed-loop wireless power charging (WPC) system for wireless charging of mobile devices. Generally, wireless charging systems need a precise output voltage and current with the highest possible efficiency. In an open-loop system, output voltage and efficiency depend strongly on the coupling coefficient and load condition. Alternatively, a closed-loop WPC system has a constant output voltage against coupling and load variations. Many studies have been carried out regarding closed-loop systems. However, those previous studies have the drawback of efficiency degradation. In this paper, we propose a maximum efficiency tracking control scheme to achieve the highest possible efficiency. Therefore, the proposed WPC system satisfies both the requirements of a constant output voltage and high efficiency. The proposed control scheme determines the current of the transmitter based on the data received by the receiver via Bluetooth. For validation, the proposed WPC system was implemented at 6.78 MHz using loosely coupled series–series resonant coils, and we verified that the proposed system can track the maximum efficiency while maintaining a constant output voltage.**

***Index Terms*—Closed-loop system, maximum efficiency tracking control scheme, optimization load, variable load, wireless power charging, wireless power transfer.**

I. INTRODUCTION

WITH the growing demand for charging of wearable devices and internet of things devices anywhere without wires, wireless power transfer (WPT) has been studied. Therefore, in recent years, most research in this area has focused on high efficiency and long charging distance [1]–[3], but it is just concerned with transferring energy. However, many real industrial and commercial applications must provide a precise output voltage with the highest possible efficiency. Unfortunately, output voltage and efficiency vary with the coupling coefficient and load conditions in an open-loop WPT system. Additionally, the coupling coefficient and load conditions vary in relation to the environment. For instance, during the charging of a smart phone, the load conditions change because the charging battery, and coupling coefficient is changed by the position of the smart phone. Therefore, in this paper, the proposed wireless power charging (WPC) system is intended to satisfy the requirements for both the constant output voltage and high efficiency.

To provide a constant output voltage, the design of the proposed WPC system was based on a postregulation closed-loop system, which is among the studied closed-loop regulation methods. There are three types of closed-loop regulation methods: frequency tracking, impedance matching, and dc/dc conversion. In frequency tracking methods, the frequency is adjusted in the "overcoupled" region because of the frequency split phenomenon to regulate the constant output voltage [2], [4], [5]. In the proposed WPC system, there is no necessity for frequency tracking because it is a loosely coupled system. In impedance matching methods, the resonant capacitor is regulated by relays or semiconductor switches at a fixed frequency [6], [7], [12]. Thus, it can regulate the output voltage by changing impedance and constant output voltage can also be maintained, but the impedance matching circuit is complex and has a loss, and control is difficult. The last type of method uses a dc/dc converter in the receiving or transmitting side [8]. It is a simple structure to provide a constant output voltage. When such a system is applied to the closed-loop regulation, it degrades system efficiency because the equivalent load impedance deviates from the optimal point; however, efficiency can be improved by the proposed maximum efficiency tracking control scheme.

To improve efficiency, the proposed system was applied to maximum efficiency tracking by the control structure (see Fig. 1). In previous studies, equivalent load impedance was controlled by the additional boost converter on receiving sides [9]. However, its additional component has a loss and increase the complexity compared with proposed structure. In other studies, the conversion ratio of the dc/dc converter was controlled on both the transmitting and receiving sides [10], [11]. This scheme is not suitable for a series resonant tank with a class D inverter because of the extremely low load impedance of the dc/dc converter on the transmitting side. Thus, the proposed MET scheme controls the current of the transmitter I_T instead of the voltage using the control structure and out-of-band signal communication (Bluetooth). Moreover, it does not need to control the load conversion ratio at the receiving side. Therefore, the equivalent load can be changed by controlling the current of the transmitter. In other words, equivalent load deviating from the optimal point can be blocked by the proposed control scheme. For validation, a transmitter composed of a class D power amplifier and control structure as well as a receiver composed of a full-bridge rectifier and dc–dc converter were

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The authors are with the School of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 350-701, Korea (e-mail: taedong14@kaist.ac.kr; duksoo@kaist.ac.kr; stkhang@kaist.ac.kr; drjwyu@ee.kaist.ac.kr).

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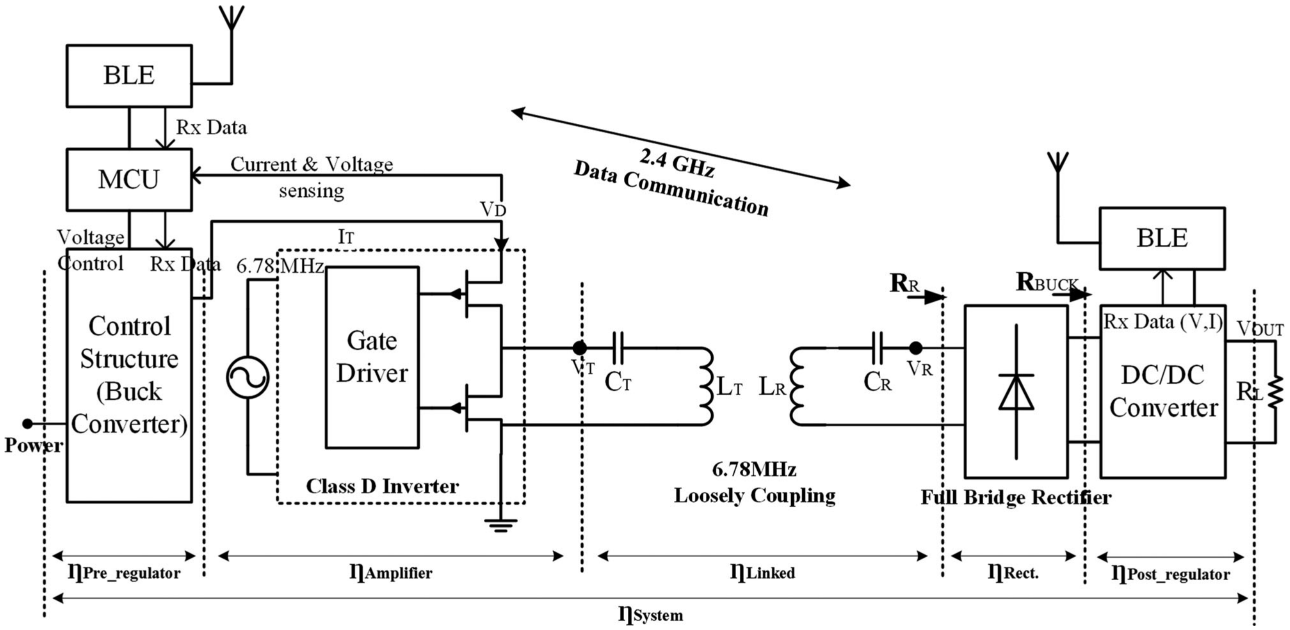

Fig. 1. Concept of proposed closed-loop loosely coupled wireless power charging system: Class D amplifier, control structure, series resonant coil, adaptive receiver, and Bluetooth low energy.

implemented at 6.78 MHz. Transmitting and receiving coils were printed on an FR4 substrate in the A4WP specific. The results of end-to-end measurement [system efficiency η_{system} in Fig. 1.] from the dc power amplifier to the dc load showed that maximum efficiency was maintained at every distance. Wherever there are receivers or whatever receiver has load condition, it can be charged with maximum efficiency.

The remaining paper is organized as follows. Section II introduces closed-loop systems and analyzes the output voltage and efficiency. Then, in Section III, we introduce the maximum efficiency tracking control scheme, and in Section IV, we present the design of the transmitter and receiver. Section V verifies the performance of the MET control scheme and presents the measured results. Finally, this paper concludes with a short summary in Section VI.

II. CLOSED LOOP WIRELESS POWER CHARGING SYSTEM

Unlike the open-loop WPT system, the closed-loop WPT system has the advantage of a constant output voltage. As shown in Fig. 2, the reported general closed-loop regulation methods can be divided into three groups: 1) frequency tracking, 2) impedance matching, and 3) dc/dc conversion (postregulation).

1) Frequency Tracking: Output voltage has two separate peak frequencies in the "overcoupled" region. Thus, this scheme controls the operating frequency to maintain the output voltage. To increase the output voltage, the operating frequency is moved to one of the divided frequencies. Otherwise, the output voltage decreases as the frequency is moved away from the peak frequencies.

2) Impedance Matching: This scheme controls the value of the capacitors by using relays or semiconductor switches. The value of the capacitors changes the output voltage. With a mismatch of the impedance between the power amplifier and load, the output voltage decreases.

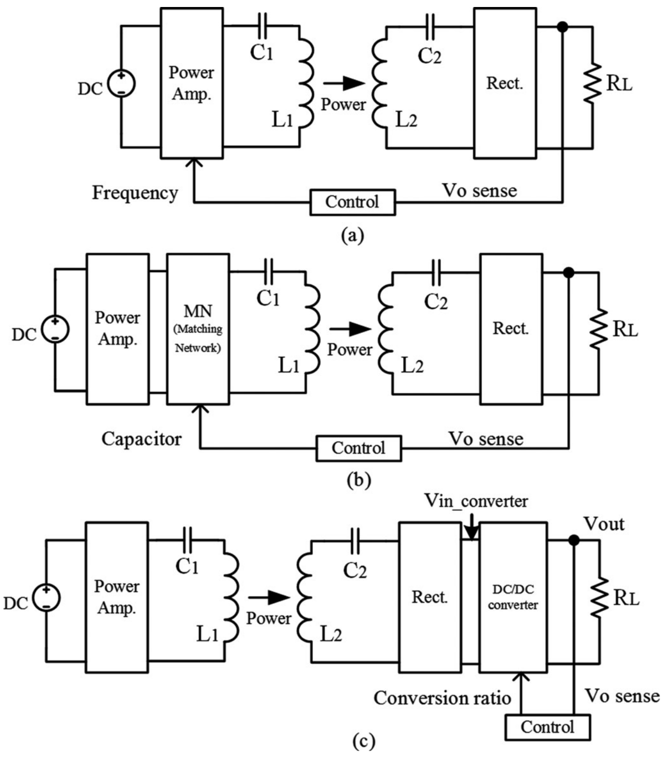

Fig. 2. Three reported closed-loop regulation group: (a) Frequency tracking. (b) Impedance matching. (c) DC/DC conversion (postregulation).

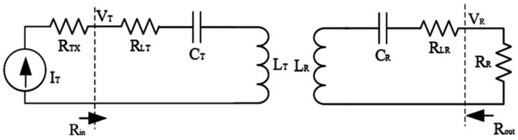

Fig. 3. Equivalent circuit of proposed wireless power charging system.

3) DC/DC Conversion (postregulation): Without changing the operating frequency, the output voltage can be regulated by a dc/dc converter. The conversion ratio is given by

$$C_{\text{load}} = \frac{V_{\text{out}}}{V_{\text{in, converter}}} \tag{1}$$

where $V_{\text{in, converter}}$ is the input voltage of the dc/dc converter. According to the input voltage, the output voltage can be maintained by varying the conversion ratio. The fixed operating frequency of the loosely coupled system does not require the frequency tracking scheme. Also, the impedance matching scheme has matching loss and a complicated matching network. Therefore, the proposed system was chosen for dc/dc conversion regulation. Although the closed-loop regulation method can provide a constant output voltage, it degrades system efficiency. To compensate the decrease, the system efficiency of the closed-loop WPC system should be improved.

III. PROPOSED MAXIMUM EFFICIENCY TRACKING CONTROL SCHEME

A. Analysis of the Proposed WPC System

Fig. 3 shows the simplified equivalent circuit of the proposed WPC system. Loosely coupled coils are in different sizes and shapes, but they share the same resonant frequency

$$w_0 = \frac{1}{\sqrt{L_T C_T}} = \frac{1}{\sqrt{L_R C_R}}. \tag{2}$$

Its linked efficiency[1] is the function of the coupling coefficient and load impedance, and the efficiency of the proposed system is driven by

$$\begin{aligned}\eta_{\text{Linked}} &= \frac{P_R}{P_T}\\ &= \frac{L_R k^2 R_R}{(R_{\text{LR}} + R_R)\left(R_{\text{LT}} C_T \left(R_{\text{LR}} + R_R\right) + L_R k^2\right)}.\end{aligned} \tag{3}$$

The efficiency η_{Linked} depends on the coupling coefficient k and the equivalent load impedance R_R. As mentioned in Section II, because the proposed closed-loop WPC system is chosen as the postregualtion method, the equivalent load impedance R_R is varied by the $V_{\text{in, converter}}$. The equivalent load impedance R_R is given by

$$R_R = \frac{R_L}{C_{\text{load}}^2} = \frac{R_L}{\left(\frac{V_{\text{out}}}{V_{\text{in,coverter}}}\right)^2} = \frac{R_L V_{\text{in,coverter}}^2}{V_{\text{out}}^2} \tag{4}$$

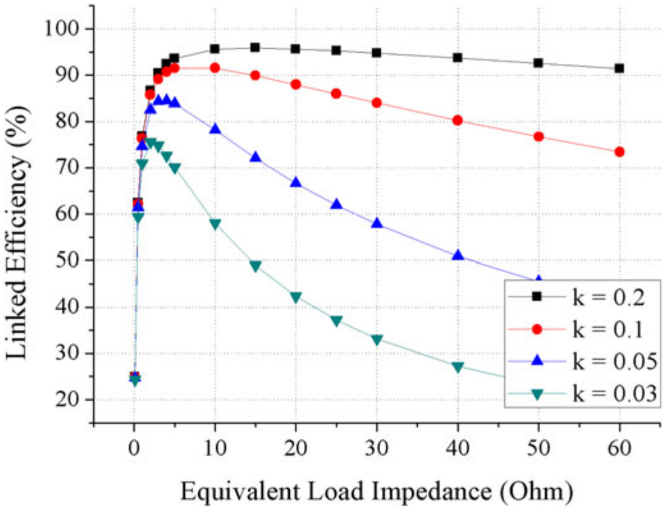

Fig. 4. Linked efficiency according to equivalent load impedance and coupling coefficient.

where R_L is the load impedance (ratio of charging current to voltage), and V_{out} is the precise charging voltage. Therefore, the linked efficiency decreases because the dc/dc converter regulates the output voltage. The linked efficiency of a function of the equivalent load impedance and the coupling coefficient was calculated and the results are plotted in Fig. 4. As seen in the figure, the linked efficiency is changed by the equivalent load impedance and the coupling coefficient, and the equivalent load impedance has an optimal point.

B. Principle of the Proposed MET Control Scheme

In a previous study [11], the drain voltage of an amplifier was controlled by the controller, but the method is not suitable for a series resonant tank because the input impedance toward the receiver R_{in} is very low at the operating frequency. If the drain voltage is high, the current of the amplifier would be extremely high, and this would cause critical damage to the amplifier. Therefore, the drain voltage of the amplifier V_D cannot reach the desired value, and the voltage-controlled method is not suitable. For this reason, we propose the MET control scheme which can control current.

To improve the efficiency degradation associated with the closed-loop regulation, we need to control the coupling coefficient and the equivalent load impedance from (3). First, the coupling coefficient changes in relation to the position of the receiver, so we cannot control it. Second, from (4), the equivalent load impedance is regulated by the input voltage of the dc/dc converter ($V_{\text{in, converter}}$). $V_{\text{in, converter}}$ is controlled by the transmitting current in the proposed system. Thus, we get the equation of the equivalent load impedance

$$R_R = \frac{L_T R_L k^2 I_T^2 - B + \sqrt{\left(B - L_T R_L k^2 I_T\right)^2 - 4AC}}{2A} \tag{5}$$

where $\text{A} = \text{V}_{\text{out}}^2 C_T$, $\text{B} = 2\text{R}_{\text{LR}} V_{\text{out}}^2 C_T$, and $\text{C} = \text{V}_{\text{out}}^2 C_T R_{\text{LR}}^2$. Fig. 5 shows the equivalent load impedance according

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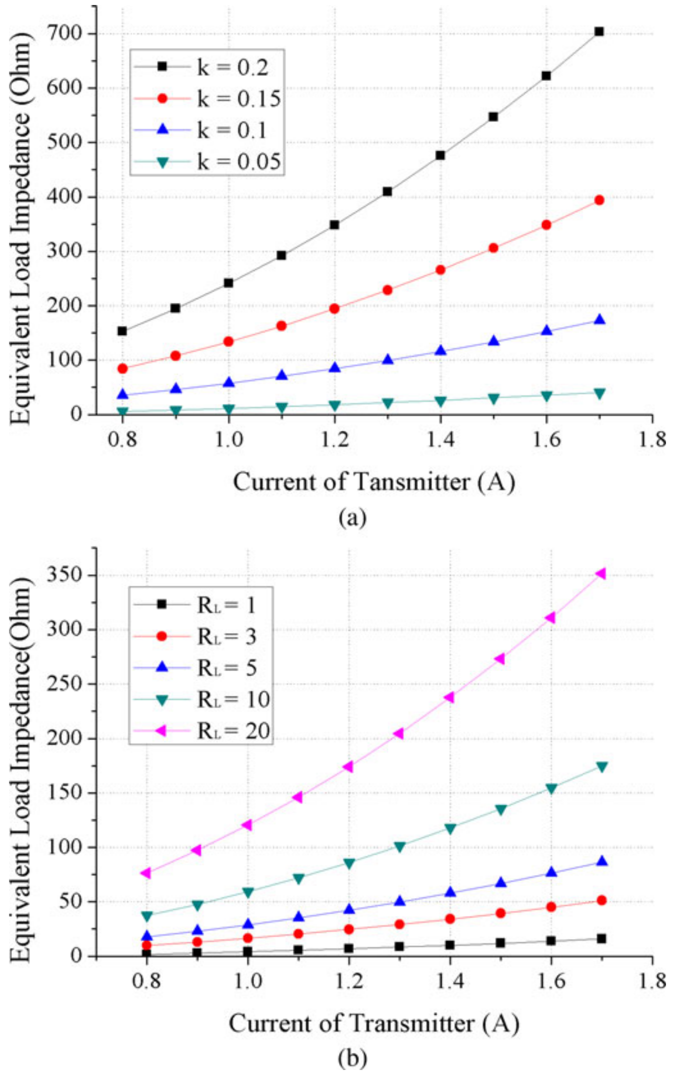
[1] Linked efficiency is an efficiency between transmitter coils to receiver coil.



(a)

(b)

Fig. 5. (a) $R_L = 5\Omega$, the equivalent load impedance according to coupling coefficient and current of transmitter. (b) $k = 0.2$, the equivalent load impedance according to load impedance R_L and current of transmitter: $A = 8.15 \times 10^{-9}$, $B = 4.89 \times 10^{-9}$, $C = 7.335 \times 10^{-10}$.

to the current of the transmitter I_T when the coupling coefficient *k* and the load impedance R_L have reasonable values. Generally, the loosely coupled system has a coupling coefficient *k* under 0.2, and the load impedance R_L ranges from one to scores of ohms in a battery case. The load value is changed by the battery states, and the coupling coefficient is changed by the position of the receiver. The equivalent load impedance R_R can be controlled by the current of the transmitter with any coupling coefficient and the load impedance. Thus, the linked efficiency can be controlled by the current of the transmitter as shown in Fig. 6. In other words, the control structure traces the maximum efficiency in variation of the coupling factor and load impedance. However, we fixed the load impedance at 5 Ω because of an implementation and experimental problem.

In short, the proposed WPC system has closed-loop regulation to provide a constant output voltage regardless of the coupling coefficient and the load impedance. With the optimal load impedance, the system has maximum efficiency. However, the equivalent load impedance deviates from the optimal point because of the closed-loop regulation. To compensate the efficiency degradation, the proposed MET control scheme moves the equivalent load impedance to the optimal point using the control structure to control the current of transmitter.

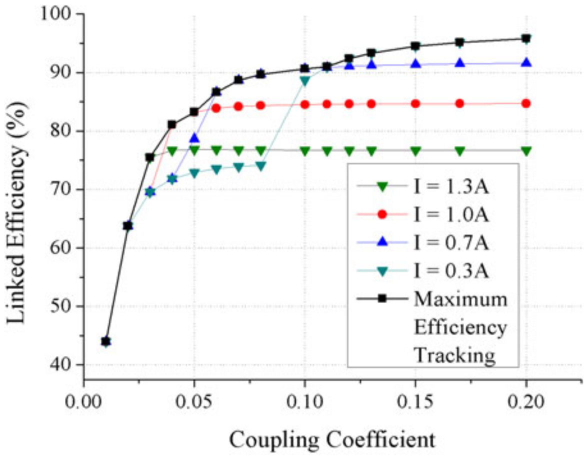


Fig. 6. Linked efficiency according to coupling coefficient and current of amplifier:maximum efficiency tracking.

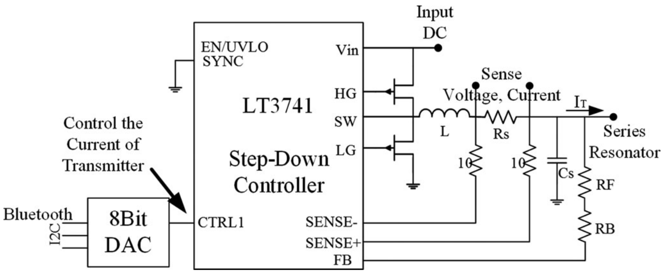


Fig. 7. Simplified Circuit of proposed control structure.

C. Design of the Control Structure

Fig. 7 shows the control structure circuit. The control structure can control the current at intervals of 10 mA using an 8-bit digital–analog converter (DAC) converter based on the received states of the receiver using Bluetooth. The control structure consists of an 8-bit DAC and a step-down controller (LT3741) that can control the current and sense the current and voltage of the amplifier. The output of the control structure generates a bandpass-filtered output with an external capacitor C_S whose value is about 1 μF [low equivalent series resistance (ESR)]. The values of the output inductor L, which reduces the current ripple, and the sense resistor R_S, which ensures the precise value to sense the current, are 10 nH and 24 mΩ, respectively. The output current is limited by the voltage of the CTRL1 pin, which is controlled by microcontrol units (MCU) via I2C communication. When there is no receiver, a short current can cause critical damage to the transistor. The control structure is needed to prevent such damage. The current is always limited because the input impedance toward the transmitting coil R_{in} is

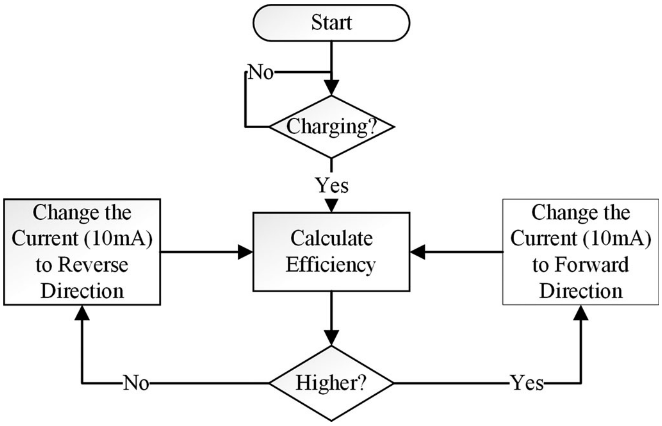


Fig. 8. Flowchart of the proposed MET control algorithm.

extremely low. Therefore, the current of the transmitter can be controlled by changing the value of the limited current.

Fig. 8 shows a flowchart of the maximum-efficiency tracking control algorithm. When the receiver is located above the transmitting coil, Bluetooth starts to connect the transmitter and the receiver. Then current and voltage are sensed on both the sides. The current and the voltage of the amplifier can be measured by the control structure, and the received data also can be measured using the sense resistor. The data of the receiver will be sent to the transmitter via Bluetooth every millisecond. Based on the data, the MCU calculates the efficiency and decreases the current of the amplifier at intervals of 10 mA. It can be controlled by the voltage of the CTRL1 pin of the step-down controller IC, which is changed by the MCU via the DAC. If the changed efficiency is higher than the previous efficiency, the current is not changed from the forward direction; otherwise, the current is changed to the reverse direction. We can find the maximum efficiency by using the algorithm as mentioned above. Thus, we can calculate the efficiency and find the maximum efficiency by changing the current of the transmitter at intervals of 10 mA. Thus, the receiver can be charged with maximum efficiency at every moment.

IV. DESIGN OF PROPOSED WPC SYSTEM

Fig. 9 shows the implemented structure of the proposed WPC system operating at 6.78 MHz. This system is composed of Class D high power amplifier (HPA) having maximum 20-W power, the control structure for controlling current of an HPA, the 5-W receiver with a full-bridge rectifier and a dc/dc buck converter, and Bluetooth (Noridc Semi. n51822). Because of the MCU of the Bluetooth, it does not need to add another MCU for maximum power tracking. Table I summarizes system parameters. The transmitting and the receiving resonant coil are fabricated on FR4 (thickness 0.6 mm, relative permittivity 4.6, tangent loss 0.015) compliant with A4WP standard [16]. The transmitting coil has the size of 209 × 140.02 mm^2, an inductance L_T of 1.69 μH, and the equivalent series resistance R_{LT} of 0.53 Ω. The receiving coil has the size of 60 × 44 mm^2, an inductance L_R of 1.60 μH, and the equivalent series resistance R_{LR} of 0.57 Ω. The coupling coefficient is under 0.2, which is a loosely coupled system. Following is the design procedure for developing the proposed WPC system along the explanation in Section III.

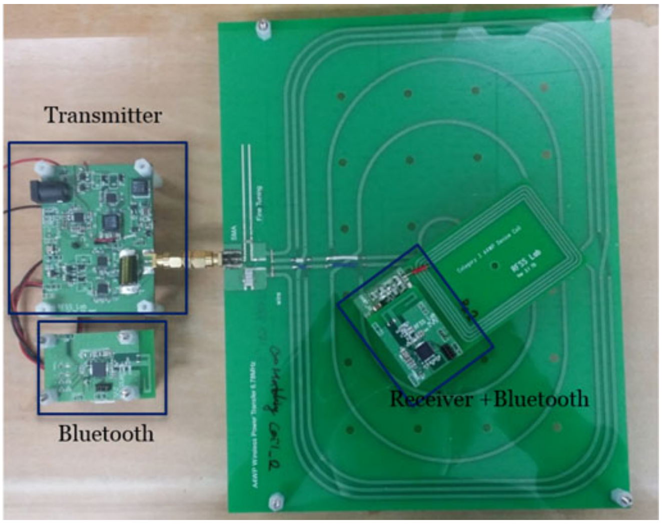


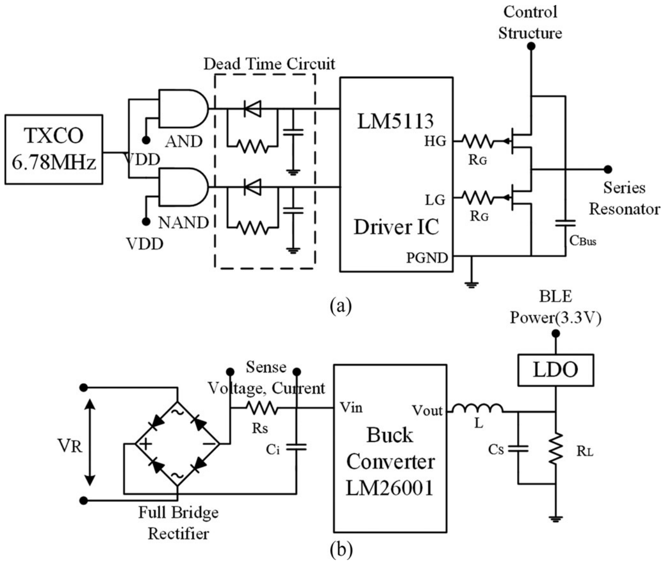
Fig. 9. Implementation of 6.78-MHz proposed closed loop wireless power charging system.

TABLE I
PARAMETERS OF THE EXPERIMENTAL SYSTEM

Parameters		Values
Tx Coil	Size	209 mm $\times$ 140.02 mm
	Inductance (R_{LT})	1.69 μH (0.53 Ω)
	Matching Capacitor	323.2 pF
Rx Coil	Size	60 mm $\times$ 44 mm
	Inductance (R_{LR})	1.60 μH (0.57 Ω)
	Matching Capacitor	330 pF
Power Amp.	Operating Frequency	6.78 MHz
	Output Power	Max. 20 W
	Dead Time Circuit	$R=$ 180 Ω , $C=$ 54 pF
Receiver	Load Impedance	5 Ω
	Received Power	5 W (5 V, 1 A)

A. *Transmitter*

The schematic of the HPA-based transmitter is shown in the Fig. 10(a). The component selected for the design of the HPA is the EPC2014 transistor with GaN FETs. We choose the GaN FETs because the output capacitor of the GaN transistor is extremely low. In other words, it has low power consumption. It is powered by the control structure connected to drain node of the transistor. The two complementary switch signals are driven by the IC driver (LM5113) and the driver is powered with 5 V and 40 mA when operating 6.78 MHz. External resistance R_G of 2.2 Ω were worked between the driver and the switches to control the peak gate current and minimize the gate voltage ripple. To avoid the short circuit current of the switches, overlapping of the two complementary signals are prevented. In order to prevent overlapping the two complementary signal, the *RC* network and the diode network are formed, that adjusts the dead time between



(a)

(b)

Fig. 10. 6.78 MHz Class D HPA-based transmitter schematic and receiver circuit. (a) Transmitter. (b) Receiver.

the complementary signals. The *RC* network changes slopes of rising and falling edges of the complementary commands.

B. *Receiver*

As shown in Fig. 10(b), the receiver is composed of the full-bridge rectifier and the dc/dc buck converter. The diode rectifier changes to dc voltage from the sinusoidal voltage of the resonant coil and the buck converter (LM26001) steps down the input voltage for the suitable charging voltage. The buck converter should be selected considering the input voltage $V_{\text{in, converter}}$ to have suitable range. The input capacitor C_i with high ESR is required to reduce noise, EMI, and ripple at the input node. The output capacitor with low ESR ($C_S = 10\ \mu$F) is chosen. The current can be sensed by the difference between sense+ node and sense− node, and the sense resistor ($R_S = 24$ mΩ) has very small voltage drop.

In order to reduce the conduction loss and the switching loss, diode should endure very fast switching. Diodes, Inc., PD3S140 is chosen and has 40-V breakdown voltage, 0.45-V forward voltage, and 1-A forward current. In addition, low parasitic capacitor of diode is a critical design parameter to have negligible reactance, so we can simply analyze the receiver ($R_R \cong R_{\text{BUCK}}$ in Fig. 1).

V. MEASURED RESULTS

Fig. 11 illustrates the experimental setup. For the experiment, the input dc voltage was supplied by an external power supply, and the electrical load was used to measure the exact load. In addition, we monitored the states of the system, including efficiency, voltage, and current, using a laptop. We measure the system efficiency as shown in Fig. 1, because it is difficult to measure linked efficiency directly.

Fig. 13 show the equivalent load impedance according to the current of the transmitter. The measured data is similar to

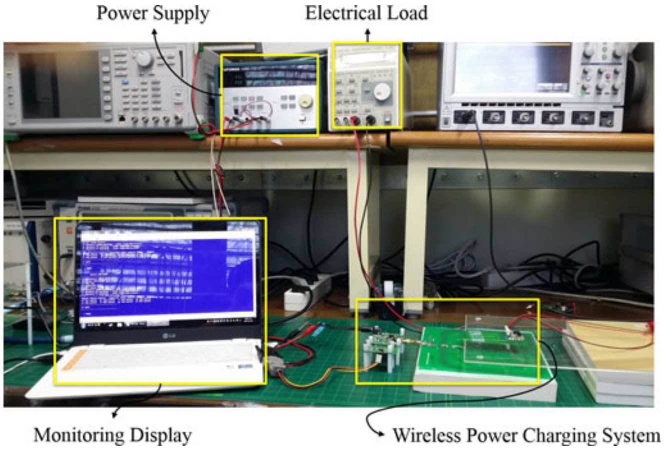


Fig. 11. Experiment Environment.

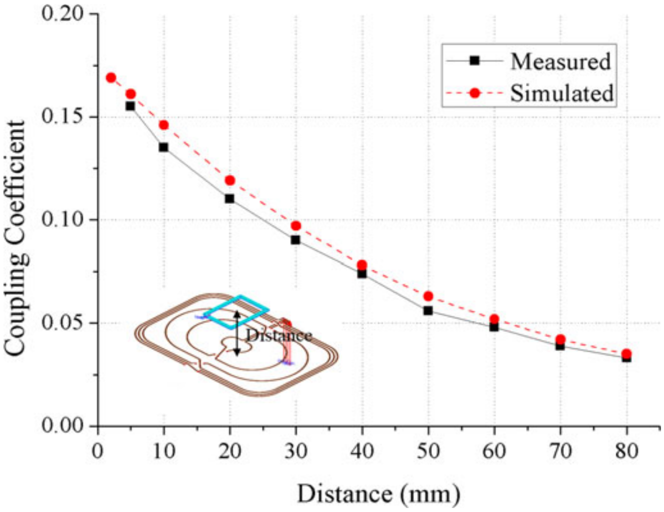


Fig. 12. Measured results and simulated results of coupling coefficient according to vertical distance between Tx coil and Rx coil.

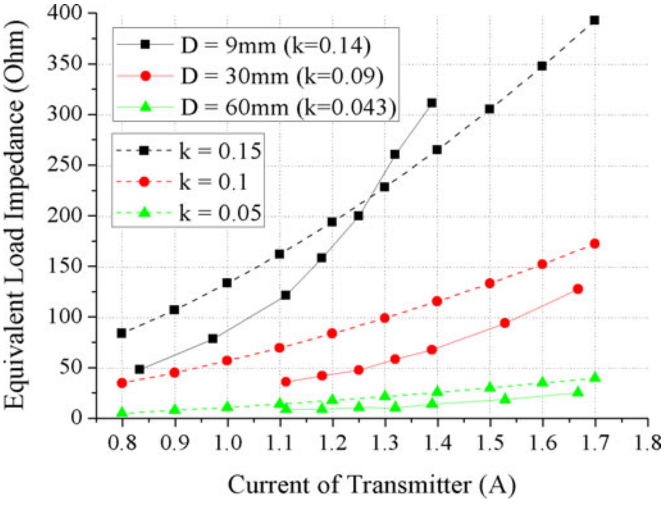


Fig. 13. Measured results (solid line) and simulated results (dash line) of equivalent load impedance according to transmitter current and vertical distance between Tx coil and Rx coil (coupling coefficient).

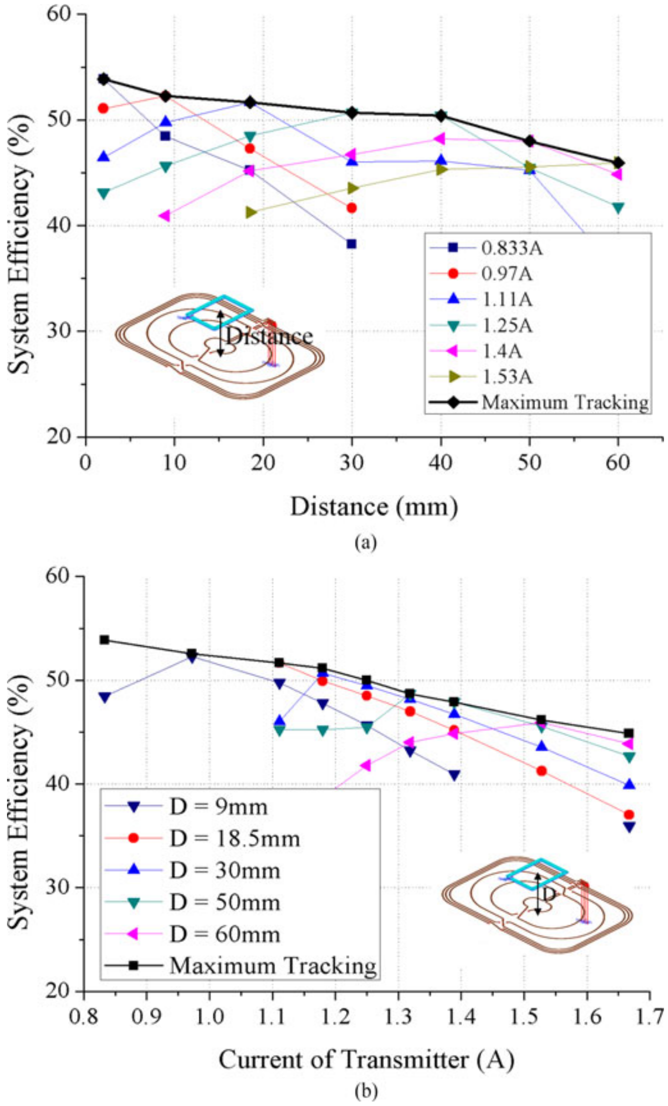


Fig. 14. Measured results of total efficiency of proposed wireless power charging system and maximum efficiency tracking (a) according to distance and (b) current of transmitter.

the simulation data, shown in Fig. 5, obtained when the load impedance R_L is 5 Ω. As mentioned in Section III, the equivalent load impedance R_R is determined by the current of the transmitter given by (5). We verified that the control structure can adjust the equivalent load impedance.

As shown in Fig. 14(b), when the current of the transmitter changes, the equivalent load impedance changes, and the variation of the equivalent load impedance changes the system efficiency. The system efficiency is varied with the current of the transmitter even at the same distance. Fig. 14(a) shows that the system efficiency traces the maximum point by controlling the current of the transmitting coil according to the position of the receiver. As shown in Fig. 12, the coupling coefficient, which is always under 0.2, varies with the distance between the transmitter and the receiver, so we measured all the data according to the distance. Therefore, the measurement data and the theoretical data are horizontal symmetric because the distance and the coupling coefficient are inversely proportional to each other [15]. Also, the system efficiency is the generic term including linked efficiency and all other block efficiencies, such as those of the power amplifier, buck converter, and rectifier. The efficiency of the buck converter is vulnerable to input voltage and load current. Thus, the graph shapes shows a little difference between the linked efficiency (see Fig. 6) and the total efficiency (see Fig. 14). However, we verified the performance of the maximum efficiency tracking control scheme using the control structure from Fig. 14.

VI. CONCLUSION

We applied a closed-loop system to maintain a constant output voltage against coupling and load variations, although system efficiency was degraded because the equivalent load impedance deviated from the optimal point. Therefore, in this paper, we proposed the MET control scheme, which can control current based on data received via Bluetooth communication, to compensate the degraded efficiency. Thus, we provide a constant output voltage with the highest possible efficiency. Our analysis showed that the efficiency can be controlled by the current of the transmitter. Thus, the proposed closed-loop WPC system has the maximum system efficiency (η_{system}) over the fluctuation of the coupling coefficient and load variation. To verify the result, we implemented the proposed loosely coupled WPC system operating at 6.78 MHz. The MET control scheme demonstrated a system efficiency (η_{system}) of about 50% consistently with a variation of the vertical distance between the transmitter and the receiver from 0 to 60 mm. The proposed WPC system can track the maximum efficiency point without sensitivity to environmental conditions.

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TaeDong Yeo received the B.S. and M.S. degrees in electronic engineering from Korea Advanced Institution Science and Technology (KAIST), Daejeon, Korea, in 2013 and 2015, respectively. He is currently working toward the Ph.D. degree in electrical engineering from KAIST.

His current research interests include near-field wireless charging system and coil design, active array antenna, and RF/Microwave circuit design.

DukSoo Kwon received the B.S. degree in electronic engineering from Kyungpook National University, Daegu, Korea, in 2013, and the M.S. degree in electrical engineering from the Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 2016.

Since 2016, he has been with the Electronics and Telecommunications Research Institute, Daejeon, Korea, where he is involved in the research of electromagnetic compatibility (EMC) and hazard assessment for electromagnetic field (EMF) exposure. His current research interests include MIMO antenna design, near-field wireless charging system, RF/Microwave circuit design, and EMI/EMC.

SeungTae Khang received the B.S. degree in electronic engineering from Chungang University, Seoul, Korea, in 2012, and the M.S. degree in electronic engineering from the Korea Advanced Institute of Science and Technology, Daejeon, Korea, in 2014, where he is currently working toward the Ph.D. degree in electronic engineering.

His current research interests include FMCW radar system, millimeter-wave transceiver design, and wireless power transfer system.

JongWon Yu (M’05) received the B.S., M.S., and Ph.D. degrees in electronic engineering from Korea Advanced Institution Science and Technology (KAIST), Daejeon, Korea, in 1992, 1994, and 1998, respectively.

From 1995 to 2000, he was with Samsung Electronics. He was also with Wide TECOM Head and Telson, from 2000 to 2001 and from 2001 to 2004, respectively. In February 2004, he was an Assistant Professor of electrical engineering with KAIST, where in February 2006, he became an Associate Professor of electrical engineering, and since February 2014, he has been a Professor at KAIST. His current research interests include microwave/millimeter-wave circuit (hybrid), wireless power transfer, wireless/near-field communication system, and radio frequency identification/ubiquitous sensor network.