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Wireless EV Charging: The Misalignment Issue

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***Abstract*—Electric Vehicles (EVs) are becoming increasingly popular as more focus is put onto climate change and its effects. Charging EVs is of course an essential part of owning an EV. Wireless EV charging can be a revolutionary technology, but some factors could hold it back. Misalignment of the charger's coils, used to generate the electromagnetic field, is a major safety concern as it could create a hazardous condition for the user. The means to control and mitigate misalignment would not only create a more efficient charger, but also become a critical safety system. This paper presents multiple solutions to solve the misalignment issue, which all solve this problem in unique ways. This includes a charger with inductor-capacitor-inductor (LCL) and capacitor-inductor (CL) compensation networks, chargers utilizing the strongly coupled magnetic resonance (SCMR) method of wireless charging, and lastly a charger with a mechanical docking structure. These solutions were analyzed from research papers retrieved from the Institute of Electrical and Electronics Engineers (IEEE) website. Each system presented has its pros and cons, which leads each solution to be best utilized in different situations.**

Keywords*—Electric Vehicles (EVs), Misalignment, LCL and CL compensation networks, Strongly Coupled Magnetic Resonance (SCMR)

Table 1 – Acronyms

Term	Acronyms
Electric Vehicles	EVs
Inductor-Capacitor-Inductor	LCL
Capacitor-Inductor	CL
Inductive Power Transfer	IPT
Strongly Coupled Magnetic Resonance	SCMR

1. Introduction

When Nikola Tesla discovered and developed alternating current electricity in the late 1800s, he dreamed of a world where electricity would be used to supply machines everywhere with power and information. Now in the 21st century, that dream is a reality. As society progresses further into this century, we advance past the need for fossil fuels to rely on renewable energy sources. Electric vehicles (EVs) are becoming increasingly popular as a means of mitigating issues associated with fossil fuel consumption in transportation systems [1].

One method of charging EVs is doing so wirelessly by using an electromagnetic field to transfer energy to the vehicle without the need for a cord. Fig. 1 shows the basic principles of a wireless EV charger.

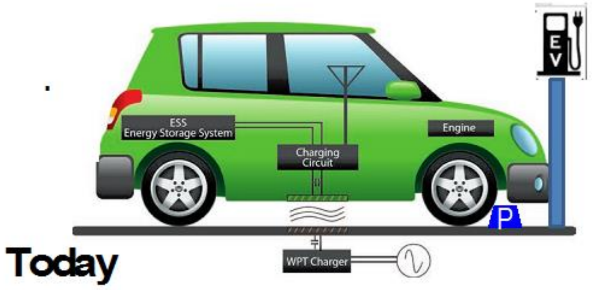


Fig.1 – Principle of statrionary wireless charging [2]

With the introduction of wireless EV charging substantial benefits can be achieved for user interaction, availability, reachability, and automation compared to wired charging. Wireless EV charging can be a revolutionary technology, but some factors could hold the technology back. Chiefly, misalignment of the charger's coils invariably causes changes in the system parameters which in turn lead to an increase in losses as well as a reduction in power throughput, making the charging process long and inefficient [3]. The efficiency of wireless charging highly relies on the alignment condition between the two charging pads. The wire-less EV chargers can commonly tolerate a misalignment error of only 10 cm, which presents a challenge to EV drivers while parking over a wireless charging station [4]. There are also concerns that misalignment can distort the field in a way that would allow the field to stretch or extend into the adjacent zone. If misalignment can cause the field to extend from under the vehicle into the user-occupied area next to the vehicle, then a hazardous condition could exist. If this is the case, then misalignment of the coils would become a critical safety issue [5]. The means to control and mitigate misalignment would not only create a more efficient charger but also become a critical safety system. To mitigate misalignment, a variety of mechanisms, such as video and infrared guidance, special mechanical or electronic maneuvering of the primary pad, and printed guidelines have been used to date. Additionally, different types of pad structures and compensation circuits can reduce the negative impacts of misalignment. However, these techniques increase the cost of construction and maintenance. In addition, having a system that requires the user to park with perfect alignment, like the guidance systems mentioned above, would harm the user acceptance of wireless EV chargers [1]. The goal of this paper is to present and outline multiple diverse solutions to the misalignment issue with their benefits and faults.

The first solution this paper analyzes, [1], is a proposed novel series-hybrid topology in which the series inductors of the primary and pick-up inductor-capacitor-inductor (LCL) networks are integrated into polarized magnetic couplers to improve the performance of the system under misalignment conditions. This system is touted as efficient, reliable, and cost-effective in comparison to other conventional LCL, and CL compensated inductive power transfer (IPT) systems. Additionally, the above-mentioned attempts have neither investigated the impact of 3-D pad misalignment nor proposed solutions to overcome any of its adverse effects [4].

The next solution [5] focuses on the design of a novel set of wireless strongly coupled magnetic resonance (SCMR) based powering systems that are less sensitive to misalignment while providing large wireless powering efficiencies. Specifically, instead of using planar coils for the transmitter and receiver, the system uses two connected orthogonal coils in a 3-D model to provide misalignment insensitivity [6].

The final solution this paper evaluates, [7], proposes a static wireless EV charging system with a mechanical structure to ensure zero airgap and zero misalignment. The mechanical structure is purely passive and does not contain any motors or drives and serves as a dock for the vehicle to connect to the charging pad.

2. Literature Review

2.1. Misalignment-Tolerant Series-Hybrid Wireless EV Charging System with Integrated Magnetics

The first solution presented in [1] is a novel series-hybrid compensation topology with integrated magnetics to improve the misalignment tolerance of IPT systems. When the magnetic coupling between the charging pads is reduced due to misalignment, it will cause the reflected impedance across $L_{pt,2}$ to reduce while inducing a larger reflected impedance across $L_{pt,1}$, as seen in Fig. 2. This then in turn leads to a reduction in power transferred through $L_{pt,2}$, but increases the power through $L_{pt,1}$. The result is a nearly constant charging profile within its designated operating region. The LCL compensated coil of this system is connected in series with the CL-compensated coil. This LCL compensation network passively limits the exponential increase in current in the series-connected CL compensated coil when the pick-up-pad moves out of the operating region. The intercoupling M_{13} between the LCL-compensated DD coil $L_{pt,1}$ and CL-compensated DD coil $L_{pt,2}$ of the series hybrid compensation topology further minimizes the circulating currents in both coils of the DD pad, as the pick-up pad moves away from the primary [1].

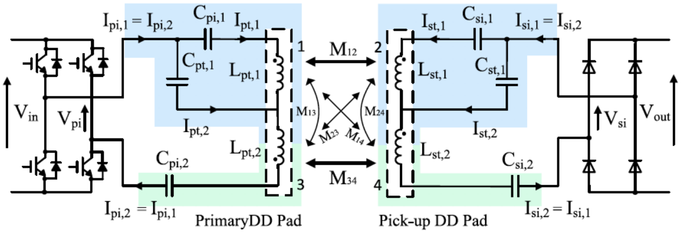


Fig.2 – Proposed novel series-hybrid compensation topology [1]

An equivalent circuit of the proposed series-hybrid IPT system is shown in Fig. 3. The DD pads in the primary and pick-up dies are modeled as for separate coils $L_{pt,1}$, $L_{pt,2}$(CL), $L_{st,1}$, and $L_{st,2}$(CL) with main couplings M_{12} and M_{34}, intercoupling's M_{13} and M_{24}, and cross-couplings M_{14} and M_{23}. The residual inductance of $L_{pt,2}$ is modeled as series inductor $L_{pt,2}$(LCL) together with the $C_{pi,1}$, $C_{pt,1}$, and $L_{pt,1}$ to from a fully tuned LCL-compensated network. The reflected voltages $V_{pr,1}$, $V_{pr,2}$, $V_{sr,1}$, and $V_{sr,2}$ relate to the currents in the DD pads due to the coupling between the coils. The pick-up side is identical to the primary and hence modeled similarly [1].

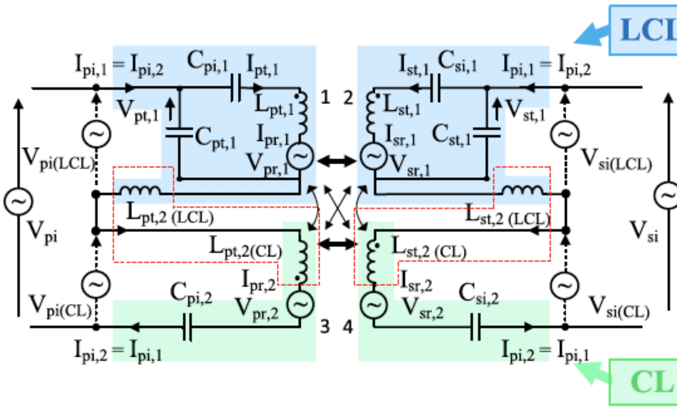


Fig.3 – Equivalent circuit of the proposed series-hybrid compensation topology [1]

2.2. Misalignment Sensitivity of Strongly Coupled Wireless Power Transfer Systems

The next solution covered by this paper, presented in [6], is a novel set of SCMR-based topologies that are less sensitive to misalignment while proving large wireless powering efficiencies. Specifically, these topologies use two connected orthogonal coils to provide misalignment insensitivity. Three SCMR systems (standard SCMR, conformal SCMR, and hybrid SCMR systems) were all studied, and compared to the proposed 3-D SCMR system in terms of angular azimuth, angular elevation, and lateral misalignment [6].

The SCMR method is a wireless power transfer method that has been recently developed, and it provides better efficiencies at a longer range than traditional near-field techniques. For SCMR to achieve high efficiency, it requires that the transmitting (TX) and receiving (RX) elements (typically loops or coils) are designed so that they resonate at the frequency where the elements naturally exhibit a maximum Q-factor. A disadvantage of conventional SCMR systems is that they are highly sensitive to the alignment between the transmitter and receiver [6].

As said above [4] studies different SCMR topologies and their sensitivity to different forms of misalignment. Angular Azimuth Misalignment is where the RX resonator and load element rotations in the XY plane around the z-axis from φ = 0° to 360, while the TX system is fixed. Angular Elevation Misalignment is where the RX system rotates in the YZ plane (elevation plane) from θ = 0° to 360 around the x-axis, while the TX system is fixed. Lastly, in the Lateral Misalignment case, the RX system is misaligned by moving it parallel to the TX system, while the distance between the planes of the RX and TX systems is kept constant [6].

2.3. Wireless EV Charging System without Air-Gap and Misalignment

The third misalignment solution this paper analyzes comes from [7] which presents a static wireless EV charging system with a mechanical structure to ensure zero air gap and zero misalignment. This proposed mechanical structure is purely passive and does not contain any motors or drives. The structure of the system utilizes the physical contact and force between two parts in the transmitter and receiver sides to move and guide the primary pad so that the primary coil will eventually move to a location that is perfectly aligned with the secondary coil, thus the air gap between the two coils will be zero as well [7].

Fig. 4 shows the transmitter of the proposed system. The primary coil along with its shielding layers is installed in the primary pad. The pad can then be turned counter-clockwise around pivot-1, which is connecting the pad and bar-1. In the position of pivot-1, a spring is installed to make sure that the pad will move back to the initial position when external force disappears. Bars 1 and 2 are connected at pivot-2. Bar-1 can rotate towards the ground around pivot point 2. Similarly, a spring is used to generate an upwards force whenever bar-1 is pushed down and shifts from its initial position. A third pivot and second spring connecting bar-2 and the pole fixed to the ground. Therefore, bar-2 can rotate along the ground around this joint and, spring-3 forces bar-3 back to its initial position after the external force is removed [7].

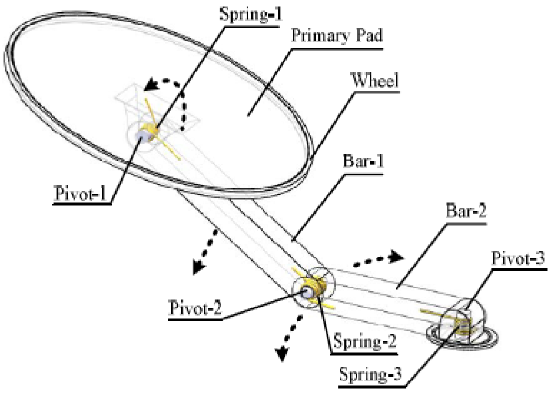


Fig. 4 Transmitter part of the proposed system [6]

Fig. 5 is the receiver part of the proposed system. The receiver consists of a secondary pad in which the receiver coil and its shielding layers are embedded. The secondary pad will be installed underneath the chassis of the car. Under the pad, there is a smooth plate with a belt around it. Another component in the receiver part is the roller. When the car moved towards the transmitter, the roller will hit the primary pad first to avoid a hard collision. Therefore, the roller will be installed in the front of the car and perpendicular to the moving direction of the car [7].

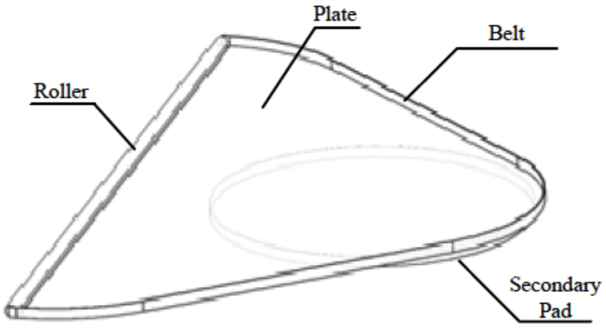


Fig.5 Receiver part of the proposed system [6]

When the car moves into a parking spot, the roller in the front of the car will hit the primary pad. As the vehicle continues to move forward, bar-1 in the transmitter will be pushed down. After the roller moves over the center of the pad, the pad will be fully attached to the plate due to the upward force generated by spring-2. Thus, there will be virtually zero air gap between the primary pad and the secondary pad [7]. When the primary pad has been fully attached to the plate on the receiver side the primary pad should embrace the “>” shape plate. This will then move the receiver into the perfect position over top of the transmitter, providing zero misalignment between the primary and secondary coils [7].

3. Results and Discussion

3.1. Misalignment-Tolerant Series-Hybrid Wireless EV Charging System with Integrated Magnetics

As discussed above in the literature review section the first solution focuses on LCL and CL compensation networks to mitigate the effects of misalignment. The proposed concept was then designed, built, and tested. As evident from Fig. 6, the output power of a baseline system changed by up to 100% due to misalignment

whereas the proposed system maintains a constant output power under the same conditions. The constant charging will reduce system complexity and cost in terms of sensors and controllers while improving the reliability of a wireless charging system. A similar power transfer profile is observed when the pick-up pad is moved along the X-axis. However, due to changes in coupling between adjacent coils of the DD pad, the prototype could only maintain a near-uniform power transfer from -80 to +120 mm misalignment in the X-axis [1].

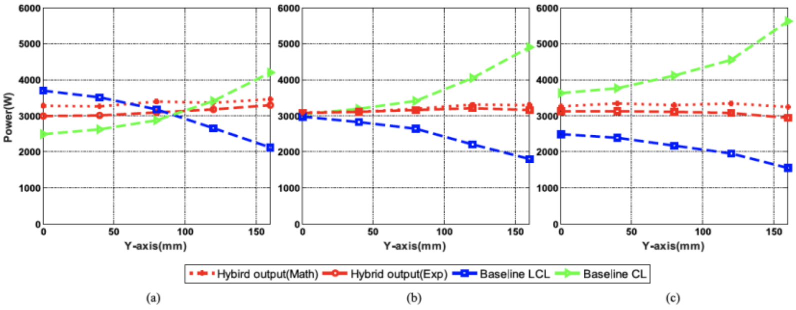


Fig.6 – Variation in output power of series-hybrid topology due to pad misalignments. (a) Z-axis:100 mm. (b) Z-axis: 120 mm. (c) Z-axis 140 mm. [1]

Fig. 7 shows the efficiency of the prototype, measured while operating under the misalignment conditions shown in Fig. 5. The efficiency varies with both vertical and horizontal displacements and drops as the pick-up pad misaligns with the stationary charger pad. The input and output currents remain approximately constant for all displacements considered. However, $I_{pt,1}$ and $I_{st,1}$ increase with increasing misalignment, leading to the contribution of conduction losses in $L_{pt,1}$ and $L_{st,1}$. This significantly increases as the pads misalign, causing a reduction in efficiency [1].

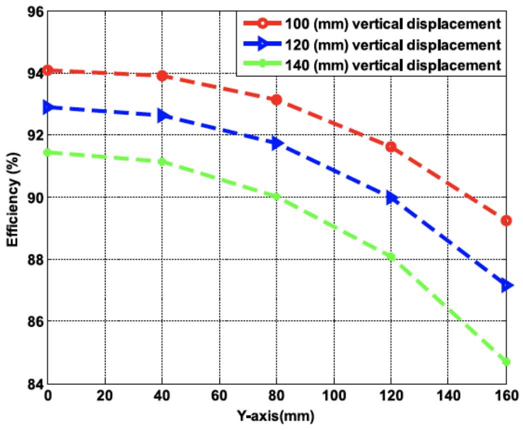


Fig.7 – Variation in efficiency due to pad misalignment [1]

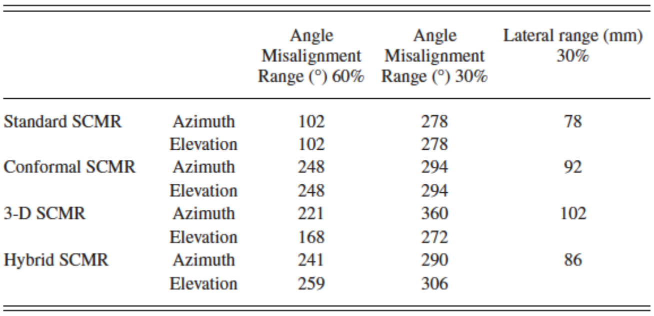
This prototype system, which operated at a fixed 100% modulation, maintained an output power within plus-minus 5% when the pick-up pad was misaligned from 160 to 160 mm along Y-axis, –80 to 120 mm along X-axis, and –20 to 20 mm along Z-axis. Although, the maximum system efficiency achieved by the prototype is only 94%. However, it could be potentially improved through the proper design of DD pads and optimizing the system [1].

This solution offers the most convenient driver experience as it leaves a large margin that is insensitive to misalignment in all three dimensions. This allows the driver to simply pull into a parking spot and receiver all the benefits of a wireless charger without worrying about lost efficiency due to misalignment. However, as discussed below there are other chargers that offer higher efficiencies.

3.2. Misalignment Sensitivity of Strongly Coupled Wireless Power Transfer Systems

Following testing, it could be concluded that CSCMR exhibited less sensitivity to misalignment because its gain (G_T) between the angles where the nulls occur increases back to its maximum whereas for standard SCMR, its G_T drops to a significantly lower value between its nulls. On the other hand, standard SCMR uses a pair of parallel loops at each of the TX and RX systems, which results in reduced G_T when the RX is rotated to 180^{o} of misalignment. 3-D SCMR exhibits no nulls for azimuth misalignment, which is a significant improvement over the standard SCMR and CSCMR. This is because each of the loops of 3-D SCMR is constructed using two orthogonal loops connected in series; therefore, for any angle of rotation, two pairs of loops are always coupled. Table 2 summarizes the measured results and compares the performance of the different SCMR systems. The angle misalignment ranges for azimuth and elevation misalignment are calculated based on the angles, for which the G_T maintains a value above 60% or 30% of the maximum GT of each system. All three proposed SCMR systems (i.e., CSCMR, 3-D SCMR, and HSCMR) exhibit a larger angle misalignment range compared to standard SCMR. 3-D SCMR exhibits the best performance regarding misalignment since it has no GT nulls over the entire 360° azimuth rotation [6].

Table 2 – Comparison of Different SCMR Systems [6]



		Angle Misalignment Range (°) 60%	Angle Misalignment Range (°) 30%	Lateral range (mm) 30%
Standard SCMR	Azimuth	102	278	78
	Elevation	102	278	
Conformal SCMR	Azimuth	248	294	92
	Elevation	248	294	
3-D SCMR	Azimuth	221	360	102
	Elevation	168	272	
Hybrid SCMR	Azimuth	241	290	86
	Elevation	259	306	

3.3. Wireless EV Charging System without Air-Gap and Misalignment

The final solution this paper covers is the static wireless EV charging system with a mechanical structure to ensure zero air gap and zero misalignment. With the static “docking” system essentially negating losses due to misalignment and air gap, the charger itself behaves similarly to a baseline WPT EV charger. The measured DC-to-DC efficiency of this system is 95.12%, while the simulation result is 95.77%. In the simulation, core loss is neglected, thus leading to slightly higher efficiency. When the duty ratio is adjusted to 0.7, the system efficiency is improved slightly to 95.36%. As discussed earlier the mechanical structure of the proposed system ensures the coils of the charger will be aligned perfectly with a negligible air-gap. This maximizes the coupling between the two coils which brings significant reductions in the volume of the system as well as pushes up the power transfer efficiency. Additionally, the dangerous magnetic flux is reduced to a minuscule level, thus human exposure risks vanish [7]. While this system does the best job of removing misalignment and curing its safety issues it also requires the most out of the driver of any system covered by this paper. The mechanical structure requires the driver to “dock” the receiver fixed to the bottom of the vehicle to the transmitter. However, the static structure does make this task easier with its “>” shape which pivots and funnels the coils into the optimum position. Additionally, while no cost analysis was conducted in any of the discussed solutions, it would not be surprising that this system would cost the most to manufacture and purchase due to the charger itself as well as its mechanical structure.

Conclusion

To conclude this paper presents multiple solutions to the misalignment issue. One solution [1] uses LCL and CL compensation networks to increase the range at which misalignment affects the efficiency of the charger. This charger proves to be the most user-friendly solution as it allows for the driver to simply pull into a charging spot and not worry about the perfect position of the car. This lends this solution to be best used in a “gas station” type setting. However, this solution does not yield the best charger efficiency. Also, this solution only solves the negative impacts of misalignment to charger efficiency, it does not remedy its various safety concerns. The next solution [4] focuses on using multiple forms of SCMR systems to remedy misalignment. This set of solutions includes Standard SCMR, Conformal SCMR, 3-D SCMR, and Hybrid SCMR. This solution does an even better job at increasing the range at which misalignment is negated. However, it accomplishes this by sacrificing efficiency. The last solution [5] uses a static structure with a mechanical system to eliminate misalignment and air-gap. This solution utilizes a “docking” system that directly connects the receiver and transmitter, thus eliminating the negative impacts of misalignment and air-gap. This allows this solution to offer the highest efficiencies of any solution presented in this paper. The solution presented in [5] presents the best solution to misalignment as it eliminates the issue however, it presents problems in doing so. While the mechanical system does its best at making it easy for the driver to dock the receiver, with the “>” shape of the transmitter, it still requires more of the driver than the other systems presented. Additionally, it would not be surprising if this solution proved to be the costliest as it requires the manufacture of the charging system as well as the mechanical system as well.

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