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Analysis of Charge Plate Configurations in Unipolar Capacitive Power Transfer System for the Electric Vehicles Batteries Charging

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Abstract

This paper analyzes the ring and square plates configurations in a unipolar capacitive power transfer (CPT) system for electric vehicle (EV) batteries charging. It is shown that the ring plates coupler provides better coupling capacitance and coefficient than the square one. In this paper, the vertical, lateral, angular and rotational misalignments were actively researched. Furthermore, the interoperability between the different plates configurations has been analyzed. The ring plate showed good compatibility only with a ring plate, while the square plate showed good compatibility with the square and disc plates.

Keywords: electric vehicles; battery charging; capacitive power transfer; unipolar system; plate configurations; interoperability.

1. Introduction

The wireless power transfer (WPT) technology has gained much attention recently due to its striking features, which plays an important role in the electric vehicles (EVs) popularity [1, 2]. Based on this technology, the power is transferred from a fixed transmitter to a fixed/movable receiver without any galvanic connection between them. Two technologies are usually used in the wireless battery charging: the capacitive power transfer (CPT), which is based on the electric field coupling and inductive power transfer (IPT), which is based on the electromagnetic field

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induction[3]. In recent years, much studies have focused on the CPT technology because of its worthwhile features, which offer less electromagnetic interferences and makes the power transmission through metal obstacles possible [4, 5].

The capacitive coupler takes two forms, unipolar and bipolar. The unipolar capacitive coupler can be used in the EVs batteries charging. The unipolar capacitive coupler structure is very simple. It consists of one plate in the transmitter side and another one plate in the receiver side, to form a path for the current-sending. The path of the current-returning is through the parasitic capacitance which arises between the vehicle chassis and the ground. The bipolar coupler consists of four plates, two in the transmitter side and two in the receiver side, to form the current sending and returning paths [1].

One way to improve the power transfer density and enhancing the power transfer transmission of a CPT system is by increasing the plates size of the capacitive coupler [4]. When the effective coupling area or plates size are increasing, this result in increasing the coupling capacitance (C_m) and coupling coefficient (k) between the capacitively coupled plates. The parameters C_m and k are specifying not only the power transfer capability of a CPT system but also the total system performance.

The parameters C_m and k are geometrical parameters. These parameters are dependent on a plate configuration. Disc plates were used, for example, to realize a bipolar coupler of a CPT for which a coupling capacitance C_m of as many as 222 pF was achieved [6]. Square plates were used, for example, to realize a unipolar CPT for a small electronic device battery charging for which were analyzed the air-gap variation, lateral, and angular misalignments [7]. The first unipolar CPT system for an EV charging was used in 2018. This first CPT was formed of two identical conductive square plates of 0.45m^2 each and was capable to transfer a power of 350W through an air-gap of 110mm with an efficiency of 70% [8]. However, although high power transfer capability is required in the EVs batteries charging, little attention has been paid to the selection criteria of the plate configuration to enhance the parameters C_m, and k. In this paper, we have analyzed the effects of the ring and square plates configurations on the parameters C_m and k, in a unipolar CPT system. Also, all possible misalignment cases influence on the CPT performance and the compatibility between the plates configurations are investigated.

2. Methodology

The unipolar capacitive coupler consists of two plates: a transmitter plate and receiver plate. In the EV CPT batteries charger, the transmitter plate is usually placed under the EV. The receiver plate is fixed at the bottom of the EV. The EV chassis and ground will be considered as conductive plates during the analysis of the unipolar CPT system.

The capacitive coupler parameters C_m and k are usually calculated by using the electric field finite element analysis (FEA) in the ANSYS Maxwell software [9]. The copper material was chosen to represent the transmitter and receiver plates during this analysis. In practice, the plates are coated with a dielectric material for purpose of isolation and enhancing the C_m value [10]. Here, the dielectric was considered as air.

This study analyzes and compares the ring and the square plates configurations and the compatibility between them in a unipolar CPT system for the EV batteries charging. This aiming to identify which structure has high values of C_m and k, and test the immunity of each plate configuration to a misalignment. In this work, four misalignments cases were considered: vertical, lateral, angular, and rotational. Our aim was to study the effect of a misalignment on the parameters C_m and k. These geometrical parameters can be used to predict the behavior and the power transfer capability of the CPT. The power transfer capability is affected also by the quality factor (Q) which is a function of the frequency and compensation resonant topology [7]. The interoperability the plates configuration was analyzed. The investigation involved fixed transmitter plate area and different receiver plate area and/or configuration. The interoperability investigation was aiming to study the compatibility between the similar and different plates configurations.

2.1. System structure

The unipolar CPT system structure for the EV batteries charging is shown in Fig. 1, where d, d_1, and d_2 are the air-gap between P_2 and P_4, P_1 and P_2, and between P_3 and P_4, respectively; C_{12}, C_{14}, C_{23} and C_{34}, are parasitic capacitances which are arising in the system between the transmitter plate (P_2) and ground (P_1), receiver plate (P_4) and P_1, P_2 and chassis (P_3), and between P_4 and P_3, respectively. The equivalent useful capacitance is C_m. The C_m is given by equations (1). The relation between C_m and k is described by equation (2) [1], the C_1 and C_2 are self-capacitances of the transmitter and receiver sides, respectively.

$$C_m = \frac{C_{13}C_{24} - C_{14}C_{23}}{C_{13} + C_{14} + C_{23} + C_{24}} \quad (1)$$

$$k = \frac{C_m}{\sqrt{C_1 . C_2}} \quad (2)$$

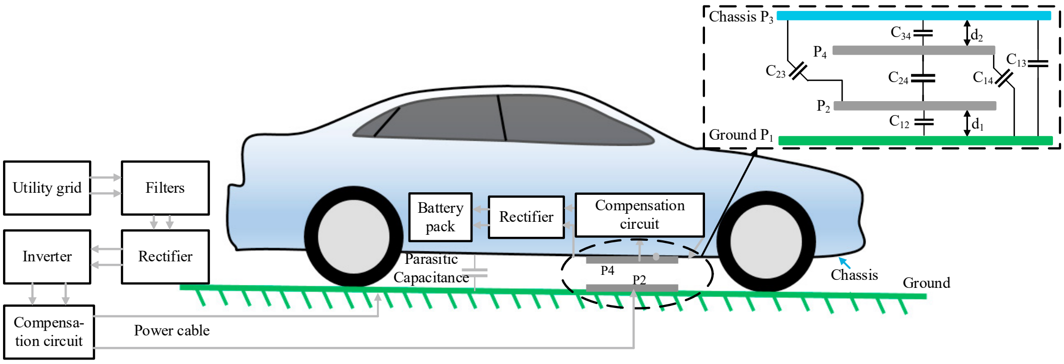

Fig. 1. Unipolar capacitive wireless power transfer system.

The system is shown in Fig. 1 consists of an off-board part (i.e. transmitter side) and onboard part (i.e. receiver side). The transmitter side is composed of: filters which block the harmonics injected back into the electrical utility grid, followed by a rectifier, and an inverter which provides a high voltage at high frequency to trigger the P_2 through a power cable. The receiver side consists of P_4, a compensation circuit, and a half/full bridge rectifier which delivers the DC electric power to the EV batteries [3]. The purpose of a compensation circuit in the transmitter and receiver sides to improve the overall system performance [11].

2.2. Plates configurations

The ring and square plates configurations are analysed in this paper. The ring plate has an outer radius r_2, and an inner radius r_1, and the square plate has a dimension (L), as shown in Fig. 2. Despite the P_1 and P_3 configurations, when the P_2 and P_4 are rings, a ring coupler is formed. Similarly, if the P_2 and P_4 are squares, a square coupler is formed. If the P_2 is ring and P_4 is square or vice versa, a hybrid coupler is formed.

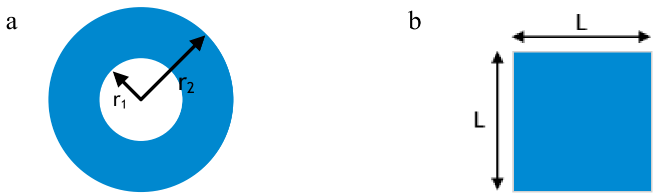

Fig. 2. Plate configurations; (a) ring; (b) square.

2.3. Plates modeling and spacing

As mentioned earlier, the copper was chosen to model the plates P_2 and P_4. The dielectric between all plates was modelled as air. The plates placed along the x-axis during the 3D electric field FEA, with dimensions and spacing for the system depicted in Fig. 1, are listed in Table 1.

Table 1: Plates dimension and spacing.

Parameter	Description	Value (cm)
P_2	Transmitter plate	40x40x0.1
P_4	Receiver plate	40x40x0.1
P_3	Chassis plate	150x100x0.2
P_1	Ground plate	150x100x0.2
d	Air-gap between P_2 and P_4	10
d_1	Air-gap between P_1 and P_2	4
d_2	Air-gap between P_3 and P_4	4

2.4. Misalignment

The misalignment is a relative movement of the receiver module (i.e. EV) with respect to a charger [3]. The P_1 and P_2 are fixed into the ground side, whereas P_4 is fixed under the bottom of the vehicle and it is movable according to the vehicle condition. However, the P_4 and P_3 are moving together with same distance and/or angle. The normal case is that in which all plates have been aligned. During static or dynamic charging, an air-gap variation (or vertical misalignment, $\triangle d$), lateral misalignment ($\triangle l$), angular misalignment with angle α, or rotational misalignment with angle θ, probably happening between the transmitter and receiver modules. The four possible interfaces between the transmitter module (which includes P_1 and P_2) and receiver module (which includes P_4 and P_3) are shown in (Fig. 3). The lateral and rotational misalignments are the most probably to happen in the practical condition.

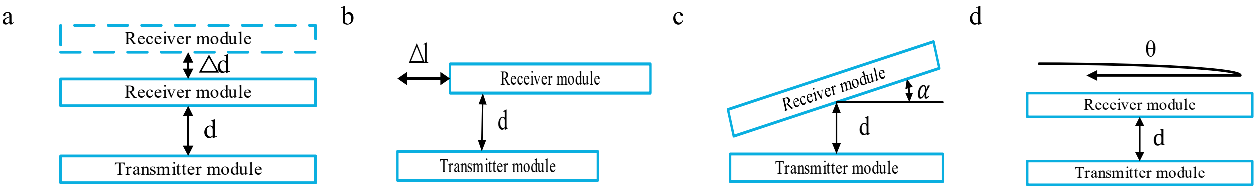

Fig. 3. Misalignment cases; (a) vertical; (b) lateral; (c) angular; (d) rotational.

3. Simulation results and discussion

The results of the FEA electric field calculation are presented in the sections 3.1, 3.2 and 3.3 for identical plates configurations i.e. P_2 and P_4 are identical. In literature, only square plates were used in the unipolar CPT systems [8]. In this section, the ring coupler and square coupler are investigated at four misalignment cases; the behaviour of both configurations was compared. Besides, the interoperability between the plates configurations is investigated. The highest C_m and k would be a desirable outcome. These parameters are desired to be a constant during a battery charging.

3.1. Ring radii ratio

A unipolar CPT system with ring plates P_2 and P_4 have been analysed. There is an infinite number of combinations of r_1 and r_2 for a specified area. To get an optimum value for C_m and k, different radii ratio (r_1/r_2) for some areas (i.e. 800, 1600 and 2400cm²) were analysed. A disc plate can be obtained when r_1=0. To investigate the effect of the radii ratio (r_1/r_2) on the C_m and k for the same area, the simulations results were conducted at three different areas. The electric field analysis results are shown in Fig. 4.

As it can be seen in the Fig. 4, for a constant plates area, the C_m stills increasing as the r_1/r_2 increases. The maximum value of C_m is obtained at larger plates area, i.e. 2400cm². On the other hand, the k is slightly decreasing as r_1/r_2 increases for a constant plates area; the maximum value of k is obtained at the area of 1600cm² and radii ratio r_1/r_2 of 0. The plates with the minimum area (i.e. 800cm²) showed better immunity of k to the r_1/r_2 variation among the other areas. The rest of the analysis will be carried out at area 1600cm², r_1/r_2=0.46 i.e. r_1=20cm, r_2=42.57cm.

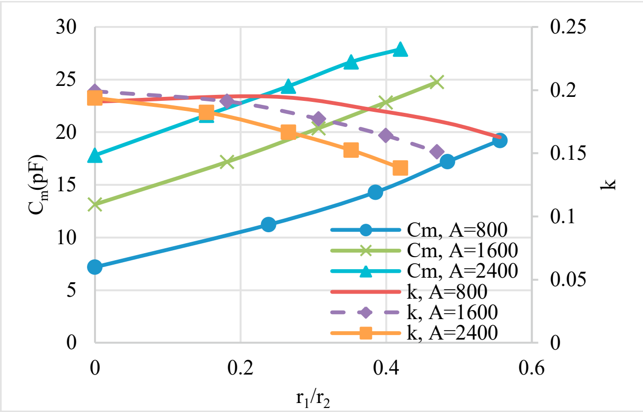

Fig. 4. Effect of r_1/r_2 variation of ring coupler on the C_m and k, at d=10cm.

3.2. Vertical and lateral misalignments

In this section, the effect of Δd on the C_m and k is illustrated in Fig. (5a). The Δl along the y-axis has the higher impact on the C_m and k than the one along the x-axis, that is because of the coupling area between P_1 and P_3 decreases along the y-axis greater than that of the x-axis. However, only the Δl along the y-axis is presented here. To study the effect of plates dimension with the same plates area on the C_m and k at Δl condition, a rectangular coupler with a dimension for each plate of 32x50cm (i.e. A=1600cm²) is also presented in Fig. (5b).

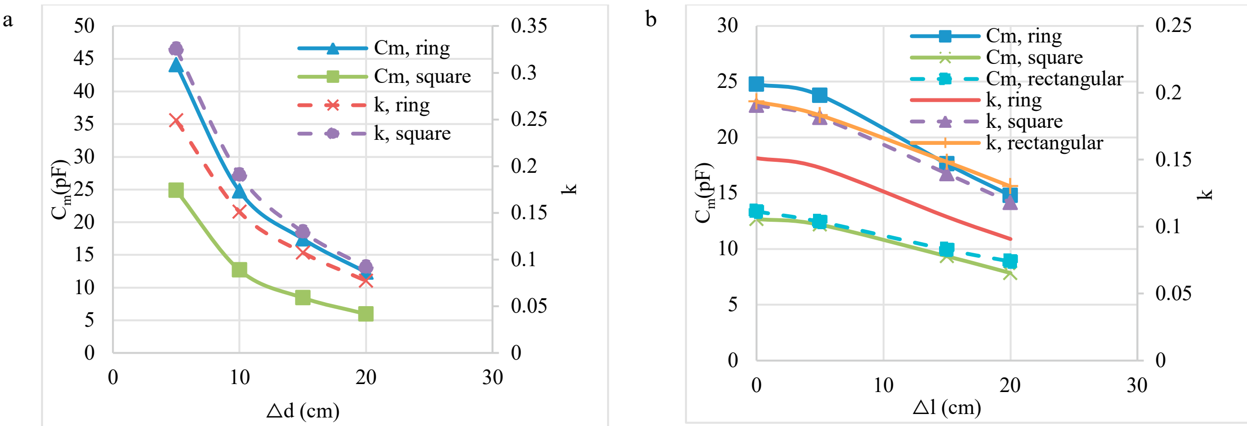

Fig. 5. Effect of misalignment on the C_m and k a) vertical misalignment; b) lateral misalignment along the y-axis at d=10cm.

As can be seen from Fig. 5a, when the Δd increases, the C_m and k are sharply declining for the ring and square couplers. Both couplers showed the similar response of C_m to the Δd. However, the k of the ring coupler is a little bit higher than that of the square one. The C_m of the ring coupler is extremely higher than that of the square one, that is because of fringing capacitance due to the hole in the ring plates i.e. r_1.

The Fig. 5b showed that the C_m and k are significantly decreasing of both couplers in the case of △l. Based on this approach, at △l=20cm the C_m declined from 24pF, 12pF to 14pF and 7pF for the ring and square couplers, respectively. On the other hand, the k decreased from 0.15, 0.19 to 0.09 and 0.11 for the ring and square couplers, respectively. The response of the square plates to △l, along the y-axis, was slightly improved, when the plates were made of the dimension along y-axis higher than that of the x-axis (i.e. 32x50cm^2) for the same plate area (i.e. 1600cm^2). All configurations showed the same response to △l. However, the △d has the higher negative impact on the C_m and k than that of the △l.

3.3. Angular and rotational misalignment

In this section, the angular and rotational misalignment were investigated. The angular misalignment along the x-axis only researched, since it has an impact higher than the one along the y-axis. That is because of P_1 and P_3 becomes closer in the angular misalignment along the x-axis than that along the y-axis. The electric field analysis results are shown in (Fig. 6).

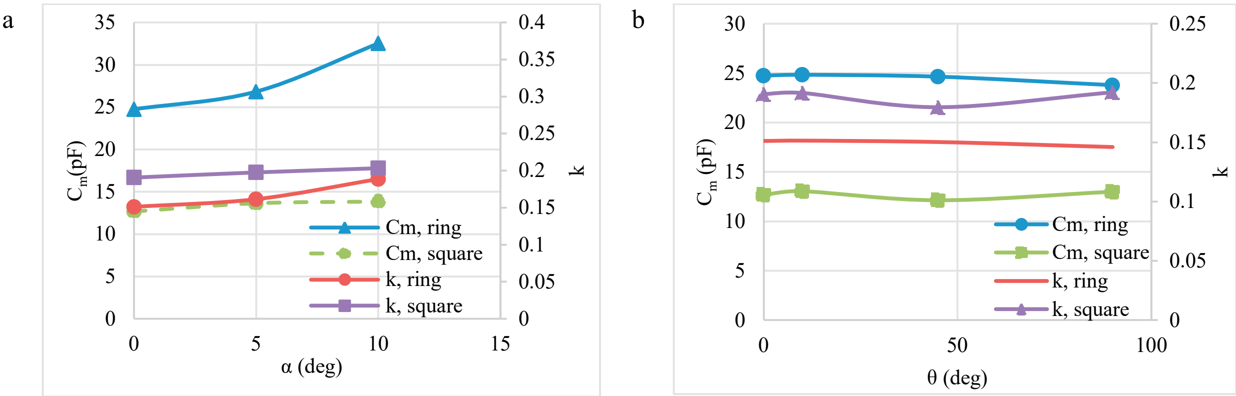

Fig. 6. Effect of misalignment of the ring and square couplers at A=1600cm^2, d=10cm; a) angular misalignment; b) rotational misalignment.

As can be seen from Fig. 6a, the C_m and k response of the ring and square configurations are significantly different. For the ring plates, the obtained outcomes showed that the C_m and k are slight increasing as the α increases, whereas for the square plates, the C_m and k are approximately constant with α variation, For the ring and square couplers in a unipolar CPT system, the C_m and k are almost unaffected by θ, as can be seen from Fig. 6b.

The sensitivity of the ring and square couplers in a unipolar CPT system to each misalignment condition in terms of C_m and k are listed in Table 2.

Table 2: Misalignment sensitivity of the ring and square couplers.

Misalignment / Coupler	Vertical	Lateral	Angular	Rotational
Ring	very sensitive	sensitive	slightly insensitive	insensitive
Square	very sensitive	sensitive	insensitive	insensitive

3.4. Interoperability

The interoperability of the charge plates means that the receiver plate can be charged with a different transmitter plate area and/or configuration. It is a fundamental matter for the commercial wireless capacitive charging [12]. The essential purpose of studying interoperability is to investigate the compatibility between the plates in a CPT system.

The compatibility between the capacitively coupled plates that is formed a hybrid coupler (i.e. P_2 and P_4 are of different configurations). Based on this approach, the compatibility of the ring plate as P_2 with radii ratio of $r_1/r_2=0.46$ i.e. $r_1=20$cm, $r_2=42.57$cm was examined at d=10cm with the followings plates as P_4: ring plate with $r_1=20$cm and variable r_2; disc plate with $r_1=0$cm and variable r_2; square plates of variables area, the electric field analysis results are illustrated in Fig. 7a. Furthermore, the compatibility of the square plate as P_2 was examined with the followings plates as P_4: ring plate with $r_1=20$cm and variable r_2; disc plate with $r_1=0$cm and variable r_2; square plates of variables area, the results illustrated in Fig. 7b. The dimension of the EV chassis and ground plates are constant during the electric field analysis as it is listed in Table 1.

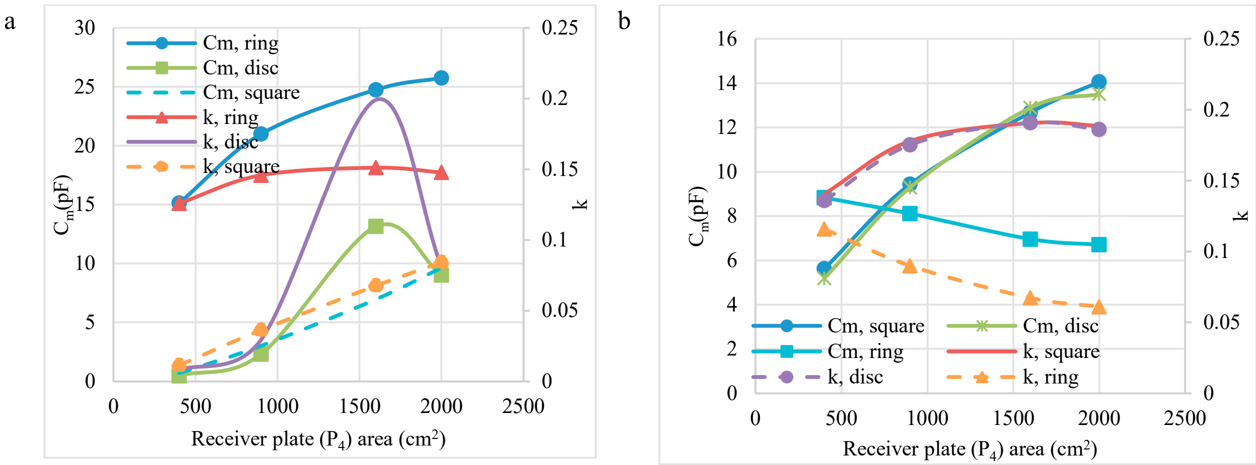

Fig. 7. Interoperability between the plates configurations with constant transmitter plate (P_2) area of 1600cm^2 and variable receiver plate (P_4) area; a) ring plate as a transmitter; b) square plate as a transmitter.

As can be seen in the Fig. 7a, the best compatibility of the ring plate as P_2 was obtained with a similar ring plate as P_4. As can be observed from the Fig. 7b, the best compatibility of the square plate as P_2 was obtained with a square plate or a disc plate as P_4.

The compatibility evaluation between different charge plates configurations in a unipolar CPT system in terms of C_m and k, are listed in Table 3.

Table 3: Compatibility between the transmitter and receiver plates.

Transmitter plate \ Receiver plate	Ring	Square	disc
Ring	good	poor	poor
Square	fine	good	good

4. Conclusion

Power capacitive coupler can be realized with the ring, square or rectangular plates. The representative parameters for the different capacitive coupler configurations are coupling capacitance and coefficient.

The aim of the present research was to examine the ring and square plates configurations in a unipolar CPT system for EV charging. The misalignments results of both configurations were compared. This study has identified that the square coupler has better angular misalignment than the ring one. The second major finding was that both couplers have a good immunity to the rotational misalignments. These findings suggest that the plate configuration plays a pivotal role in the CPT system evaluation.

The second aim of this study was to investigate the compatibility between the plates configurations with similar/different configurations and/or areas. The results of this study indicate that the square plates configuration showed good compatibility with square and disc plates configurations. These findings will be of interest for the commercial wireless capacitive charging.

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