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Introducing Relay-Repeaters for Hybrid Inductive-Capacitive Wireless Power Transfer

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***Abstract*—Hybrid inductive-capacitive wireless power combines both the magnetic and electric field simultaneously to transfer energy from a transmitter to a receiver. However, since it acts in the near-field, the power transfer range is limited. In this work, we introduce a new concept, a relay-repeater, that functions as an intermediate structure to strengthen the field, extending the power transfer range. It is comparable to relay resonators for inductive and electric field repeaters for capacitive power transfer, but uses both magnetic and electric coupling. We propose an equivalent circuit representation, determine impedance parameters and present relevant figures of merit. Moreover, we demonstrate the potential advantages of the relay-repeater at extended distances with regard to efficiency and power transfer by applying the model to a numerical example.**

***Index Terms*—hybrid wireless power transfer, inductive coupling, electric coupling, relay resonator, field repeater**

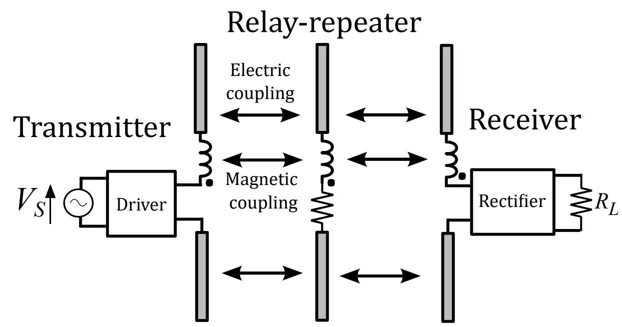

Fig. 1. A HWPT system with a relay-repeater circuit inserted between transmitter and receiver, both electrically and magnetically coupled.

I. INTRODUCTION

Wireless power transfer (WPT), particularly for portable devices, provides significant benefits, including enhanced convenience and user experience by eliminating the need for physical cables to charge or power devices [1]. With regard to near-field WPT, two approaches can be applied:

- *Inductive power transfer* (IPT) uses coupled inductors to transfer energy from a transmitter coil to a receiver coil via a time-varying magnetic field as medium.
- *Capacitive power transfer* (CPT) applies a time-varying electric field via coupled capacitive plates to transfer the energy wirelessly.

Recently, mixed inductive-capacitive or hybrid wireless power transfer (HWPT) has gained attention by the research community leveraging both the magnetic and electric channel simultaneously for power transfer in the near-field. This approach offers several advantages [1]–[4]:

- *Size reduction*: Utilizing both the magnetic and electric fields enables greater power transfer within the same physical space or allows for smaller transmitter and receiver sizes while maintaining the same power transfer.
- *Component reduction*: WPT requires a resonant circuit. By integrating coils and capacitors for both energy transfer and resonance, higher power density is achieved with fewer and/or smaller components, leading to a lighter and more cost-effective system.
- *Increased tolerance to misalignment*: By exploiting the different properties of magnetic and electric couplings, HWPT systems can maintain optimal performance regardless of changes in lateral or vertical alignment of the receiver. This flexible operation ensures reliable power transfer even under varying positional displacements.

A disadvantage of near-field WPT (including IPT, CPT and HWPT) is the limited range of power transfer. Both efficiency and power transfer are limited for larger transmitter-receiver distances.

In order to address this drawback, *relay resonators* were introduced in IPT [5]. These are intermediate coil structures between transmitter and receiver, physically disconnected from both, to increase system performance by strengthening the magnetic field. Not only do relay resonators allow for increasing the total power transfer distance, they also allow for

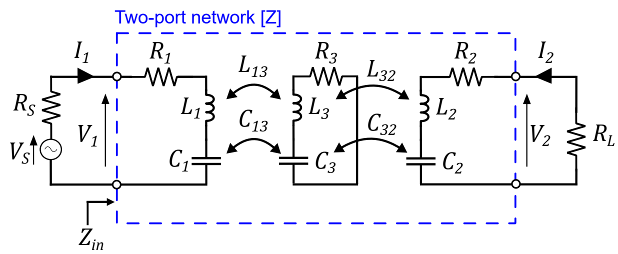

Fig. 2. An equivalent circuit representation of a HWPT wireless power transfer system with one relay-repeater.

changing the spatial flow of power transfer, or can be used to power multiple loads located at different physical locations.

Analogous as relay resonators for IPT, *electric field repeaters* were introduced for CPT to fulfill the same purpose [6], [7]. Intermediate capacitive plates allow for the continuation of a strong electric field from transmitter to receiver to increase power transfer.

In this work, we introduce a new concept for HWPT called a *relay-repeater*. We combine the relay resonator of IPT and the electric field repeater of CPT into a new intermediate structure that strengthens both the magnetic and electric field (Fig. 1). In this way, the same benefits as relay resonators for IPT and electric field repeaters for CPT can be applicable for HWPT such as an increase in power transfer range. More specifically:

- We propose an equivalent circuit for a series HWPT system with relay-repeater.
- We model the structure as a two-port network and derive the impedance matrix.
- We determine the expressions of two relevant figures of merit (efficiency and power transfer) for the relay-repeater structure.
- Finally, we apply the proposed model to a numerical example, demonstrating the potential benefits of the relay-repeater structure, particularly at extended distances.

II. Methodology

A. Equivalent circuit

The equivalent circuit of a series inductive-capacitive HWPT system is shown in Fig. 2. The power supply is represented by a sinusoidal voltage source V_S with internal resistance R_S, operating at an angular frequency ω_0. The load R_L is assumed purely resistive. The subscripts 1 and 2 denote the transmitter and receiver respectively.

Between transmitter and receiver, we introduce a relay-repeater, indicated by subscript 3. This intermediate circuit is physically separated from the supply and load. However, it is magnetically coupled to transmitter and receiver via mutual inductances L_{13} and L_{32}, respectively. The coupled coils in the equivalent circuit representation are L_1, L_2 and L_3. Notice that the coil L_3 of the relay-repeater is magnetically coupled to both the transmitter and receiver coil. This magnetic coupling is similar to relay resonators in IPT [5].

However, different to relay resonators, the relay-repeater circuit is *also* electrically coupled: the mutual capacitances C_{13} and C_{32} represent the electrical coupling to transmitter and receiver, respectively. This coupling can be represented by coupled capacitors C_1, C_2 and C_3, where again C_3 shares its coupling with both transmitter and receiver. This electric coupling is similar to the concept of electric repeaters in a CPT system [6], [7]. However, the intermediate circuit is now both magnetically and electrically coupled, hence the name ’relay-repeater’.

The magnetic and electric coupling factors between the transmitter and the relay-repeater are defined by:

$$k_{m13} = \frac{L_{13}}{\sqrt{L_1 L_3}} \tag{1}$$

$$k_{e13} = \frac{C_{13}}{\sqrt{C_1 C_3}} \tag{2}$$

Similarly, the couplings between the relay-repeater and receiver are expressed as k_{m32} and k_{e32}. The direct coupling between transmitter and receiver is assumed zero, i.e., $k_{m12} = k_{e12} = 0$.

Resistive losses in the circuits are represented by the resistances R_i (i =1,2,3). It is assumed that the transmitter, relay-repeater, and receiver circuit resonate synchronously at the same angular frequency ω_0, which can be ensured by choosing the value of the components such that $\omega_0^2 = \frac{1}{L_i C_i}$.

It is important to note that Fig. 2 is an *equivalent circuit model* of a series HWPT configuration, and does not correspond to the physical setup of the system. It has been shown that this equivalent circuit representation is a valid characterization for both relay IPT and repeater CPT systems, and procedures exist to determine the values of the equivalent circuit values from measured physical parameters [8], [9]. However, further research on HWPT is necessary to determine the conditions under which Fig. 2 is a valid representation of a relay-repeater system, in particular for integrated HWPT configurations [2].

B. Impedance matrix

We describe the HWPT setup as a two-port network, fully characterized by its impedance matrix $\boldsymbol{Z}$ which relates the voltages and currents at input and output port (Fig. 2):

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} z_{11} & z_{12} \\ z_{21} & z_{22} \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}. \tag{3}$$

In this subsection, we determine the elements of the impedance matrix as function of the system parameters.

The voltages over the resistances V_{Ri}, the coils V_{Li} and the capacitors V_{Ci} are defined such that:

$$V_1 = V_{R1} + V_{L1} + V_{C1} \tag{4}$$

$$V_2 = V_{R2} + V_{L2} + V_{C2} \tag{5}$$

$$0 = V_{R3} + V_{L3} + V_{C3} \tag{6}$$

The voltages V_{Ri} over the resistances equal

$$V_{Ri} = R_i I_i \tag{7}$$

At the resonant frequency ω_0, Kirchhoff's voltage law results into the voltages V_{Li} over the coils:

$$V_{L1} = j\omega_0 L_1 I_1 + j\omega_0 L_{13} I_3 \tag{8}$$

$$V_{L2} = j\omega_0 L_2 I_2 + j\omega_0 L_{32} I_3 \tag{9}$$

$$V_{L3} = j\omega_0 L_3 I_3 + j\omega_0 L_{13} I_1 + j\omega_0 L_{32} I_2 \tag{10}$$

with I_3 the current in the intermediate relay-repeater circuit.

Analogous, the current-voltage relationships for the capacitors are given by:

$$I_1 = j\omega_0 C_1 V_{C1} - j\omega_0 C_{13} V_{C3} \tag{11}$$

$$I_2 = j\omega_0 C_2 V_{C2} - j\omega_0 C_{32} V_{C3} \tag{12}$$

$$I_3 = j\omega_0 C_3 V_{C3} - j\omega_0 C_{13} V_{C1} - j\omega_0 C_{32} V_{C2} \tag{13}$$

Solving the system of equations (3) to (13) results in the elements of the impedance matrix $\boldsymbol{Z}$ of the series HWPT system:

$$z_{11} = \frac{\lambda_{11}}{\Lambda} - \frac{\gamma_{11}}{\Gamma} + j\omega_0 L_1 + R_1 \tag{14}$$

$$z_{22} = \frac{\lambda_{22}}{\Lambda} - \frac{\gamma_{22}}{\Gamma} + j\omega_0 L_2 + R_2 \tag{15}$$

$$z_{12} = z_{21} = \frac{\lambda_{12}}{\Lambda} - \frac{\gamma_{12}}{\Gamma} \tag{16}$$

where we introduced several parameters to alleviate the notation as indicated in Table I.

TABLE I
DEFINITION OF PARAMETERS.

$\alpha = C_2 C_3^2 - C_3 C_{32}^2$	$\beta = C_1 C_3^2 - C_3 C_{13}^2$
$A = jBR_3\omega_0 + C_1 C_2$	$B = C_1 C_2 C_3 - C_1 C_{32}^2 - C_2 C_{13}^2$
$\Lambda = BL_3 A\omega_0^2 - A^2$	
$\Gamma = -C_3 B L_3^2 \omega_0^5 + 2jC_3 B L_3 R_3 \omega_0^4 + (C_3 B R_3^2 + BL_3 + C_1 C_2 C_3 L_3)\omega_0^3 - j(B + C_1 C_2 C_3) R_3 \omega_0^2 - C_1 C_2 \omega_0$	
$\lambda_{11} = B^2 L_{13}^2 R_3 \omega_0^4 + jC_2 L_{13}\omega_0 (C_{13} A - C_1 B L_{13} \omega_0^2)$	
$\lambda_{22} = B^2 L_{32}^2 R_3 \omega_0^4 + jC_1 L_{32}\omega_0 (C_{32} A - C_2 B L_{32} \omega_0^2)$	
$\lambda_{12} = B^2 L_{13} L_{32} R_3 \omega_0^4 + jC_1 L_{13}\omega_0 (C_{32} A - C_2 B L_{32} \omega_0^2)$	
$\gamma_{11} = R_3\omega_0 (C_2 C_3 C_{13} L_{13} \omega_0^2 - 2\alpha L_3 \omega_0^2 + 2C_2 C_3 - C_{32}^2) + j\omega_0^4 (C_{13} C_2 C_3 L_{13} L_3 - \alpha L_3^2) + j\omega_0^2 (\alpha R_3^2 + 2C_2 C_3 L_3 - C_{32}^2 L_3 - C_{13} C_2 L_{13}) - jC_2$	
$\gamma_{22} = R_3\omega_0 (C_1 C_3 C_{32} L_{32} \omega_0^2 - 2\beta L_3 \omega_0^2 + 2C_1 C_3 - C_{13}^2) + j\omega_0^4 (C_{32} C_1 C_3 L_{32} L_3 - \beta L_3^2) + j\omega_0^2 (\beta R_3^2 + 2C_1 C_3 L_3 - C_{13}^2 L_3 - C_{32} C_1 L_{32}) - jC_1$	
$\gamma_{12} = R_3\omega_0 (C_2 C_3 C_{13} L_{32} \omega_0^2 - 2C_{13} C_3 C_{32} L_3 \omega_0^2 + C_{13} C_{32}) + j\omega_0^4 C_{13} C_3 L_3 (C_2 L_{32} - C_{32} L_3) + j\omega_0^2 C_{13} (C_3 C_{32} R_3^2 + L_3 C_{32} - C_2 L_{32})$	

C. Figure of merits

Typically, either one of two figures of merit are of importance for a WPT system [5]:

- *The power conversion efficiency* η, defined as the ratio between the active power delivered to the load and the active input power of the system. Maximizing the efficiency corresponds to minimizing the reflections at the output port.
- *The amount of power transferred to the load*, characterized by the transducer gain G_T and defined as the ratio between the active power delivered to the load and the available input power. Maximizing the transducer gain corresponds to minimizing the power reflections at both the input and the output ports. For a fixed available input power of the supply, maximizing G_T corresponds to maximizing the amount of power delivery to the load.

1) Power conversion efficiency: The input impedance $Z_{in} = R_{in} + jX_{in}$, as indicated in Fig. 2, for a general two-port network with resistive load R_L is given by [5]:

$$Z_{in} = \frac{V_1}{I_1} = z_{11} - \frac{z_{12} z_{21}}{z_{22} + R_L}. \tag{17}$$

The power conversion efficiency η (also called power gain) expresses the ratio of the output power, dissipated in the load, to the input power delivered by the supply. It equals [5]:

$$\eta = \frac{R_L}{R_{in}} \left| \frac{z_{21}}{z_{22} + R_L} \right|^2 \tag{18}$$

Since the elements of the impedance matrix of the HWPT system with relay-repeater are known by equations (14) to (16), the power conversion efficiency η of the system can be determined.

2) Amount of power transfer: The transducer gain G_T is a measure for the amount of power the load receives. For a general two-port network, its expression as function of the impedance matrix elements is given by [5]:

$$G_T = \frac{4 \left| z_{21} \right|^2 R_S R_L}{\left| (z_{11} + R_S)(z_{22} + R_L) - z_{12} z_{21} \right|^2} \tag{19}$$

Since the elements of the impedance matrix of the HWPT system with relay-repeater are known, the transducer gain G_T of the system can be determined.

TABLE II
GIVEN PARAMETERS FOR THE ANALYZED HWPT SYSTEM.

Quantity	Value	Quantity	Value
R_i	0.72 Ω	L_i	11.21 μH
R_S	50 Ω	C_i	15.16 pF
R_L	50 Ω	f_0	12.21 MHz

III. NUMERICAL ANALYSIS

In order to analyze the effect of introducing a relay-repeater in a HWPT system, we consider the hybrid inductive-capacitive design of Cheng et al. [10]. The system consists of

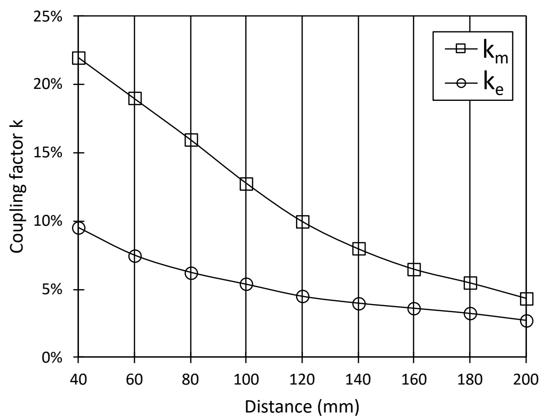

Fig. 3. Magnetic and electric coupling factor as function of the distance between transmitter and receiver for the analyzed HWPT system.

a symmetrical hybrid coupler, characterized by the numerical parameters summarized in Table II. The system operates at the resonance frequency f_0 of 12.21 MHz. No relay-repeater is present between transmitter and receiver. The magnetic and electric coupling factors as function of distance for this system are given in Fig. 3 [10].

Given the numerical parameters of the system, we calculate the efficiency η and the transducer gain G_T for two distinct configurations: (i) First, we consider the HWPT system without relay-repeater. The distance between the transmitter and repeater is d. (ii) Next, we add a relay-repeater to the system, exactly in the middle between the transmitter and repeater. In other words, the distance between the transmitter and relay-repeater equals $d/2$. Also the distance between relay-repeater and receiver is $d/2$. We apply identical parameters R_i, L_i, and C_i for transmitter, receiver and relay-repeater, in order to only analyze the effect of adding a relay-repeater circuit to the system.

First, we consider the set-up without relay-repeater. Based on the impedance matrix of a series HWPT system [11], the efficiency η and transducer gain G_T can be calculated from equations (18) and (19) for varying distances, taken into account the coupling factors of Fig. 3. It can be seen that for this specific given system, the efficiency η decreases for increasing distances (Fig. 4), whereas an optimum distance exists that maximizes the amount of power transfer (Fig. 5).

Next, we analyze the configuration with a relay-repeater present. Because the intermediate relay-repeater is equidistant from transmitter and receiver, we assume $k_{m13} = k_{m32}$ and $k_{e13} = k_{e32}$. Their value is again based on Fig. 3, but now for the distance $d/2$. As a result, the magnetic and electric coupling factors are higher than for the configuration without relay-transmitter, given a fixed distance between transmitter and receiver. Combining equations (14), (15), (16), (18) and (19) results in the efficiency η and transducer gain G_T as function of distance (Fig. 4 and 5).

It can be seen that for larger distances, the efficiency is higher for the configuration with relay-repeater (Fig. 4). This is a result of the higher magnetic and electric coupling factors, due to the intermediate relay-repeater. However, for lower distances, the configuration with relay-repeater shows a lower efficiency. This is attributed to the losses dissipated in the extra resistance R_3, which is not present in a situation where a relay-repeater circuit is omitted.

With regard to the amount of power transfer, it can be seen that for this specific example, the introduction of a relay-repeater is beneficial for all considered distances (Fig. 5). The transducer gain G_T is always higher for a configuration with relay-repeater, and as a result, more power can be delivered to the load if the intermediate structure is present.

In particular for longer distances, the effect of the introduction of a relay-repeater is significant. Consider for example a distance of 200 mm between transmitter and receiver. Whereas the efficiency and transducer gain for the configuration without relay-repeater have dropped to η=83% and G_T=25%, the values for the system with relay-repeaters remain high for both (η=96%; G_T=96%). This indicates that applying a relay-repeater structure can be in particular beneficial for longer distances, analogous as relays resonators for IPT and electric repeaters for CPT.

Finally, it is important to note that this specific numerical

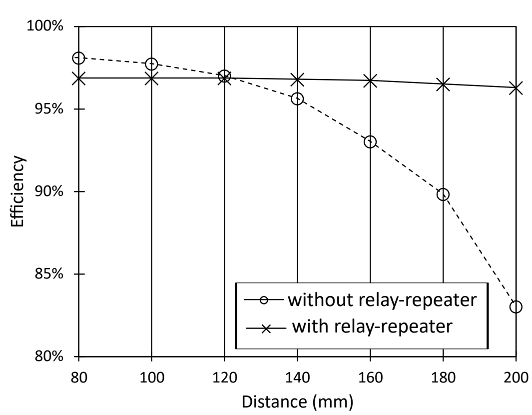

Fig. 4. The efficiency η as function of the distance d between transmitter and receiver for the configuration with and without relay-repeater.

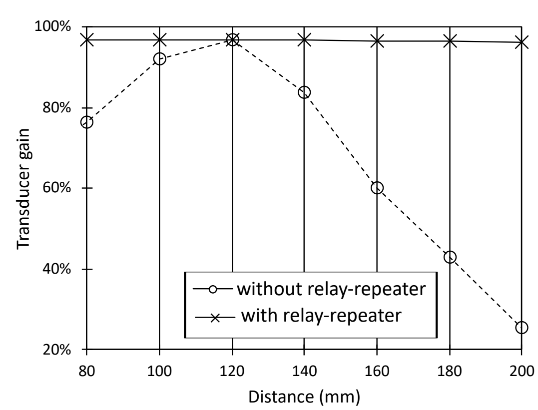

Fig. 5. The transducer gain G_T as function of the distance d between transmitter and receiver for the configuration with and without relay-repeater.

example is just an indication of the possible benefits of relay-repeater structures in HWPT set-ups. More rigorous analysis and experimental studies are paramount to analyze the effects of this novel concept.

IV. Conclusion

We introduced the concept of the relay-repeater as intermediate structure between transmitter and receiver of a HWPT system. By modeling its equivalent circuit as a two-port network, we characterized this novel structure by its impedance matrix and determined relevant figure of merits. Finally, we showed by a numerical example that the relay-repeater structure can increase both efficiency and power transfer for extended distances.

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