Electromagnetic simulation of the misalignment resilience of a capacitive power transfer system with a matrix structure

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***Abstract*—The inability to ensure good alignment between the source and load is one of the main barriers to various near-field wireless power transfer methods. Misalignment reduces the coupling between the transmitter and receiver, thereby limiting the overall reliability and performance of the power transfer system. Capacitive power transfer is an interesting alternative near field wireless power transfer method to the more conventional inductive power transfer. Incorporating a matrix structure into a CPT system is a solution to increase misalignment resistance. Despite the potential, an in-depth analysis of a CPT system with a matrix structure subjected to misalignment conditions is still unexplored. This paper investigates the resilience of a CPT system to lateral and rotational misalignment conditions using electromagnetic simulations.**

***Index Terms*—capacitive power transfer, matrix structure, misalignment resilience, electromagnetic simulation**

Capacitive power transfer (CPT) is a near field wireless power transfer (WPT) method that is gaining interest across various applications. Similar to inductive power transfer (IPT), CPT uses electromagnetic waves to transfer energy wirelessly. Although short transmission distance, high voltage stress and low coupling capacitance are limitations of CPT, it offers the advantages of flexibility, lower cost, high reliability and reduced susceptibility to electromagnetic interference [1]–[3]. As a result of these advantages, CPT has attracted interest in a number of applications including the biomedical field, the EV charging industry and electrical machines [1].

One of the main barriers to both IPT and CPT is the inability to ensure good alignment between the source and the load. Various types of misalignment can occur when wirelessly charging an electronic load, including but not limited to vertical, horizontal, angular and rotational misalignment [1]. Misalignment reduces the coupling between the transmitter and receiver, thus limiting the overall reliability and performance of the power transfer system. In literature various strategies are proposed to counteract this barrier. Multi-coil or plate structures, meta-materials, compensation strategies and position control methods are examples used to increase the misalignment tolerance in WPT systems [2], [4]–[7].

In contrast to the various multi-coil structures reported to enhance the misalignment robustness of IPT-systems, the multi-plate or matrix structure of CPT systems is less investigated. In a CPT system with matrix structure (Fig. 1) the receiver or transmitter is built from multiple plates arranged side by side in a 2D plane. By varying the matrix plate connections depending on the relative transmitter-receiver position, greater robustness to misalignment is achieved.

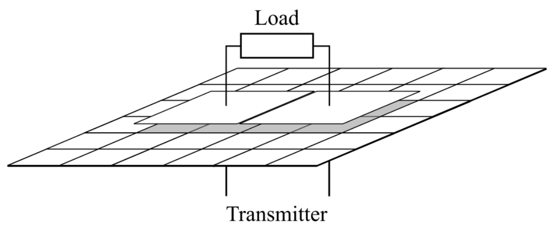

Fig. 1. A CPT system with a matrix structure as transmitter.

In literature diverse examples of matrix structures for CPT systems have been reported [8]–[10]. Despite the reported systems, an in-depth analysis of the influence of the matrix structure on the robustness against misalignment remains unexplored. This paper addresses this knowledge gap. Using the electromagnetic simulation software CST-studio, the resilience of a CPT system with a matrix structure against rotational and lateral misalignment is analysed for various matrix plate dimensions.

I. Simulation setup

A. Simulation model

In CST-studio, a CPT system with a matrix structure is constructed (Fig. 2). In the simulation, energy is transferred over a distance of 1 mm. The receiver consists of two identical square plates with a length of 100 mm, while the transmitter is configured as a square matrix structure with an external length of 650 mm. For both the transmitter and receiver, the distance between two adjacent plates is set to 1 mm. Perfect electrical material is used for both the transmitter and receiver plates, with the background material specified as vacuum.

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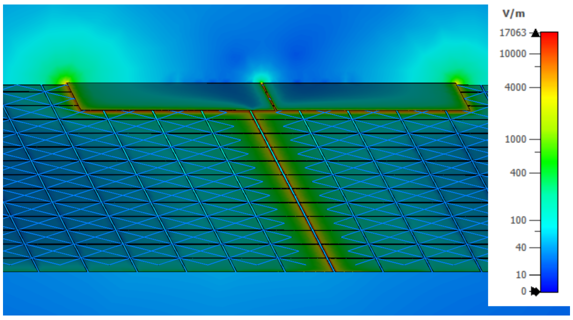

Fig. 2. Electric field simulation of a CPT system with a matrix structure in CST-studio.

Using configurable electrical connections, the transmitter matrix plates are divided into two groups to form parallel-plate capacitances with the receiver plates. As a result a four-plate CPT system is built. A schematic representation of the system consists of two main coupling, two leakage and two cross coupling capacitances (Fig. 3). Another method of representing the two-port network (Fig. 3) is the equivalent pi-model (Fig. 4). The pi-model comprises a primary, secondary and mutual capacitance and is the general model used in literature to represent a CPT system [2], [3].

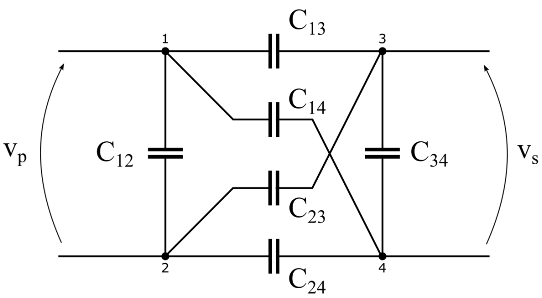

Fig. 3. The electric schematic of a four plate CPT system.

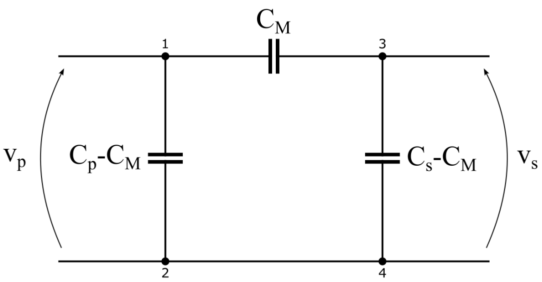

Fig. 4. The equivalent pi-model of a CPT system.

B. Analytical verification

To validate the simulations, a standard four-plate CPT system with identical transmitter and receiver is analytically examined (Fig. 5). The verification model consists of four square plates, each 0.1 mm thick and 100 mm long. The transfer distance and the distance between adjacent plates are 1 mm.

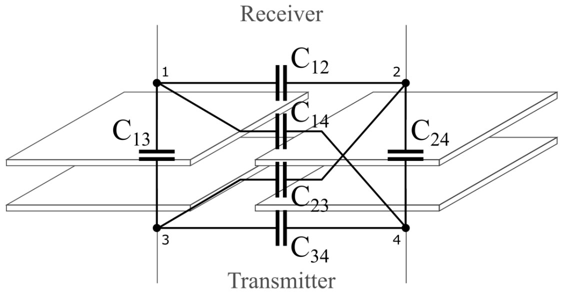

Fig. 5. A standard four plate CPT system with the electric schematic.

The main coupling capacitances, C_{main} (C_{13} and C_{24}) can be modelled as a parallel plate capacitance with negligible plate thickness. Using Nishiyama's equation (1) to calculate the parallel plate capacitance [11], 91.97 pF is obtained. In this equation, ϵ_0 is the permittivity of vacuum, d the plate separation distance and l the length of the square parallel plate capacitance.

$$C_{main} = \frac{\epsilon_0 l^2}{d}(1 + 2.343(\frac{d}{l})^{0.891}) \tag{1}$$

The corresponding simulated main coupling capacitance is 91.38 pF. Similar to the main coupling capacitances, the leakage capacitances, C_{leak} (C_{12} and C_{34}), can be represented as parallel plate capacitances. For these capacitances the plate thickness is significant. Therefore, equation (2) based on Palmer and Yang is used [12]. In the equation of Palmer and Yang, ϵ_0 is the permittivity of vacuum, t the plate thickness, d the plate separation distance, l the length and w width of the rectangular parallel plate capacitance.

$$\begin{aligned} C_{leak} = \frac{\epsilon_0 wl}{d}[1 + \frac{d}{\pi w} + \frac{d}{\pi w}\ln(\frac{2\pi w}{d}) + \\ \frac{d}{\pi w}\ln(1 + \frac{2t}{d} + 2\sqrt{\frac{t}{d} + \frac{t^2}{d^2}})] \end{aligned} \tag{2}$$

Both analytically and with CST-studio, a value of 1.93 pF is found for the leakage capacitances. In contrast to the main coupling and leakage capacitances the cross coupling capacitances, C_{14} and C_{23}, have no direct plate overlap. The cross coupling capacitances are therefore neglected in the analytical verification method. With CST-studio a cross coupling capacitance of 0.58 pF is still retrieved. Using the calculated main coupling, leakage and cross coupling capacitances and the equations (3)-(5), the mutual, primary and secondary capacitances of the pi-model can be determined [13].

$$C_M = \frac{C_{13}C_{24} - C_{14}C_{23}}{C_{13} + C_{14} + C_{23} + C_{24}} \tag{3}$$

$$C_P = \frac{(C_{13} + C_{14})(C_{23}+C_{24})}{C_{13} + C_{14} + C_{23} + C_{24}} + C_{12} \tag{4}$$

$$C_S = \frac{(C_{13} + C_{23})(C_{14} + C_{24})}{C_{13} + C_{14} + C_{23} + C_{24}} + C_{34} \quad (5)$$

Based on the analytical results, 45.98 pF is found for the mutual capacitance and 47.91 pF for both the primairy and secondary capacitance. In the simulation environment, there is a direct determination of the mutual, primary and secondary capacitance. The simulated mutual capacitance is 45.40 pF while the primary and secondary are both 47.90 pF. The resulting relative error between the simulated and calculated capacitances is 1.26% for the mutual capacitance and 0.02% for the primary and secondary capacitances.

II. Results

To investigate the influence of a matrix structure on the misalignment robustness of a CPT system, the pi-model capacitances of a standard four-plate CPT system (the verification model, Fig. 5) are compared with the corresponding capacitances of a CPT system with a matrix structure (Fig. 1). The square plates of the transmitter matrix structure are dimensioned at 24.25 mm, meaning that exactly 16 transmitter plates are positioned directly under one receiver plate when no misalignment occurs.

For the lateral misalignment, the receiver is initially displaced along the Y-axis, which is defined as the axis passing through the gap between the receiver plates (Fig. 6). Restarting from the origin point, the receiver is moved along the X-axis, an axis perpendicular to the Y-axis. To compare the results of different matrix structures, the lateral displacement factor α, defined as the ratio of the lateral displacement to the length of a transmitter plate (6) is used to express the misalignment.

$$\alpha = \frac{\text{Lateral misalignment distance}}{\text{Transmitter size}} \quad (6)$$

This factor is formulated such that a displacement of one is equivalent to moving the receiver over one transmitter plate, restoring transmitter receiver alignment.

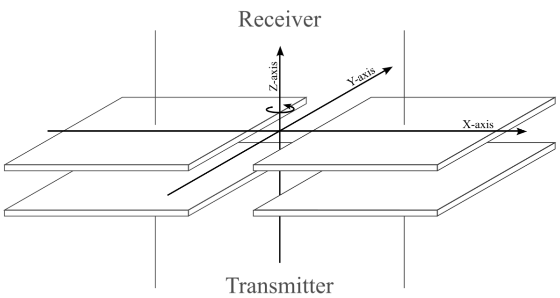

Fig. 6. The lateral (X-axis and Y-axis) and rotational (Z-axis) displacement axis illustrated on a four plate CPT system.

For the four-plate reference system, lateral misalignment along the Y-axis reduces the plate overlap between the initially aligned transmitter and receiver plates. This reduction in plate overlap reduces the mutual, primary and secondary capacitance values as the displacement factor increases (Fig. 7). Conversely, for the CPT system with the matrix structure, the initial reduction in plate overlap is cancelled out by a corresponding alignment of the receiver with a new transmitter plate of the matrix structure. As a result, the mutual, primary and secondary capacitances are independent of the misalignment along the Y-axis.

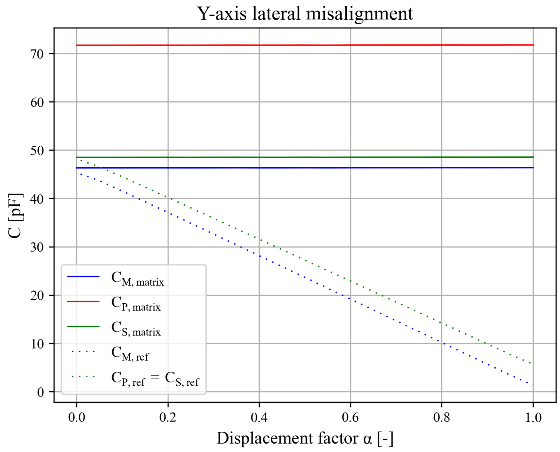

Fig. 7. The simulated pi-model capacitances of a four plate CPT system ($C_{M,ref}$, $C_{P,ref}$, $C_{S,ref}$) and a matrix CPT system ($C_{M,matrix}$, $C_{P,matrix}$, $C_{S,matrix}$) as a function of Y-axis misalignment.

Similar to misalignment along the Y-axis, misalignment along the X-axis reduces the receiver-transmitter plate overlap in the four-plate CPT reference system. As the misalignment factor increases, a segment of a transmitter plate aligns with both receiver plates. This plate overlap increases the cross coupling capacitance at the expense of the main coupling capacitance. These effects lead to a non-uniform decrease of the mutual, primary and secondary capacitances of the four-plate CPT reference system (Fig. 8). The cross coupling capacitance of the matrix CPT system has the same effect with lateral displacement along the X-axis. This variation causes a decline in the mutual and primary capacitance to the point where a row of transmitter plates aligns with the center of the gap between the two receiver plates. At this point the transmitter matrix structure can be reconfigured. With a reconfigured transmitter a further increment in the displacement factor results in the enhancement of the transmitter and receiver alignment, thus increasing the mutual and primary capacitance.

In the rotational misalignment the receiver is rotated by 90° around the centre point (Fig. 6). For the four-plate CPT reference system, the rotation of the receiver plates causes the mutual, primary and secondary capacitance to drop due to the increased misalignment of the transmitter and receiver plates (Fig. 9). In the CPT system with matrix structure, the applied rotational misalignment is counteracted by the configurable matrix structure. The matrix configuration is set to force maximum overlap between the transmitter and receiver plates for any misalignment condition. At 45° the matrix structure is diagonally divided into two equal parts, maximising the primary capacitance of the matrix structure. In addition at the rotational misalignment of 45°, a diagonal row of transmitter plates aligns with the gap between the two receiver plates. This maximises the transmitter area coupled to both receiver plates and limits the mutual coupling capacitance.

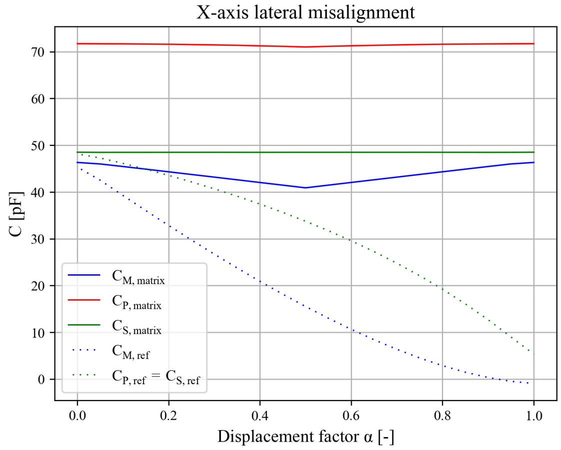

Fig. 8. The simulated pi-model capacitances of a four plate CPT system ($C_{M,ref}$, $C_{P,ref}$, $C_{S,ref}$) and a matrix CPT system ($C_{M,matrix}$, $C_{P,matrix}$, $C_{S,matrix}$) as a function of X-axis misalignment.

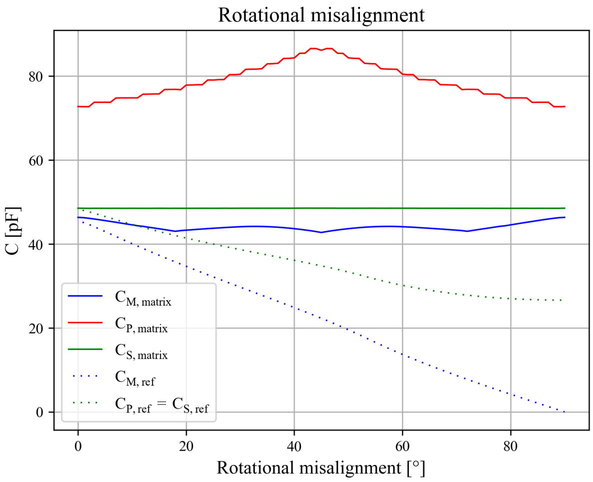

Fig. 9. The simulated pi-model capacitances of a four plate CPT system ($C_{M,ref}$, $C_{P,ref}$, $C_{S,ref}$) and a matrix CPT system ($C_{M,matrix}$, $C_{P,matrix}$, $C_{S,matrix}$) as a function of rotational misalignment.

Incorporating a matrix system enhances the resilience of a CPT system against lateral and rotational misalignment (Fig. 7-9). A minimal capacitive coupling occurs when a row of transmitter plates aligns with the gap between the receiver plates. This minimum can be adjusted by changing the dimensions of the individual transmitter plates of the matrix structure. For a CPT system with a matrix structure comprising square transmitter plates with a length (L_{Tx}) of 39 mm, 24.25 mm and 14 mm, the dependency of the mutual capacitances as a function of lateral misalignment along the X-axis is investigated (Fig. 10). If perfectly aligned, the mutual capacitance is almost independent of the implemented matrix configuration. As the size of the plate overlap affects the increase in the cross coupling and the decrease in the main coupling capacitance, the minimum mutual capacitance increases as the size of the worst case plate overlap decreases. This corresponds to an increase in the minimum mutual capacitance with a reduction in the size of the individual matrix plates.

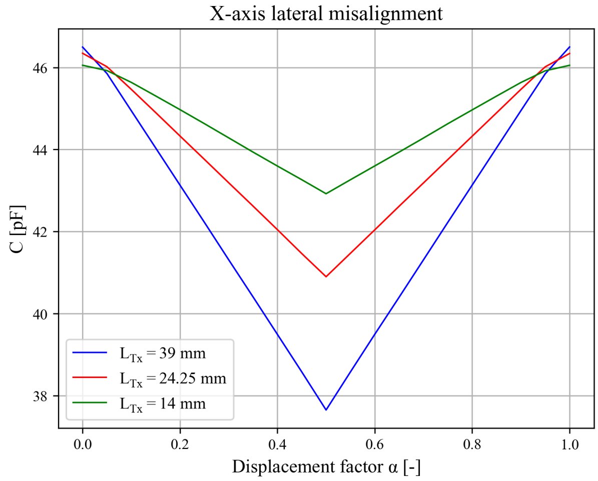

Fig. 10. The simulated mutual capacitances of a CPT system with different matrix structure dimensions ($L_{Tx} = 14\,\text{mm}, 24.25\,\text{mm}, 39\,\text{mm}$).

III. Conclusion

Provided that the receiver remains between the outer boundaries of the matrix structure of the transmitter, a CPT system with a matrix structure improves the resilience against various misalignment conditions compared to a standard four-plate CPT system. Misalignment of the receiver along the Y-axis has a negligible effect on the pi-model capacitances of the CPT with matrix structure. The pi-model capacitances are affected by rotating along the Z-axis or translating along the X-axis. Due to increasing cross coupling capacitances and a reduction in the main coupling capacitances, the minimum mutual capacitance is obtained when a row of transmitter plates is aligned with the gap between the two receiver plates. The value of this minimum capacitance depends on the dimensions of the individual transmitter plates constituting the matrix structure, decreasing as the number of transmitters beneath a receiver plate increases. For the square plate matrix structure with square plate lengths of 14 mm, 24.25 mm and 39 mm, a maximum relative capacitance decay of 6.8%, 11.7% and 19.0% is obtained.

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