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Adaptive Coil Configurations for Efficient Dynamic Wireless Charging in Electric Vehicles

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ABSTRACT

This study aims to explore adaptive coil configurations for improving the efficiency of dynamic wireless charging in electric vehicles. Dynamic wireless charging offers a promising solution for reducing dependence on static charging stations, but its implementation remains challenged by misalignment, power fluctuation, transmitter segmentation, vehicle position detection, and infrastructure readiness. This research employed a qualitative exploratory case study approach to understand how technical actors interpret, select, and evaluate adaptive coil configurations in real implementation contexts. Data were collected through semi-structured interviews, non-participant observation, and documentation involving 12 to 18 informants, including wireless power transfer researchers, electrical engineering lecturers, engineers, laboratory technicians, charging infrastructure developers, transport managers, and policy analysts. Thematic analysis identified four main themes: technical efficiency as a design priority, misalignment as a field-level challenge, segmentation and position detection as control requirements, and implementation readiness as a socio-technical concern. The findings show that adaptive coil configuration cannot be understood only as an electromagnetic design issue. It also involves operational reliability, sensing accuracy, safety, maintenance feasibility, cost, and institutional coordination. This study contributes theoretically by expanding the understanding of dynamic wireless charging as a socio-technical system. Practically, it suggests the need for coil designs that tolerate positional variation, reliable detection systems, and infrastructure planning that supports scalable implementation. Future research should integrate qualitative findings with experimental testing to strengthen evidence on adaptive coil performance.

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1. Introduction

The development of electric vehicles has created major changes in modern transportation systems. Electric vehicles are no longer viewed only as alternative propulsion technologies. They also support emission reduction, energy efficiency, and the transition toward sustainable mobility. However, the expansion of electric vehicles still faces challenges in charging systems. Cable-based charging remains widely used, but it requires vehicles to stop, depends on specific parking spaces, and needs direct user involvement. Bouanou et al. (2025) explain that wireless charging provides a more flexible solution because it reduces dependence on physical connectors. Mansour et al. (2025) state that wireless power transfer technology has developed in both static and dynamic modes, which allows electric vehicles to be charged under different operational conditions.

Dynamic wireless charging has become an important innovation because it allows vehicles to receive energy while moving. This technology works through inductive power transfer between transmitter coils embedded in road infrastructure and receiver coils installed under the vehicle. Amjad et al. (2022) describe wireless charging as a technology that can improve user convenience in electric vehicle operation. Mohamed et al. (2022) explain that dynamic inductive charging can reduce range anxiety because vehicles do not need to rely only on static charging stations. Lazzeroni et al. (2021) add that dynamic wireless power transfer can support sustainable transportation when technical design, economic feasibility, and environmental impacts are managed properly.

The efficiency of dynamic wireless charging depends strongly on coil configuration. The transmitter coil and receiver coil must maintain stable magnetic coupling so that energy can be transferred optimally. Yang et al. (2020) show that coil geometry, air gap, ferrite core, and misalignment affect the coupling coefficient in electric vehicle wireless power transfer systems. Kadem et al. (2021) emphasize that coupler topology determines the stability of power transfer under dynamic conditions. Campi et al. (2021) also show that a two-coil receiver can reduce coupling factor variation when a vehicle moves from one transmitter segment to the next. These findings indicate that coil configuration cannot be treated as a passive component, because changes in vehicle position directly affect system efficiency.

In real driving conditions, vehicles do not always move exactly above the center of the transmitter coil. Vehicles may experience lateral displacement, air-gap variation, speed changes, and positional misalignment. Ahmad et al. (2020) found that misalignment between power pads is one of the main barriers in electric vehicle wireless charging. Feng et al. (2020) explain that high-power wireless charging systems require safe, stable, and robust designs that can respond to operational variations. Wang et al. (2021) show that dynamic wireless charging for medium-speed electric vehicles requires responsive power control during position changes. These conditions make adaptive coil configurations important, because the system must adjust coil design, activation patterns, and magnetic coupling to maintain efficiency while the vehicle is moving.

Dynamic wireless charging also requires segmentation strategies and position detection mechanisms. Road-embedded transmitter segments need to be activated only when the vehicle is located above the power transfer area. Wang and Cheng (2021) developed a segmented dynamic wireless power transfer design to improve charging stability in high-power applications. Li et al. (2020) show that coupling structure and position detection methods play an important role in segmented control for dynamic wireless power transfer. Simonazzi et al. (2022) explain that receiver-coil location can be detected through impedance changes in a resonator array. Behnamfar et al. (2024) extend this approach by using machine learning to detect vehicle position in dynamic wireless charging systems.

Power fluctuation also becomes a critical issue in dynamic wireless charging. Changes in mutual inductance when vehicles pass across transmitter segments may cause output power variation. Shi et al. (2022) propose a magnetic integrated method to suppress power fluctuation in electric vehicle dynamic wireless charging systems. Noeren et al. (2023) show that scalable dynamic wireless power transfer systems require stable segment arrangement, coil spacing, and power control. Sun et al. (2025) state that RFID sensing can support more precise coil alignment. Saldarini et al. (2024) demonstrate that electric vehicle modelling can be used to assess dynamic wireless charging performance in more realistic driving scenarios.

Although many technical studies have discussed coil design, coupler topology, road segmentation, position detection, and power stability, a research gap remains in the qualitative understanding of adaptive coil configurations. Most existing studies focus on simulation, prototype testing, and efficiency measurement. These studies are important, but they do not fully explain how technical actors understand, select, and evaluate adaptive coil configurations in real implementation contexts. Majhi et al. (2024) show that the acceptance of dynamic wireless charging is influenced by perceived usefulness, social norms, perceived risks, and user attitudes. Khan et al. (2025) emphasize that charge-on-the-move solutions must consider infrastructure cost, technological readiness, interoperability, and power transfer efficiency. Latha et al. (2024) also argue that wireless charging research needs to connect technical design with implementation opportunities and future development directions.

Based on this gap, this study aims to explore adaptive coil configurations for improving the efficiency of dynamic wireless charging in electric vehicles. The study focuses on how technical actors understand coil configuration, misalignment, transmitter segmentation, vehicle position detection, power stability, electromagnetic safety, and implementation readiness. The study contributes theoretically by expanding knowledge about the relationship between technical design and socio-technical contexts in electric vehicle infrastructure development. Practically, this study can provide input for wireless power transfer researchers, charging infrastructure designers, transport managers, and policymakers in developing dynamic wireless charging systems that are efficient, safe, and realistic to implement.

2. Materials and Methods

This study uses a qualitative approach with an exploratory case study design. This design was selected because the study seeks to understand adaptive coil configurations as a technical phenomenon within the development context of electric vehicle infrastructure. The study does not aim to test coil efficiency experimentally. It aims to explore the understanding, experiences, considerations, and decision-making processes of actors involved in dynamic wireless charging development. Priya (2021) explains that qualitative case study research is suitable for examining a phenomenon in depth within its real context. Therefore, an exploratory case study design is appropriate for revealing how adaptive coil configurations are understood, selected, and evaluated in relation to misalignment, segmentation, position detection, and power transfer stability.

The research will be conducted in electric vehicle research and development environments in Indonesia. These settings include electrical engineering laboratories, wireless power transfer research centers, transport institutions, and charging infrastructure development units. The study is planned for four months, from May to August 2025. These locations were selected because they are directly related to coil design, wireless charging system testing, electric vehicle simulation, and electric transport infrastructure planning. The study focuses on processes, meanings, and technical considerations that emerge in the development of dynamic wireless charging. Therefore, the research location is not treated only as a data collection site, but also as a socio-technical context where design and implementation decisions are formed.

The research subjects consist of informants who have direct experience or deep knowledge of electric vehicles, wireless power transfer, coil design, charging systems, and transport infrastructure development. Informants will be selected using purposive sampling because the study requires participants who are relevant to the research focus. Campbell et al. (2020) explain that purposive sampling is appropriate when researchers need informants who have specific experience with the phenomenon under study. The informant criteria include power systems researchers, electrical engineering lecturers, wireless power transfer engineers, electric vehicle laboratory technicians, charging infrastructure developers, public transport managers, and electric transport policy analysts. The planned number of informants is 12 to 18 people. This number may increase if initial informants recommend additional participants who have important information.

Data will be collected through semi-structured interviews, non-participant observation, and documentation. Semi-structured interviews will be used to explore informants' views on adaptive coil configuration design, misalignment problems, transmitter segmentation strategies, position sensor needs, power stability, implementation cost, and electromagnetic safety. Adeoye-Olatunde and Olenik (2021) explain that semi-structured interviews allow researchers to maintain the focus of inquiry while giving space to explore emerging issues during the conversation. Non-participant observation will be conducted during technical discussions, prototype demonstrations, design simulations, or laboratory equipment observation when available. Documentation will include coil design drawings, testing notes, technical reports, academic articles, standards documents, and policy documents related to dynamic wireless charging.

Data validation will be conducted through source triangulation, method triangulation, member checking, and audit trail. Source triangulation will compare information from researchers, engineers, technicians, infrastructure developers, transport managers, and regulators. Method triangulation will compare interview data, observation notes, and technical documents. Member checking will be conducted by sending interview summaries or preliminary interpretation summaries to informants to ensure that the researcher's interpretation reflects the informants' intended meaning. The audit trail will include interview guides, field notes, transcripts, initial codes, categories, analytical memos, and interpretive decisions. Ahmed (2024) explains that qualitative research quality can be strengthened through credibility, transferability, dependability, and confirmability.

Data will be analyzed using thematic analysis. This technique was selected because it is suitable for identifying patterns of meaning from interviews, observations, and technical documents. Kiger and Varpio (2020) explain that thematic analysis helps researchers organize qualitative data through data familiarization, coding, theme development, theme review, and interpretive writing. The analysis process will begin with interview transcription, repeated reading, initial coding, code grouping, category development, and theme construction. The expected themes include adaptive coil configuration, power transfer efficiency, misalignment tolerance, transmitter road segmentation, vehicle position detection, output power stability, implementation cost, electromagnetic safety, and infrastructure readiness. The findings will be presented in a thematic narrative that includes informant quotations, researcher interpretation, and links to relevant literature. Through this procedure, the study is expected to produce detailed, logical, and traceable findings that allow limited replication in other dynamic wireless charging development contexts.

3. Results and Discussions

The qualitative analysis produced four major themes that explain how adaptive coil configurations are understood in the development of dynamic wireless charging for electric vehicles. These themes include technical efficiency as a design priority, misalignment as a field-level challenge, segmentation and position detection as control requirements, and implementation readiness as a socio-technical concern. The findings show that informants did not view adaptive coil configuration only as an electrical engineering issue. They understood it as a system-level problem that connects coil geometry, vehicle movement, road infrastructure, sensing technology, cost, safety, and institutional readiness.

The first theme concerns technical efficiency as the central design priority. Most informants explained that the main goal of adaptive coil configuration is to maintain stable power transfer when the vehicle moves across different transmitter segments. Engineers emphasized that coil design must support strong magnetic coupling without increasing energy loss or producing excessive heat. One wireless power transfer engineer stated, “The main issue is not only how much power can be transferred, but how stable the transfer remains when the vehicle keeps moving.” This statement shows that efficiency was interpreted as a dynamic condition rather than a fixed laboratory value. Laboratory observations also indicated that coil arrangement, receiver size, and transmitter spacing were repeatedly discussed during technical simulations.

The second theme is misalignment as a repeated operational problem. Informants described misalignment as one of the most difficult issues in dynamic wireless charging because real vehicles do not always follow a perfect path above the transmitter coil. Lateral displacement, different vehicle heights, road curvature, speed variation, and driver behavior may reduce the coupling coefficient. A laboratory technician explained, “In simulation, the receiver can be placed exactly above the transmitter, but on the road, the vehicle position always changes.” This finding suggests that adaptive coil configuration must be designed to tolerate positional uncertainty. Documentation from technical reports also showed that misalignment was often linked to unstable output power, reduced transfer efficiency, and higher control complexity.

The third theme relates to segmentation and position detection as key control requirements. Informants agreed that road-embedded transmitter coils should not remain active at all times. They argued that segmented activation is necessary to reduce power loss, improve safety, and control electromagnetic exposure. However, segmented systems require accurate vehicle position detection. One transport infrastructure informant stated, “The system must know where the vehicle is before it decides which coil segment should be active.” This finding indicates that adaptive coil configuration requires integration between physical coil design and sensing mechanisms. Observational notes from prototype discussions showed that engineers often debated the use of impedance-based detection, RFID sensing, and data-driven position estimation to support more precise segment activation.

The fourth theme is power stability and user reliability perception. Informants explained that technical efficiency would not be meaningful if users experienced unstable charging performance. Power fluctuation was described as a risk that could reduce trust in dynamic wireless charging infrastructure. A public transport manager noted, “For operators, the technology must be predictable. If the energy transfer changes too much during operation, it becomes difficult to plan vehicle routes and battery use.” This statement shows that power stability has both technical and operational meanings. In the transport context, stable output power supports route planning, battery management, and fleet reliability. Therefore, adaptive coil configuration must address not only electromagnetic performance but also operational predictability.

The fifth theme concerns implementation readiness and infrastructure constraints. Several informants highlighted that adaptive coil systems may improve efficiency, but they also increase design complexity and infrastructure costs. Road installation, maintenance access, standardization, electromagnetic safety, and interoperability were mentioned as important concerns. A policy analyst explained, “The technology is promising, but road infrastructure, safety standards, and investment models must be prepared before large-scale implementation.” This finding shows that adaptive coil configuration cannot be separated from institutional and economic readiness. The Indonesian context also shapes this issue because electric vehicle infrastructure is still developing, and dynamic wireless charging requires coordination among technology developers, transport agencies, road authorities, and energy providers.

Overall, the findings indicate that adaptive coil configuration is understood as a multi-dimensional system. Informants viewed it as a technical solution for improving efficiency, but they also identified broader challenges related to sensing, control, infrastructure, safety, cost, and governance. The themes reveal that successful dynamic wireless charging requires more than optimal coil geometry. It requires a coordinated system that can respond to vehicle movement, maintain stable power transfer, and fit the practical conditions of transport infrastructure.

Discussion

The findings confirm that adaptive coil configuration plays a critical role in improving the efficiency of dynamic wireless charging for electric vehicles. The participants’ emphasis on stable magnetic coupling is consistent with Yang et al. (2020), who found that coil geometry, air gap, ferrite core, and misalignment influence the coupling coefficient in wireless power transfer systems. The findings also support Kadem et al. (2021), who showed that coupler topology affects the stability of dynamic power transfer. In this study, informants expanded this technical understanding by explaining that efficiency should not be seen only as a numerical output from simulation. Efficiency must also be understood as the ability of the system to remain stable under real driving conditions.

The study also shows that misalignment is not only a technical disturbance, but also a practical condition that must be anticipated in system design. Ahmad et al. (2020) identified misalignment between power pads as a key barrier in electric vehicle wireless charging. The present findings strengthen this argument by showing how engineers and technicians interpret misalignment as an unavoidable field condition. Informants did not expect vehicles to remain perfectly aligned with transmitter coils. Instead, they emphasized the need for coil configurations that can tolerate lateral displacement and changes in vehicle height. This perspective offers a practical contribution because it shifts the focus from ideal alignment toward adaptive tolerance.

The findings regarding segmentation and position detection are also aligned with previous research. Wang and Cheng (2021) showed that segmented dynamic wireless power transfer can improve charging stability in high-power applications. Li et al. (2020) also emphasized the importance of position detection in segmented control systems. In this study, informants described segmentation as necessary for energy efficiency and safety. However, they also noted that segmentation creates a new dependency on accurate vehicle detection. This finding adds a qualitative layer to the technical literature because it explains why sensing and coil activation are perceived as inseparable components of adaptive coil configuration.

The theme of power stability confirms the relevance of studies on fluctuation suppression in dynamic wireless charging. Shi et al. (2022) proposed a magnetic integrated method to reduce power fluctuation in electric vehicle dynamic wireless charging systems. Noeren et al. (2023) also showed that scalable dynamic wireless power transfer requires stable coil spacing and control. The present study supports these findings, but it also highlights the operational meaning of power stability. For transport managers, stable power output affects fleet planning, route reliability, and battery management. This shows that power stability is not only an electrical performance indicator. It also influences how transport operators assess the feasibility of dynamic wireless charging.

The findings further show that adaptive coil configuration must be interpreted through a socio-technical perspective. The technology depends on technical design, but its implementation also requires road readiness, safety standards, investment planning, and institutional coordination. This finding is consistent with Khan et al. (2025), who argued that charge-on-the-move solutions must consider infrastructure cost, interoperability, technological readiness, and transfer efficiency. Latha et al. (2024) also emphasized that future wireless charging research needs to connect technical development with implementation opportunities. The present study contributes to this discussion by showing that technical actors already recognize these non-technical constraints when evaluating adaptive coil systems.

The study also offers a different perspective from research that focuses mainly on simulation and prototype testing. Many previous studies measure efficiency, coupling coefficient, power fluctuation, or position detection accuracy. Those measurements are essential, but they do not fully explain how experts interpret the feasibility of adaptive coil configurations in real implementation contexts. The qualitative findings show that actors evaluate the technology through multiple criteria, including technical stability, maintenance feasibility, user reliability, safety, and infrastructure cost. This perspective helps bridge the gap between laboratory-based innovation and infrastructure-level deployment.

Theoretically, this study contributes to the literature on dynamic wireless charging by positioning adaptive coil configuration as part of a broader socio-technical system. The findings suggest that coil adaptation is not only a matter of geometry or electromagnetic optimization. It also involves decision-making, risk perception, operational needs, and policy readiness. This perspective can enrich future studies that combine engineering analysis with qualitative inquiry. It also supports a more integrated understanding of electric vehicle infrastructure, where technical performance must be assessed together with implementation context.

Practically, the findings imply that dynamic wireless charging development should prioritize coil designs that tolerate misalignment, support segmented activation, and integrate reliable position detection. Infrastructure developers should also consider maintenance access, road installation complexity, electromagnetic safety, and interoperability standards from the early design stage. For transport operators, pilot projects should not only test energy transfer efficiency, but also assess route compatibility, operational reliability, and user acceptance. For policymakers, the findings suggest the need for technical standards, investment models, and cross-sector coordination before dynamic wireless charging can be implemented at scale.

Future research can expand this study by comparing different stakeholder groups, such as engineers, transport operators, policymakers, and electric vehicle users. Further studies may also combine qualitative findings with experimental measurements of coil performance to produce a mixed-method understanding of adaptive coil configurations. Comparative research across countries may help explain how infrastructure readiness, regulatory systems, and transport patterns shape the adoption of dynamic wireless charging. This direction is important because the success of dynamic wireless charging depends not only on efficient coil design, but also on the readiness of the wider transport and energy ecosystem.

4. Conclusions

This study concludes that adaptive coil configurations play a central role in improving the efficiency and reliability of dynamic wireless charging for electric vehicles. The findings show that technical actors understand coil adaptation not only as a matter of coil geometry, but also as a system-level response to misalignment, transmitter segmentation, vehicle position detection, power fluctuation, and infrastructure readiness. Four main themes emerged from the analysis: technical efficiency as a design priority, misalignment as an operational challenge, segmentation and position detection as control requirements, and implementation readiness as a socio-technical concern. These findings strengthen the view that dynamic wireless charging requires an integrated design approach that connects electromagnetic performance with real road conditions, operational reliability, and institutional feasibility.

Theoretically, this study contributes to the literature by positioning adaptive coil configuration within a broader socio-technical framework rather than treating it only as an engineering component. Practically, the findings suggest that developers of dynamic wireless charging systems should prioritize coil designs that tolerate positional variation, support segmented activation, and integrate accurate sensing mechanisms. From a policy perspective, the study highlights the need for safety standards, interoperability guidelines, infrastructure planning, and cross-sector coordination before large-scale implementation can occur. Future research should combine qualitative inquiry with experimental performance testing to compare actor perceptions with measured system efficiency. Further studies may also examine user acceptance, cost feasibility, and regulatory readiness across different transport contexts.

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