Null-free two-dimensional capacitive wireless power transfer based on inversion of electric field distribution

Yasumasa Naka\textsuperscript{1a}, Ryoichi Baba\textsuperscript{1}, Shinji Abe\textsuperscript{1}, and Takashi Ohira\textsuperscript{1b}

\textsuperscript{1} Research Center for Future Vehicle City, Toyohashi University of Technology
Hibarigaoka1-1, Tempaku-cho, Toyohashi, Aichi 441-8580, Japan
\textsuperscript{a)} yasumasa.naka.qj@tut.jp, \textsuperscript{b)} ohira@tut.jp

Abstract: One of the crucial challenges of capacitive two-dimensional wireless power transfer (2-D WPT) is the variation in transfer efficiency depending on the RX position. In this paper, we suppress this variation using an inversion of the electric field distribution. First, we analyze the E-field distribution on a comb-like TX electrode for use in capacitive 2-D WPT. The null points are generated on the comb-like electrode, and their positions are identified by deriving the input admittance. Then, we confirm that they are inverted by open-/short- termination switching. Finally, the variation in the power transfer efficiency is suppressed by switching the termination condition.

Keywords: 2-D wireless power transfer, capacitive power transfer, electric field distribution

Classification: Energy in electronic communications

References

[1] A. Hashizume, Y. Narusue, Y. Kawahara, and T. Asami, “Receiver localization for a wireless power transfer system with a 2D relay resonator array,” \textit{Proc. of 2017 IEEE International Conference on Computational Electromagnetics.}, pp. 127–129, Kumamoto, Japan, Mar. 2017. doi:10.1109/COMPEM.2017.7912817.

[2] H. Shinoda and T. Terada, “Propagation analysis using plane coupler for 2D wireless power transmission systems,” \textit{IEICE Trans. Electron.}, vol. E96-C, no. 8, pp. 1041–1047, Aug. 2013. https://doi.org/10.1587/transele.E96.C.1041

[3] A. Noda and H. Shinoda, “Antinull 2-D waveguide power transfer based on standing wave diversity,” \textit{IEEE Trans. Microw. Theory and Tech.}, vol. 66, no. 1, pp. 306–318, Jan. 2018. doi:10.1109/TMTT.2017.2721403

[4] Y. Ozawa, Q. Chen, K. Sawaya, M. Oouchida, and M. Tokieda, ”Design of a wide planar waveguide antenna for UHF near-field RFID reader with high reading rate,” \textit{IEEE Journal of Radio Frequency Identification}, vol. 5, no. 1, pp. 46–52, March 2021. doi:10.1109/JRFID.2020.3039016

[5] Y. Mizutani, T. Sasatani, Y. Narusue, Y. Kawahara, and T. Asami, “Investigation on electrode configurations for a capacitive power transfer system using a receiver array and a sheet transmitter,” \textit{IEICE Technical Report (Japanese Edition)}, vol. 116, no. 321, pp. 7–11, Nov. 2016.
1 Introduction

Two-dimensional wireless power transfer (2-D WPT) has been attracting research attention as a contactless and positioning-free power supply [1, 2, 3, 4, 5, 6]. A capacitive technique can expand the feeding area by enlarging the TX electrode. Furthermore, the propagation loss is small because the operation frequency is only a few megahertz. Therefore, this is more suitable for 2-D WPT compared with inductive and evanescent-field techniques. A comb-like TX electrode was proposed for use in capacitive 2-D WPT [5, 6]. The coupling capacitance (TX to RX) is generated at any position on the feeding area. However, the null points, which decrease the power transfer efficiency, are increased as the TX area expands. Solutions have been proposed for capacitive one-dimensional WPT [7, 8]. However, no solution has been developed for capacitive 2-D WPT.

In this paper, we suppress the variation in power transfer efficiency that occurs depending on the RX position. First, we analyze the E-field distribution on the comb-like electrode. The null points of the E-field distribution are generated on the electrode. Then, we represent the comb-like electrode as transmission lines. The positions of the null points are identified by deriving the input admittance of the transmission lines. We confirm that they are inverted by open-/short-termination switching. In [3, 4], they have been employed using many switching devices (circuits/diodes) to realize the null-free 2-D WPT. In contrast, the comb-like electrode only uses the one terminal circuit. Finally, the variation in power transfer efficiency is suppressed by switching the one termination condition.
2 Comb-like TX electrode structure and E-field distribution

As shown in Fig. 1(a), the comb-like TX electrode and the two circular RX electrodes are assembled on electromagnetic software (CST Microwave Studio). The electrodes are made of aluminum; its thickness is 0.5 mm and conductivity is $3.56 \times 10^7$ S/m. The circular RX electrode is placed at 84 mm intervals. Also, there is a 20 mm air gap between the TX and RX electrodes. The comb-like electrode is composed of 85 open stubs (5.53 m) and 2 connection lines (14.5 m). The length of the open stubs correspond to $\lambda/8$ (6.78 MHz), $\lambda/4$ (13.56 MHz), $\lambda/2$ (27.12 MHz), and $3\lambda/4$ (40.68 MHz). These frequencies show the industrial, scientific, and medical bands. There is a 134 mm air gap between the TX electrode and the GND plate. The GND plate is made of copper; it thickness is 0.5 mm and the conductivity is $5.96 \times 10^7$ S/m.

The simulated electric-field distributions on the TX electrode are shown in Fig. 1(b). At 13.56 MHz and 40.68 MHz, the electric field strengths all over the TX electrode are weak. Here, we focus on 6.78 MHz because the E-field strength is high. However, the null points are generated periodically in the X-direction.

![Fig. 1. Structure of comb-like TX electrode and electric field distribution.](image-url)
3 Formulation and solution

3.1 Null point formulation

In this section, we formulate the null positions. First, we represent the one-half comb-like electrode as transmission lines, as shown in Fig. 2(a). A capacitive coupler (TX and RX electrodes) is represented as two coupled lines [9]. We focus only on the TX electrode because the RX electrode is small enough for the 6.78 MHz wavelength.

Next, we derive the input admittance at each connection part of the open stubs and a connection line, as shown in Fig. 2(a). Lossless approximation is applied in the derivation. The 1st input admittance \( Y_1 \) at the termination is expressed as Eq. (1). \( jY_0 \tan \beta L \) is the admittance of an open stub [10]. \( Y_0 \) is the characteristic admittance of the transmission lines. 2nd/Nth admittances are expressed in Eqs. (2) and (3), respectively.

\[
\begin{align*}
|E| \quad (\text{V/m}) \\
|Y_N| \\
\text{Number of open stubs}
\end{align*}
\]

(a) Equivalent circuit of one-half comb-like electrode.

\[
\begin{align*}
|E| \quad (\text{V/m}) \\
|Y_N| \\
\text{Number of open stubs}
\end{align*}
\]

(b) Open termination.

\[
\begin{align*}
|E| \quad (\text{V/m}) \\
|Y_N| \\
\text{Number of open stubs}
\end{align*}
\]

(c) Short termination.

Fig. 2. E-field strength and admittance of comb-like electrode at each position (6.78 MHz).
\[ Y_1 = Y_{\text{term}} + jY_0 \tan \beta L. \]  

(1)

\[ Y_2 = Y_0 \frac{Y_1 + jY_0 \tan \beta \Delta L}{Y_0 + jY_1 \tan \beta \Delta L} + jY_0 \tan \beta L. \]  

(2)

\[ Y_N = Y_0 \frac{Y_{N-1} + jY_0 \tan \beta \Delta L}{Y_0 + jY_{N-1} \tan \beta \Delta L} + jY_0 \tan \beta L. \]  

(3)

Here, \( Y_{\text{term}} \) in each termination condition is expressed as follows:

\[
Y_{\text{term}} = \begin{cases} 
0 & \text{(open)} \\
\infty & \text{(short)} 
\end{cases}.
\]  

(4)

\( Y_N \) is calculated using the following values: \( Y_{\text{term}} = 0 \) S, \( Y_0 = 0.0068 \) S, \( L = 5531 \) mm, \( \Delta L = 294 \) mm, and \( \beta L = 0.147 \) rad at 6.78 MHz and in air environment. \( \Delta L \) is the distance between the open stubs, and the value is 252 mm (84 mm × 3). However, \( \Delta L \) becomes 1.17 × 252 mm by parameter fitting due to the effect of the transmission line width of 84 mm.

The results of the calculated admittance and E-field strength are compared in Fig. 2(b). The E-field strength decreases where the admittance is large (i.e., current reduction). Thus, the positions of the null points are identified by \( Y_N \). Furthermore, the extremum values of admittance and E-field strength are inverted by switching to short termination from the open one, as shown in Fig. 2(c). The E-field distribution in the Z-direction is determined by the length of the open stubs and the wavelength. We can move the distribution in the X-direction by changing the termination condition. Therefore, the frequency of 6.78 MHz (i.e., \( \lambda/8 \) of the stub length) is optimal for the null-free 2-D WPT using the comb-like electrode.

### 3.2 Evaluation of power transfer efficiency at each RX position

We calculate \( \eta_{\text{max}} \), which is an achievable maximum efficiency under the conjugated matching condition. \( \eta_{\text{max}} \) is calculated using Eqs. (5), (6), and (7) [11]. The calculation is repeated by moving the RX position in the longitudinal direction (paths A, B, and C) on electromagnetic software, as shown in Fig. 3(a).

\[
kQ = \frac{|Z_{21}|}{\sqrt{R_{11}R_{22} - R_{12}R_{21}}} \]  

(5)

\[
\rho = \sqrt{1 + (kQ)^2} \]  

(6)

\[
\eta_{\text{max}} = \frac{\rho - 1}{\rho + 1}. \]  

(7)

In Figs. 3(b) and (c), the null points of \( \eta_{\text{max}} \) are confirmed under the open-/short-termination conditions. The calculated \( \eta_{\text{max}} \) values fluctuate from 12.1% to 97.1% and from 5.9% to 98.0% under the short- and open-termination conditions, respectively. By contrast, the variation in \( \eta_{\text{max}} \) is suppressed from 88.5% to 98.0% by switching the conditions, as shown in Fig. 3(d). Specifically, we can identify the switching method by the detected decrease in the received power. Likewise, the method is also supported by the detect power reflection, as a decrease in received power increases the power reflection.

© IEICE 2021
4 Conclusion
In this paper, we suppressed the variation in power transfer efficiency that occurs depending on the RX position in capacitive 2-D WPT. First, we analyzed the E-field distribution on a comb-like TX electrode. The null points of the distribution were generated on the electrode. Then, we represented the comb-like electrode as transmission lines. The null points were identified by deriving the input admittance. We confirmed their inversion through the switching of the open-/short-termination conditions. Finally, we suppressed the variation in the power transfer efficiency within 10%, and the value was over 88% in the 14.5 m × 5.53 m square area. The proposed switching method is verified by detect changes in the received power and power reflection. Our future task is a demonstration of the method.

Acknowledgments
This work is funded by Knowledge Hub Aichi: Priority Research Project from Aichi Prefectural Government.

© IEICE 2021