Distance Detection System for Digital Transmitter Coil Achieving Distance-Variation-Tolerant Wireless Power Transfer

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***Abstract*— In this paper, a distance detection system that only processes the information in the transmitter (TX) side is proposed. By using the distance detection system, the radius of the digital TX coil can change automatically depending on the distance and thus achieve the maximum efficiency tracking. A wireless power transfer (WPT) prototype is fabricated and experimental results demonstrate that, compared with using the conventional TX coil with a constant radius, the efficiency is improved from 12% to 20% at the distance of 4 times the RX coil radius.**

Keywords—Coil-to-coil efficiency, coil design, distance variation, distance detection, impedance measurement, magnetic resonance coupling, mutual inductance, optimal radius, wireless power transfer.

I. Introduction

Wireless power transfer (WPT) using magnetic resonance coupling has been applied in a wide range of applications such as electric vehicles (EVs), portable electronics and biomedical implanted devices [1]–[4]. The distance (d) variation between the transmitter (TX) and receiver (RX) coils is a common problem. For example, EVs with different ground clearances [2] can have a different d. In portable electronics [3], it is preferred that these devices are not put on the wireless charging pad but can be held in hand and operated during wireless charging. Thus, d can change during operations. In biomedical implanted devices [4], the different body postures of the patients can also change d and affect the system's efficiency. Thus, a d-variation-tolerant WPT method is required for practical applications.

The efficiency of a WPT system is determined by both the coil-to-coil efficiency (η) and the impedance matching condition [1]. When d changes, the coupling between the TX and RX coils varies and then affects η. In addition, the coupling variation changes the input impedance of the TX coil and there will be an impedance mismatch with the source impedance. Therefore, the maximum system efficiency cannot be achieved when d varies.

Several adaptive impedance matching methods with respect to d have been proposed. The first method uses the adaptive frequency tracking [5]. The optimal frequency is tracked to overcome the frequency-splitting phenomenon even when the coupling between TX and RX coils enters the over-coupling region. However, it can be problematic since the industrial, scientific, and medical (ISM) bands are very narrow. The second method has the same operating frequency but uses the adaptive impedance matching network [1], [6]–[7], which requires complex control and affects the system's reliability. The third method uses coil repeaters between the TX and RX coils [8]–[12], in which a large number of repeaters adds the system's complexity. In addition, the impedance matching condition in [8]–[9] is adjusted manually, which makes the system impractical.

Though the above methods can achieve the impedance matching condition with respect to d, η cannot be improved since the coil design is not discussed. In [13], the optimal design of the RX coil was discussed. From a practical point of view, however, a TX-only tuning is preferred since the RX coil should be as simple as possible. On the other hand, [14] shows the optimal layout of the TX coil, but how to adaptively change the coil's radius is not discussed.

In [15], the topology of digital TX coil that consists of several sub-coils connected in parallel is proposed and its radius can be changed by selectively turning on one of these

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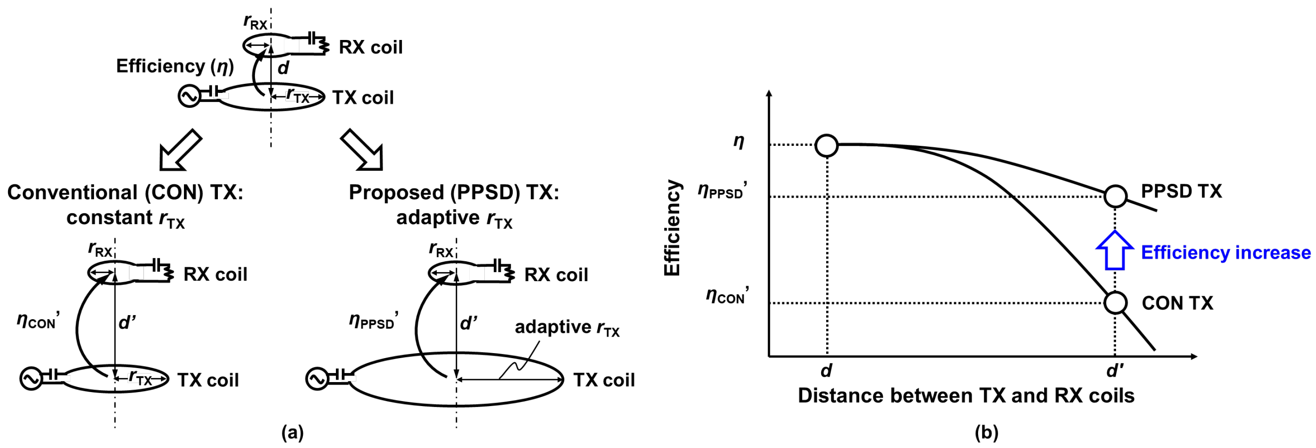

Fig. 1. (a) Conventional TX coil with constant r_{TX} and the proposed TX coil with adaptive r_{TX} depending on d. (b) Schematic of d dependence of η.

sub-coils. However, its radius is changed manually, which is far from practical applications. In this paper, we propose a d detection system that only processes the information in the TX side. Based on the d detection system, the digital TX coil can change its radius automatically and realize the tracking of the maximum η at different d. The rest of the paper is organized as follows. Section II discusses the optimal radius of the TX coil for the maximum η. In Section III, the digital TX coil integrated with the d detection system is proposed. Experimental results are presented in Section IV. Finally, conclusions are given in Section V.

II. Optimal Transmitter Coil Radius for Maximum Efficiency

In this paper, as shown in Fig. 1, it is assumed that the RX coil is perfectly aligned with the TX coil and changes its position along the central axis. The radii of the TX and RX coils are r_{TX} and r_{RX}, respectively. In a conventional (CON) design, the TX coil has a constant radius, whereas in the proposed (PPSD) design, the TX coil has an adaptive r_{TX} that depends on d. As d increases to d', η_{PPSD}' using the PPSD TX coil is higher than η_{CON}' using the CON TX coil.

In a WPT system, η is defined as the ratio of the power delivered to the load (R_L) to the power input into the TX coil. Under the condition that R_L is the optimal value, η can be expressed as [16]

$$\eta = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2}, \tag{1}$$

where

$$k^2 Q_{TX} Q_{RX} = \frac{\left(2\pi f_0 M\right)^2}{R_{TX} R_{RX}}. \tag{2}$$

Here, f_0 is the resonance frequency. M is the mutual inductance between the TX and RX coils. R_{TX}, R_{RX} are the parasitic resistances of the TX and RX coils, respectively. k is the coupling coefficient between the TX and RX coils. Q_{TX} and Q_{RX} are the quality factors of the TX and RX coils, respectively.

Thus, η can be optimized by maximizing $k^2Q_{TX}Q_{RX}$.

$k^2Q_{TX}Q_{RX}$, on the other hand, is correlated with the physical parameters of the coils. Firstly, we discuss the calculation of the coils' resistances. For loosely wounded coils, the proximity effect is negligible, so R_{TX} and R_{RX} can be simplified to [14]

$$R_{TX} = \frac{2m r_{TX}}{\sigma\varpi\delta},\; R_{RX} = \frac{2n r_{RX}}{\sigma\varpi\delta}. \tag{3}$$

Here, σ is the conductivity of copper (5.96×10^7 S/m), ϖ is the diameter of the copper wire (1 mm). The skin depth (δ) can be calculated as $(\pi\mu_0 f_0\sigma)^{-1/2}$, where μ_0 is the vacuum permeability ($4\pi\times10^{-7}$ H/m). m and n are the number of turns of the TX and RX coils, respectively.

Secondly, under the condition that $r_{RX} \ll r_{TX}$, M can be obtained as [17]

$$M = \frac{\mu_0\pi}{2} mn \frac{{r_{TX}}^2 {r_{RX}}^2}{\left(d^2 + {r_{TX}}^2\right)^{3/2}}. \tag{4}$$

By substituting (3) and (4) into (2), $k^2Q_{TX}Q_{RX}$ is expressed as

$$k^2 Q_{TX} Q_{RX} = \left(\frac{\pi^2\mu_0\sigma\varpi\delta f_0}{2}\right)^2 mn \frac{{r_{RX}}^3}{\left(r_{TX} + d^2/r_{TX}\right)^3}. \tag{5}$$

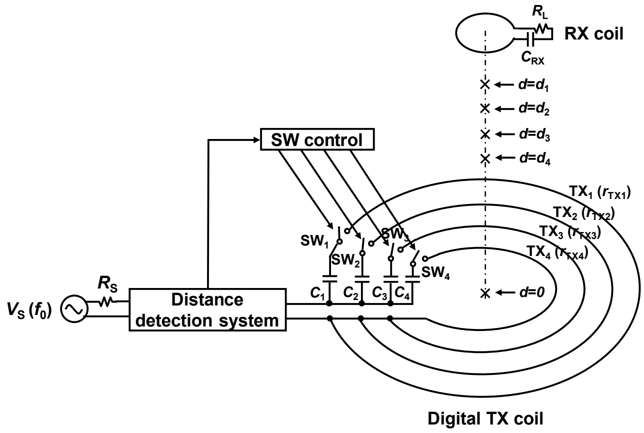

Fig. 2. A WPT system consisting of the proposed digital TX coil, the RX coil, and the d detection system.

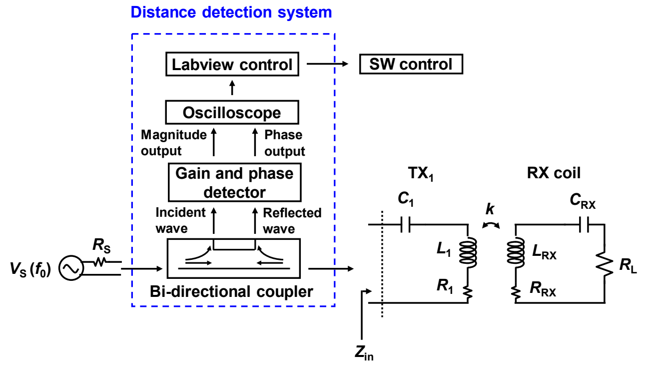

Fig. 3. Block diagram of d detection system in Fig. 2. TX_1 in the digital TX coil is used. d can be detected by measuring Z_{in}.

It can be derived that when f_0, m, n, and r_{RX} are constants, $k^2Q_{TX}Q_{RX}$ reaches the maximum when r_{TX} equals its optimal value ($r_{TX,\,OPT}$) which is obtained as

$$r_{TX,\,OPT} = d \;. \tag{6}$$

Equation (6) means, under the condition that $r_{RX} << r_{TX}$, using the TX coil with r_{TX} that equals d, we can achieve the maximum η.

III. Digital Transmitter Coil with Proposed Distance Detetion System

A. Digital Transmitter Coil Topology

Fig. 2 shows a WPT system consisting of a voltage source (V_S) with a source resistance (R_S), the digital TX coil, the RX coil, and the proposed d detection system followed by a switch (SW) control unit. In this paper, we assume the RX coil has four positions, namely, d_1, d_2, d_3, and d_4. The digital TX coil consists of four concentric sub-coils (TX_1, TX_2, TX_3, and TX_4). For TX_p (p = 1, 2, 3, and 4), its radius (r_{TXp}) is determined according to (6). Its number of turns, inductance and parasitic resistance are represented by m_p, L_p, and R_p, respectively. The compensation capacitor has the capacitance of C_p. For the RX coil, the inductance and compensation capacitance are represented by L_{RX} and C_{RX}, respectively. f_0 of each sub-coil in the digital TX coil is the same as that of the RX coil. With respect to d_p detected by the d detection system, the corresponding TX_p is selected.

B. Proposed Distance Detection System

Fig. 3 shows the block diagram of the proposed d detection system in Fig. 2. According to (4), d is correlated with M. At the same time, M can be known by measuring the input impedance (Z_{in}) of the TX coil [16]. Thus, d can be detected by measuring Z_{in}. Different from [10] and [11], where the communication channel between the TX and RX coils is necessary, the d detection system here only processes the information of the TX side and makes the whole system easier and more reliable. In this paper, TX_1 in the digital TX coil is used for d detection. The details are given as follows.

Using a bidirectional coupler and a gain phase detector, Z_{in} can be measured from the ratio of the amplitude of the reflected and incident waves, namely, the reflection coefficient (Γ).

$$Z_{in} = Z_0 \frac{1+\Gamma}{1-\Gamma}, \tag{7}$$

where Z_0 is the characteristic impedance of the transmission line and equals 50 Ω.

M is correlated with Z_{in} and expressed by [16]

$$M = \frac{\sqrt{(Z_{in} - R_1)(R_L + R_{RX})}}{2\pi f_0} \,. \tag{8}$$

Thus, by combining (4), (7), and (8), d can be detected as

$$d = \sqrt{\left(\frac{\left(\mu_0 \pi^2 f_0 m_1 n r_{TX1}{}^2 r_{RX}{}^2\right)^2}{(Z_{in} - R_1)(R_L + R_{RX})}\right)^{1/3} - r_{TX1}{}^2} \;. \tag{9}$$

With the developed d detection system, the algorithm of selecting the corresponding sub-coil in the digital TX coil is given. Firstly, SW_1 is turned on and d_p is detected, followed by turning off SW_1 and then turning on the corresponding SW_p. Here, p = 1, 2, 3, and 4. Thus, in an electronical way, the radius of the digital TX coil can be automatically controlled to the optimal value for the maximum η at each d.

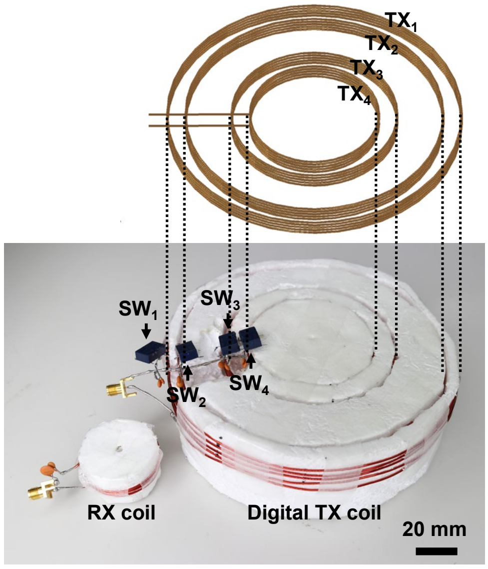

Fig. 4. Photograph of fabricated digital TX coil and RX coil.

TABLE I
MEASURED PARAMETERS OF DIGITAL TX COIL AND RX COIL

	Digital TX Coil				RX Coil
	TX_1	TX_2	TX_3	TX_4	
f_0	13.6 MHz				
Radius	r_{TX1} = 80 mm	r_{TX2} = 70 mm	r_{TX3} = 45 mm	r_{TX4} = 35 mm	r_{RX} = 20 mm
Inductance	L_1 = 15.3 μH	L_2 = 12.4 μH	L_3 = 4.77 μH	L_4 = 2.73 μH	L_{RX} = 0.554 μH
Parasitic resistance	R_1 = 2.6 Ω	R_2 = 2.3 Ω	R_3 = 1.0 Ω	R_4 = 0.70 Ω	R_{RX} = 0.18 Ω
Capacitance	C_1 = 11 pF	C_2 = 13 pF	C_3 = 32 pF	C_4 = 52 pF	C_{RX} = 247 pF
Quality factor	503	461	408	333	263

Note: Number of turns of the digital TX and RX coils are 5 and 3, respectively. Thicknesses of the digital TX and RX coils are 15 mm and 7 mm, respectively.

IV. MEASUREMENT RESULTS

In order to verify the effectiveness of the proposed d detection system in the digital TX coil, a WPT prototype is fabricated, and experimental results are presented.

A. WPT Prototype Implementation

In this paper, it is assumed that the RX coil has 4 known positions, namely, d_1 = 80 mm, d_2 = 65 mm, d_3 = 50 mm, and d_4 = 35 mm. The RX coil and digital TX coil consisting of four concentric sub-coils were fabricated, as shown in Fig.4. Four relays (TQ2-L2-4.5, Panasonic Electric Works) with an on resistance of less than 50 mΩ were used as SWs. r_{RX} is 20 mm, and all radii of the sub-coils in the digital TX coil are determined by the electromagnetic simulation results in [15]. The difference from (6) is analyzed in [15] and mainly ascribed to the approximation made in (4). Table I lists the measured parameters of each coil. Considering the coils' thicknesses, d is defined as the distance between the geometrical center points of the digital TX coil and the RX coil.

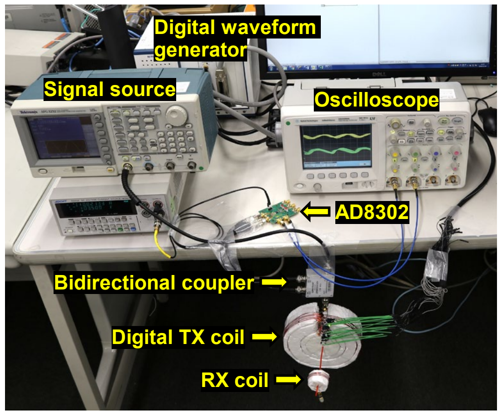

Fig. 5. Photograph of the WPT prototype consisting of digital TX coil with the developed d detection system and the RX coil. R_L = 50 Ω.

Fig. 5 shows the photograph of the WPT prototype consisting of the digital TX coil with the proposed d detection system and the RX coil. A signal source (AFG3252, Tektronix) is used to generate a sinusoidal wave signal with a peak-to-peak value of 5 V at 13.6 MHz. R_S is 50 Ω. A bidirectional coupler (ZFBDC20-61HP+, Mini-Circuits) and a gain phase detector (AD8302, Analog Devices) perform Z_{in} measurement. The output waveforms are measured by an oscilloscope (D5054A, Agilent Technologies). A labview control program is run to perform the d detection and then generate the control voltages for the SWs through a digital waveform generator (PXIe-6555, National Instruments).

B. Evaluation of WPT Prototype

Firstly, the d detection system was evaluated, in which measured M according to (8) and calculated M according to (4) are compared in Fig. 6. In addition, the calculated M by including the coils' thicknesses is also shown for comparison. It is shown that the difference between measured and calculated M becomes smaller when the coils' thicknesses are included. The percentage error is estimated as 14% at d = 35 mm and decreases to 2.7% at d = 80 mm. The remaining difference is mainly ascribed to the fact that no impedance calibration is performed in Z_{in} measurement. To guarantee the correct d detection, the measured M is calibrated using the calculated M at d = 65 mm as a reference. After M calibration, the detected d (d_{det}) is calculated according to (4). Fig. 7 shows the relationship between d_{det} and d. Their strong correlation guarantees the correct operation of SW control unit.

In addition, a network analyzer (E5061B, Keysight Technologies) was used to measure the S parameters between the TX and RX coils, and η is calculated as $|S_{21}|^2/(1-|S_{11}|^2)$. Fig. 8 shows the measured d dependence of η. Compared with the conventional TX coil with a constant radius, the proposed

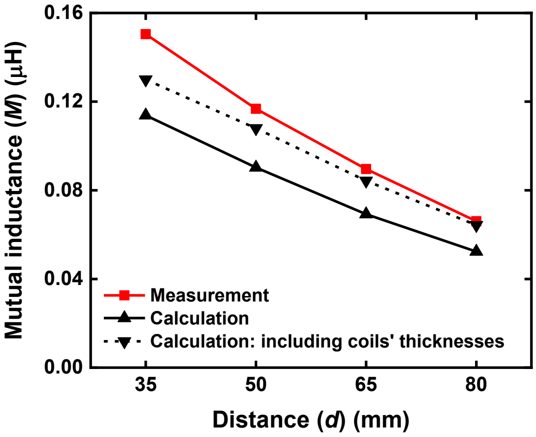

Fig. 6. d dependence of measured and calculated M.

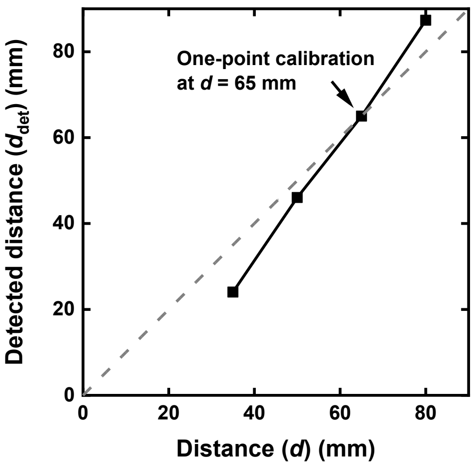

Fig. 7. Correlation between d_{det} and d.

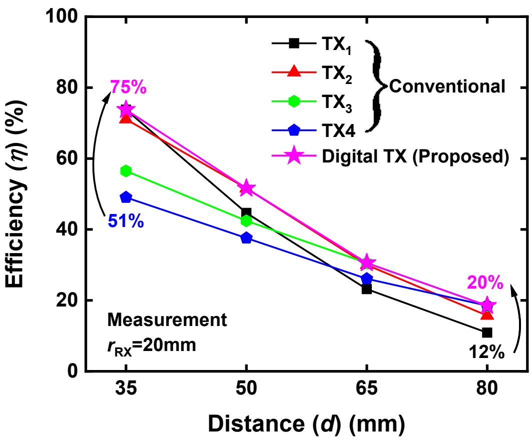

Fig. 8. Measured d dependence of η using the proposed digital TX coil, compared with the conventional TX coil with a constant r_{TX}.

digital TX coil with an adaptive radius achieves the maximum η at different d. For example, at d = 80 mm, η is improved from 12% to 20% (almost doubled) by turning on TX_1 rather than TX_4. Similarly, for d = 35 mm, η is improved from 51% to 75% by turning on TX_4 rather than TX_1.

V. Conclusions

A distance detection system that only processes information in the TX side is proposed and implemented in the digital TX coil for wireless power transfer robust against distance variation. Experimental results demonstrate that, based on the proposed distance detection system, the radius of the digital TX coil can adjust automatically depending on the distance. Compared with the conventional TX coil with a constant radius, the WPT efficiency is improved from 12% to 20% (almost doubled) at the distance of 4 times the RX coil radius.

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