A New Hybrid Magnetic Coupler for Large Misalignment Tolerance in Inductive Power Transfer System

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Abstract. Wireless charging has been widely used in a variety of applications. However, pad misalignment can influence system parameters that can lead to increased losses as well as reduction in power throughput. In this article, a new coupler based on solenoid-quadrature coils (SQ) is proposed. By combining with hybrid compensation networks, this coupler can stabilize the system mutual inductance within a certain offset range in order to keep power throughput at a certain level. As a result, this coupler can greatly improve the anti-misalignment capability of the wireless charging system. A 20W prototype is developed and tested in the lab. The experimental results validate that the proposed hybrid SQ-SQ coupler system has an improved misalignment performance.

1. Introduction
Recently, inductive power transfer (IPT) technology has been well adopted in various applications [1]–[3]. However, the inevitable misalignment between the transmitter and the receiver can cause parameter variations. Especially with the change of mutual inductance, output voltage / current varies widely leading to high power losses. Therefore, the technique to improve misalignment tolerance is a critical problem to solve.

Researchers have demonstrated that a load-independent output and a stable output power under the condition of pad misalignment can be achieved by combining LCL-LCL and S-S compensations [4]–[7]. Furthermore, some novel couplers, such as double-D (DD), double-D quadrature (DDQ), and bipolar (BP), have been designed to improve the magnetic coupling and tolerance to pad misalignment [8, 9]. For example, the coupling structure proposed in Ref. [10] can improve the misalignment tolerance in the winding direction. However, there is not much improvement in the vertical direction of the winding, and this method costs more magnetic core. In order to increase the misalignment tolerance in the vertical direction of the winding, some methods have been proposed [11-12]. The coupling structure proposed in [12] adds a Q coil outside the solenoid to improve the misalignment tolerance in the direction of the vertical solenoid winding. In addition, the IPT system’s three-dimensional (3-D) misalignments tolerance can be increased by combining magnetic pads design with compensation circuits [13]. Unfortunately, tolerance to the direction of magnetic core (longitudinal) misalignment of polarized charging pads is still unsatisfactory due to lack compensation in the direction of magnetic field coupling.

This paper presents a novel hybrid magnetic coupler combined with LCL-S circuit for inductive power transfer system with high misalignment tolerance in vertical /horizontal, including diagonal. The proposed coupler based on solenoid-quadrature coils (SQ) can compensate for the system mutual inductance within a certain offset range, which can keep power throughput at a certain level.
Laboratory measurements show excellent agreement with the simulated values. Overall, the proposed hybrid SQ-SQ coupler provides a practical method to improve the longitudinal misalignment performance of most inductive power transfer systems.

2. Magnetic Coupler Design and Misalignment Analysis

In order to improve the anti-misalignment ability of the system, the coupler SQ-SQ is proposed in this paper. A solenoid coil (S coil) is added to the Q coil to form the solenoid-quadrature pad (SQ) as shown in Fig. 1 (a). The 3-D model is shown in Fig. 1 (b).

![Fig. 1. Proposed coil structures. (a) SQ primary pad model. (b) 3-D model.](image_url)

The Q coil sits below the S coil, its position ensures that it is magnetically decoupled from the S coil and it can be treated independently. The reason is that the S coil and Q coil in the same pad are decoupled because the solenoid structure is polarized producing parallel flux, while Q coil is non-polarized producing perpendicular flux. Therefore, there is no energy transfer between the transmitter to ensure more power being transferred to the receiver. In addition, when the pad is accurately aligned, the S/Q coil in transmitter and the Q/S coil in receiver are decouple because the net flux is zero. In this case, there are only main couplings (S/S and Q/Q, namely k12 and k34) without cross couplings(S/Q and Q/S, namely k14 and k32). When the receiver is moved along the z directions, the position of S and Q in the coil is always placed symmetrically, so the two coils decouple and cross couplings are always zero. Viewed from the magnetic field direction, however, when the pad is moving along the center line in the x direction, the S coil is always aligned below the Q coil, so the net magnetic flux is zero. The S and Q coil are still decoupled. Consequently, there are only main couplings. Conversely, as the receiver is moved along the y-axis (longitudinal), the S coil in primary or second pad and Q coil in second or primary pad are coupled. In this case, main couplings decreases while the cross couplings increases, which can compensate for magnetic field coupling. Ferrite cores are placed close to the SQ pad in order to increase the coupling of the magnetic field. To eliminate leakage fluxes, the aluminum plate is placed under coupling structures.

To verify that, MAXWELL was used for magnetic field simulation and experiment to verify the change of coupling coefficient. The finished coil pads are shown in Fig. 2(a). The plane is referenced to the axes shown in Fig. 2(b). The coupling coefficient of the coupler structure simulated by MAXWELL with an air gap of 70 mm and experimental results are shown in Fig. 3. The main coupled coefficients (k12 and k34) and the cross coupled coefficients (k23 and k14) vary greatly when pads are misaligned along y direction as shown in Fig. 3(a) and (b). The main coupled coefficients are dropping because that single transmitter S or Q coil and single receiver S or Q coil pass through the process from aligning and misaligning. The cross coupled coefficients progress from uprising to subsiding because that single transmitter S or Q coil and single receiver Q or S coil pass through the process from aligning and misaligning. The cross coupled coefficients progress from uprising to subsiding because that single transmitter S or Q coil and single receiver Q or S coil pass through the process from aligning to misaligning. The reason is that when the S and Q coil aligned, no coupling occurs because the net flux is zero. The k12 and k34 increase after zero coupling point due to the continuous strip of ferrites [8]. The results will suffice to indicate that when the misalignment occurs in y-axis, the coupling coefficient of coils 14 and 23 supplement the coupling coefficient variation of coils 12 and 34. This is so, in order to stabilize the system total coupling within a certain offset range. As shown in Fig. 3(c) and (d), when misalignment occurs along the x direction, the main coupling coefficients (k12 and k34) are slowed down since the magnetic flux reduces as the misalignment between transmitter and receiver increases. The cross coupling (k14 and k23) is always zero, which also confirms the
previous theoretical analysis. It can be seen from Fig. 3 that the simulation results are consistent with the experimental results, where the value is different due to the simulation coil design used a simplified model. Fig. 3(c) and (f) shows the coupling coefficient changes in diagonal directions. Like the misalignment processes along the \( y \) direction, the coil coupling variation is also complementary.
3. Experiment and Analysis

The LCL-S hybrid IPT topology [4] has certain anti-vertical-misalignment capability because the combination of converters with opposite changing trend can offset the change of total output voltage when the mutual inductance changes. Therefore, it can improve the anti-misalignment ability in the \( x \) and \( z \) directions. The circuit is shown in Fig. 4. As space is limited, the misalignment in the \( z \) and diagonal direction won't be described here. The parameters of LCL-S topology circuit are presented in Table 1.

![Double-sided S-LCC hybrid IPT topology](image)

**Table 1. System specification and parameter values.**

| Parameter | Value                  | Parameter | Value                  |
|-----------|------------------------|-----------|------------------------|
| \( V_{in} \) | 30.38 V               | \( L_{pt2} \) | 204.25 \( \mu \)H       |
| \( R_{w} \)  | 10 \( \Omega \)       | \( L_{st1} \) | 97.6 \( \mu \)H         |
| \( f \)     | 100 kHz               | \( L_{st2} \) | 196.21 \( \mu \)H       |
| \( L_{pt1} \) | 98.31 \( \mu \)H     | \( C_{1} \)  | 115 nF                  |
| \( C_{p1} \) | 332 nF                | \( C_{s1} \) | 335 nF                  |
| \( C_{pt2} \) | 12.4 nF               | \( C_{2} \)  | 115 nF                  |
A laboratory setup is built to verify the proposed hybrid magnetic coupler. In order to confirm the above results, Fig. 5 show the output voltage diagram to demonstrate its high tolerance to pad misalignments. In the y direction, some coils have coupling coefficient decrease while others have coupling coefficient increase, so that output of overall system can be maintained at a high level within a certain misalignment range, as shown in Fig. 5(a). With the x-misalignment, the output voltage is drawn in Fig. 5(b). It can be seen that the output voltage remains relatively stable within the misalignment range from -10 cm to +10 cm. Due to the symmetry of the coil, the result is the same in the opposite direction misalignment.

4. Conclusions
This paper introduced a new hybrid coupler called SQ-SQ which is added to the IPT system to improve the misalignment tolerance by compensating for the system mutual inductance within a certain offset range. The theoretical and experimental results validate that the proposed hybrid SQ-SQ coupler combined the double-sided LCL-S system has an improved misalignment performance along the y, x and diagonal direction. The results prove that hybrid SQ-SQ coupler is a good candidate for all IPT applications.

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