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Advancements and Challenges in Magnetic Coupler Designs for Dynamic EV Wireless Charging

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***Abstract*— Dynamic wireless power transfer for charging in motion Electric vehicles eliminate the drawback of limited cruising ability and regular parking charging in stationary wireless charging. However, it still faces some challenges due to coupling variation. Enhancing the coil structure design is an effective way to tackle that problem. This paper presents a critical literature review of the latest research on the transmitter and receiver coil design for both stretched and segmented tracks. It addressed in detail the different topologies of magnetic couplers..**

***Keywords*— Dynamic Wireless charging System (DWCS), Dynamic Wireless Power transfer (DWPT), stretched track, Segmented track.**

I. Introduction

Several studies have been submitted to cover the different aspects of DWCS. Three main categories can be used to classify them: designing magnetic coil topologies, compensation network optimization and control methods. This paper will discuss magnetic coupler designs. It gives critical discussion and comparison between Long-Track Coil Designs and Lumped Coil Designs.

II. Inductive Coil Designs

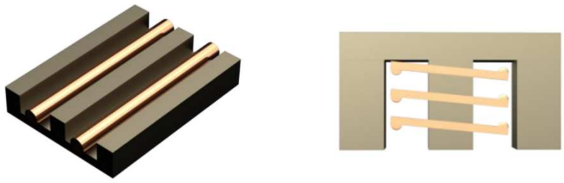
Based on the transmitter coil length, DWCS could be divided into two categories: long track transmitter or stretched track, and segmented coil or lumped track [1]. In respect of coil structure, the inductive coil is considered as the main element in WPT. It has a primary and secondary side where power is transferred through them. It determines several factors in wireless charging of electric vehicles, including efficiency, power transfer capabilities, and misalignment tolerance.

A. Stretched Track (Long track) Coil Design

In long track coil, the length of the transmitter coil in this case is several times the length of the pick-up coil. It offers several advantages such as continuous power transfer, low construction cost and time, and simple control features [2]. The electromagnetic interference (EMF) high rate and low efficiency is a major drawback [2]. Different geometries were presented such as E-Type, U-Type, W-Type, I-Type, S-Type, N-Type and coreless type.

1) E-Type rail

E type has been suggested by OLEV (on line electric vehicle) project in its 1st generation[3], Both primary and secondary coils were E-Type as shown in Fig (1). This configuration suffers from two major drawbacks: the 1st related to efficiency drop in case the air gap or lateral misalignment is large, while the 2nd is the air gap limitation, since at least 12 cm air gap is needed for freely driving vehicles, the 1st generation of OLEV is not proper to actual road situations [4].



(a) (b)

Fig. 1. E-Type rail (a) transmitter coil (b) Pick-up coil

2) U-Type rail

U type has been proposed in OLEV 2nd generation [4]. INTIS research center used double U-type power supply rail as a common configuration for stationary and dynamic WPT, It has two U-type power rails in parallel [5]. Endesa research team in VICTORIA project adopted U type to ensure the interoperability between stationary and dynamic charging [5]. The main constraints of U-Type are its output power and construction expenses [4].

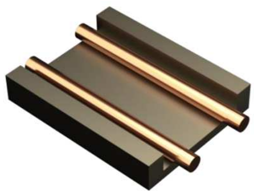


Fig. 2. U-Type rail

3) W-Type rail

W type constructed in OLEV third generation, known as the extremely slim W-type construction. Adopting a fish bone-like core structure reduces the amount of core in comparison to the second generation. Hence, the cost is reduced in compared to U type [4].

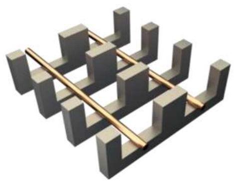


Fig. 3. W-Type rail

4) I-Type rail

The tiny width leads to cost reduction compared to U and W rail type. It shows a very low EMF value. I- Type was proposed as 4th OLEV generation [5]. [12] proposed enhancement for the OLEVs to improve air gap, reduced the width of the power supply rail, and minimized the EMF level.

Fig. 4. I-Type Cross section

5) S- Type rail

For further cost reduction, S-Type porposed. Its width is lesser than I- Type. Hence it redcues the construction cost and deployment time. It has an ultra slim width. Compared to the I-type, it has been reduced by more than two times. While the EMF is similar to the I-Type one [5].

Fig. 5. S-Type Power Supply rail

6) Corelless power supply rail

To guarantee widespread use of DWCS, the compatibility with stationary wireless charging in accordance with SAE J2954 standard must be assured. Moreover, low construction cost and time, low voltage stress, and large lateral tolerance should be granted. To achieve that coreless power supply rail had been presented in the OLEV 6th Generation [5]. It's like U and W Type without the core plate to create a homogeneous magnetic field across road. However, the suggested coreless power rail's mutual inductance is halved compared to the traditional with-core power rail.

Fig. 6. coreless Power supply rail

7) N- Type rail

The N-type power supply rail is suggested as an alternative to the I-type power supply rail to increase magnetic core utilization and lower construction expenses. The flux density in the middle of the pole is minimal. Therefore, the middle core can be reduced to save the costs [6]

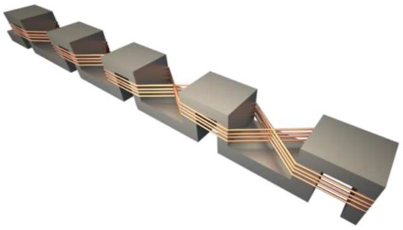


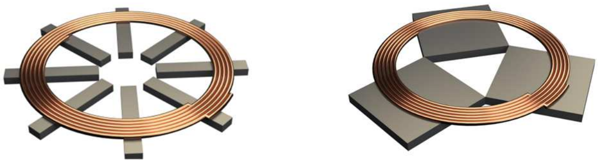
Fig. 7. N-Type power supply rail

B. Lumped Coil (Segmented coil) Coil Design

As an alternative to the long power supply rail concept, a lumped WPT incorporating multiple small power pads developed by Auckland University Researchers . The size of a power pad is about the same as that of a pick-up coil to avoid unwanted energizing and leakage magnetic fluxes. However, there are several factors to consider, including greater control complexity and deployment, as well as the cost of maintaining ground-based power pads [7].

1) Unipolar Q

A unipolar coil is distinguished by the presence of only one magnetic pole per coil face. The coil includes simple topologies, such as circular, square, and spiral. The flux lines exit the coil face with a north pole and enter the coil face with a south pole, traveling around the coil edge [7]. In circular coupler, the mutual inductance profile follows a radial symmetry based on the distance from the coil center [2]. Ferrite bars can be adopted instead of ferrite plates to reduce weight and EMF. Because of their favorable single-sided fields, CPs were among the first magnetic structures to be employed commercially. However, they have a discernible issue with the effective magnetic field between the pick-up coil and transmitter [5]. Moreover, the circular-type coils limited lateral tolerance and low power transfer capability make them unsuitable for high-power WPT [5].



(a) (b)

Fig. 8. Circular coil with (a) Ferrite bars (b) Ferrite plates

2) Bipolar DD

A bipolar coil has a more complex architecture, with coil faces including both north and south poles. The flux lines exit the region of the coil facing with the north pole and enter the region with the south pole on the same coil face. As a result, flux lines are constrained in the area above and below the coil. The most crucial aspect of Bipolar pad design, if the BPP is viewed as receiver-side, is adjusting the amount of overlap between the two coils to prevent mutual coupling. And that will be ensured by calculating the coupling coefficient between the two coils of BPP [5].

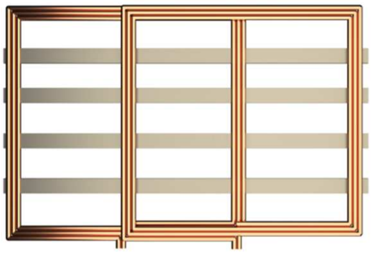


Fig. 9. Bipolar coil

3) Double D Structure

Two D-shaped pieces positioned back-to-back in the same plane make up a DD coil. the voltage at the pick-up terminals is equal to the total of the voltages induced in its two sections. The mutual inductance coupling of the DD coil is often given in two orthogonal directions x direction and y direction. The Y-direction mutual inductance has a smooth changing profile, while x-direction mutual inductance drops to zero even when the pick-up is moving over the primary DD coil. At zero mutual inductance, both the voltage and power transmission are zero. This pick-up position is known as a null power point [5]. This is a main drawback of DD coil.

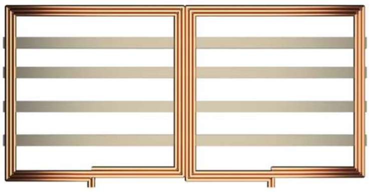


Fig. 10. Double-D coil

4) DDQ structure

To address the shortcoming of DD coils, an additional coil is put in the center of the pick-up, as shown in figure (14). The flux generated by the primary DD coil is captured by this coil, which is known as a quadrature coil (Q-coil), The Q-coil's mutual inductance is maximized concisely with the decrease of the DD-shaped pick-up's mutual inductance [5]. As a result, DDQ is preferable to be used in Pick-up (secondary coil).

Fig. 11. Double-D quadrature coil

5) DOUBLE DD STRUCTURE

The system can transfer more power by using multiple transmitter coils. Each coil will transfer its portion of power, according to that, the load on each coil will be reduced. [8] proposed a double DD coil structure which consists of two bipolar DD coils as shown in fig (12). Rotating the coils by 90° lowered the coupling coefficient between the DD coils to zero. It means that the coils can be activated independently with two different currents.

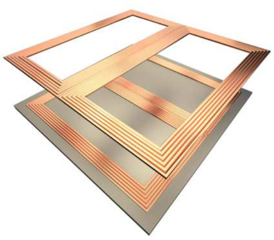


Fig. 12. Exploded double DD coil structure (2DD)

1. DOUBLE DDQ STRUCTURE

Adding Q coil to the receiver side increases the misalignment tolerance of the DD transmitter and the receiver coil. The two DD coils were rotated 90° so they are not magnetically linked. In addition, the Q coil is not magnetically connected to the DD coils. The proposed coil construction, called a double DDQ coil or 2DDQ coil, was employed on both the transmitter and receiver sides. This coil arrangement had three uncoupled coils. Each coil could be activated independently. When added the Q coil only on the receiver side only, it will increase the misalignment tolerance. But when add the Q coil to the transmitter as well, the power transferred can be increased [8].

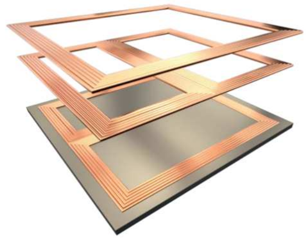
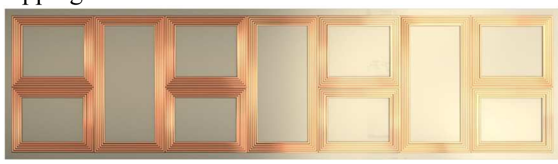


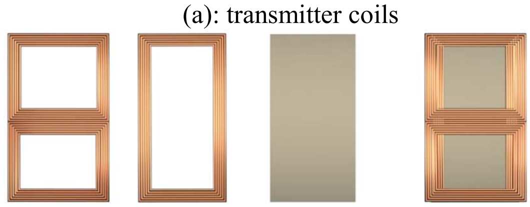
Fig. 13. Exploded DDQ coil structure (2DDQ)

6) DD+Q transmitter with ovelapped ddq receiver

[9] proposed new structure for the magnetic coupler to mitigate the power null and power pulsation phenomenon. The main contribution is to reduce the mutual coupling, to achieve that the neighboring transmitter coils use two types of coils: unipolar (Q) and bipolar (DD). Q and DD coils are positioned next to one another and alternately, without overlapping.



(a): transmitter coils



(b): receiver coil

Fig. 14. DD+Q Coupler Structure

7) N-Type transmitter and Multi-phase coil receiver.

Since double D receiver coil has a sinusoidal variation with significant fluctuation and a zero point along the driving direction, dual-phase, three phase and four-phase coil receiver are suggested as a solution to that problem and to increase the output power [11]. Multi-phase structure optimizes the distance between phases to improve the coupling coefficient and reduce cost and loss. Receivers with two, three, or four phases decrease the fluctuation factor. while the benefits of the narrow-width power supply rail are maintained [11].

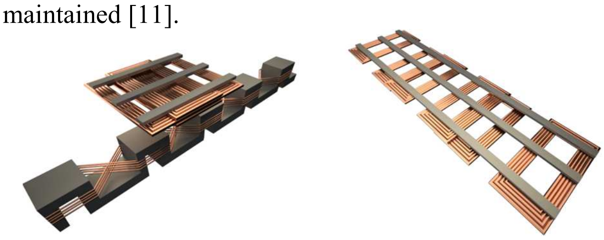


Fig. 15. (a). N-type power supply rail and the dual-phase coil receiver. (b) Three-phase receiver with adjacent partially overlapped coils

III. Critical Discussion and Comparison

A. Performance comparison of long track (Stretched) Coil Designs

Rail type	Performance and features	Challenges
E-Type	Relatively straightforward design with low construction cost.	Efficiency declines with larger air gaps or lateral misalignments, making it unsuitable for real-world applications
U-Type	Higher efficiency and wider air gap. Used in VICTORIA project by Endesa researcher to Ensure interoperability with both dynamic and stationary systems.	Increased construction costs and output power limitations
W-Type	Enhance the coupling coefficient, lower magnetic resistance in compared to E and U Types, and no need for aluminum shielding	Not explicitly discussed but appears to retain some complexity
I-Type	Narrow design reduces costs and electromagnetic field (EMF) emissions. And shows higher power and efficiency	Limited scalability and potential challenges in maintaining structural integrity
S-Type	Ultra-slim design further reduces costs and deployment times, maintaining low EMF. High misalignment tolerance	Lesser efficiency and power in compared to I-Type
Coreless -Type	Enhances compatibility with stationary WPT systems	Sacrifices mutual inductance
N-Type	Improves magnetic core utilization and further reduces construction costs	Same drawback of I and S type: Sinusoidal fluctuation induced voltage in the DD receiver coil

B. Performance comparison of Segmented Coil Designs

Coil type	Strengths	Weaknesses
Circular Coils	Simpler design with radial symmetry	Limited lateral tolerance and low power transfer capabilities
Bipolar & DD	Improve flux control and coupling efficiency	Susceptible to "null power points" where power transfer drops to zero
DDQ & 2DDQ	Address null power points by incorporating additional quadrature coils, enhancing misalignment tolerance	Increased complexity and cost
Multi-Phase Coils	Reduce fluctuations and null points while maintaining efficiency	Require optimized design for effective integration, potentially raising costs

IV. Conclusions

This paper provides a comprehensive review of the coil structure design in DWPT. Different topologies of the magnetic coupler have been introduced. A comparative assessment of diverse coil structures is presented. Long-track designs generally reduce deployment complexity. Designs like S-Type and N-Type prioritize cost and time efficiency, ideal for large-scale implementation, but suffer from lower efficiency and higher EMF emissions. Segmented designs improve efficiency and reduce magnetic leakage but are more complex and costly to maintain. However, advanced segmented designs like DDQ and multi-phase systems excel in tolerating misalignment but demand sophisticated control mechanisms. Furthermore, Segmented systems, while efficient, face challenges in balancing cost and operational reliability in real world scenarios

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