https://doi.org/10.31449/inf.v50i10.9393

ANN-Based Control and Misalignment Compensation for Dynamic Wireless Power Transfer Systems in EV Charging

Runkun Guo
ShanXi Institute of Mechanical&Electrical Engineering, Chang Zhi 046011, China
E-mail: wooride@126.com

Keywords: dynamic wireless charging, coil design and analysis, EV system, accurate alignment control, energy transmission optimization, ANN

Received: May 26, 2025

The potential of dynamic wireless power transfer (DWPT) to link electric vehicles to charging stations without the need for physical connections has attracted a lot of interest. Two of the most crucial characteristics for real-world uses of wireless dynamic charging are stable output power and good system efficiency. Nevertheless, researchers face a significant obstacle in their pursuit of more efficient power transmission. The literature explores several methods to optimize power transmission efficiency. The control method, compensation capacitance, magnetic coupler design, and power electronic circuit are all part of the research. Additionally, whether the wireless charging system is static or dynamic determines the sort of inquiry that is conducted. An efficiency optimization strategy, namely an ANN, is suggested for low-speed dynamic charging application situations to regulate the output voltage and increase system efficiency. It is possible to create a stronger magnetic field devoid of dead spots by overlapping two DD coils. As the receiver travels along the track, an optimal current control mechanism is suggested to dynamically modify the direction and ratio of the two transmitter currents. This technology may maximize the dynamic charging system's efficiency while regulating the output power to the appropriate value simultaneously. Ansys Maxwell is used to represent wireless coils that have angular misalignment. By using angular motion to align the coils, the suggested practical EV system successfully decreases misalignment that occurs while two-wheelers are parked. To do this, just turn the transmitter coil so it faces the right way. To further aid automated alignment, tiny sensing coils are used to detect misalignment. In order to charge batteries in both constant current as well as constant voltage modes, a power management mechanism is also required. In order to verify how well the suggested approach works, a 600W model is built. The suggested technique achieves system efficiency for charging dynamically of 92.5% and 95.4%, according to the testing data. When both DD coils are activated to the same current, the suggested technique improves efficiency by a maximum of 15%. For maximum capacity use and extended lifetime of lithium-ion batteries, it is essential to charge them effectively using both CC and CV modes. Also, it demonstrates that magnetic separation material may greatly enhance wireless charging system performance with big misalignment.

Povzetek: Študija obravnava optimizacijo dinamičnega brezžičnega polnjenja električnih vozil z uporabo nevronske mreže in izboljšane zasnove tuljav za povečanje učinkovitosti, stabilnosti izhodne moči ter zmanjšanje vpliva neporavnanosti, pri čemer dosega več kot 92 % učinkovitost sistema.

1 Introduction

A potential new way to reduce pollution and our dependency on fossil fuels has been the meteoric ascent of electric vehicles in recent years [1]. Significant obstacles to its broad acceptance are the inconvenient need to recharge batteries and the short driving range. Limitations in flexibility, security risks, and user irritation are some of the drawbacks with traditional plug-in charging methods. These techniques need a physical connection between the car and charging infrastructure [2]. A solution to these issues is wireless charging, which improves safety and flexibility by doing away with the requirement for a physical connection. With dynamic charging, electric vehicles can be topped up while on the go, greatly extending their range and doing away with the need to pull over for charging. On long-distance trips, when drivers could be away from charging facilities for days at a time, this technology really shines [3]. Electric cars may also find a home in public and commercial transportation systems that use dynamic charging, as these vehicles often adhere to predetermined routes and make numerous stops. To reduce downtime and increase efficiency, charging pads may be integrated into the road infrastructure. This allows these vehicles to be charged continually while they are in operation [4]. But before dynamic charging catches on, a few things have to be ironed out. Installation costs, charging efficiency, and pedestrian and driver safety are a few of these factors. Dynamic charging technology is a thrilling step toward a greener transportation system, despite these obstacles.

Reaching interoperability among various power coil systems is a hurdle in DWPT. Making sure a vehicle with a certain power coil can use any DWPT infrastructure it comes across may be difficult since different manufacturers use different coil concepts, frequencies, and power levels [5]. The broad adoption of DWPT equipment might be impeded if this leads to a fragmented market using incompatible solutions. The need to standardize the size and location of power coils is another obstacle. For cars to be able to align into the power coils and transmit power efficiently, this is of the utmost importance [6]. Vehicle production and infrastructure construction may both benefit from standardization's ability to bring costs down. Costs and effort may add up quickly when power coils are embedded into preexisting infrastructure without proper planning and collaboration with local authorities. Further complicating matters and driving up deployment costs is the possibility that improvements to the power grid may be necessary to accommodate the increased power needs of DWPT equipment [7].

Because of their potential impact on power transfer efficiency, resonance along with compensation is critical design considerations for DWPT systems. Ensuring stability and resonance under different load circumstances is a significant problem when developing the architecture of the compensation network. Because of the potential impact of lateral misalignment on resonance in in-motion DWPT systems, this is of the utmost importance [8]. Particularly for DWPT system interoperability, the Tx and Rx coils' resonance frequencies are compatible. For optimal power transmission, make sure the Tx and Rx coils' resonance frequencies are in sync and that the Q factor is high. Health and safety issues aside, resonance has the potential to disrupt other electrical gadgets. Consequently, DWPT systems must be meticulously designed and tested to guarantee safe operation free from detrimental influence [9].

The alignment, distance, system resonance frequency, and power electronics efficiency of the transmitting and receiving coils, among other criteria, determine the greatest possible power transfer efficiency in WPT systems. In real-world scenarios, such as charging electric vehicles, a high PTE is essential for effective energy transmission. Attaining MPTE in DWPT devices is not without its difficulties and restrictions, however [10]. A significant obstacle that might decrease coupling and MPTE is the lateral misalignment of coils that occurs during in-motion charging. Furthermore, substantial power losses might occur due to coupling interference caused by surrounding metallic objects like buildings and automobiles [11]. The skin effect as well as eddy currents may amplify losses in DWPT systems operating at high frequencies and with high power. To get the most out of power transmission, you also need to choose the resonance frequency carefully. The need of a compensation system to maximize the efficiency of power transmission in less-than-ideal situations is an additional obstacle. In order to prevent power losses and decreased efficiency, this network's design must account for reactive components such as inductance and capacitance [12]. To summarize, optimizing and designing system components with great care is essential for DWPT systems to achieve MPTE.Other issues that must be addressed include metallic objects, coil alignment, along with compensation network design [13].

Because of their versatility and ease of use, WPT systems have become quite popular. Attaining maximum power point tracking is critical for optimizing the efficiency of such systems. In order to maximize power transfer in WPT systems, many approaches have been put forth to deal with issues such frequency tracking, coil misalignment, as well as impedance matching [14]. Prior studies have shown that coil misalignment may be reduced by using a buck converter on the receiving side. To further improve MPPT control in magnetically coupled resonant WPT systems, a single-ended primary inductance converter converters cascaded at the receiver may be used [15]. Constant maximum power maintenance becomes critical in dynamic circumstances. A control approach has been developed to tackle this issue, guaranteeing that optimum power supply will occur regardless of changes in the system or fluctuations in the load. Improving efficiency over different distances and alignments, neural network-based solutions also provide better mutual inductance estimate for MPPT in wireless power transfer arrays [16].

1.1 Coil types

While WPT systems have made use of a variety of coil designs, the ones that work best for high-frequency wireless transfers are circular coils because their roundness minimizes eddy currents [17]. Circular coils provide a strong magnetic field, which improves the performance of WPT devices. Any longitudinal or lateral misalignment considerably affects power transmission when the vehicle is in motion, and the charging process is a temporary state while using an electric car. Each of the WPT applications' respective coils is detailed in Table 1.

Table 1: Different types of coils

Coil Type	Description	Coil Type	Description
Circula	1. CP creates a vertical flux channel, and the pad size is 1/4 of that height. 2. The button is badly misplaced and does not have polarization. 3. In SWC, the basic system is often used as a transmitter. 4. The protective impact is diminished.	Square	1. Sharp edges cause a higher inductance value, and under fully aligned settings, it has smaller self-inductive behavior compared to CP. 2. Sharp edges cause eddy currents and hot spots. 3. Not recommended for projects that need a lot of electricity.
Hexagonal	1. Attaining perfect alignment allows for the most efficient flow of power. 2. The efficiency of power transmission is significantly reduced when there is misalignment. 3. A non-polarized pad with low leakage flux that is often used on the receiving end.	Rectangular	1. Because the RP perpendicular flux route is half as tall as the pad, it is better for horizontal misalignment than square or circular. 2. Cover with a non-polarized, moderate leakage flux. 3. It is common for both the sender and the receiver to utilize.
Double D	4.Outperforms non-polarized pads in terms of horizontal displacement tolerance. 5.Includes a polarizing pad and a substantial shielding effect. 6.Less leakage flux is present. 7.Usually in the case of the transmitter.	Double D Quadrature	4.An improved choice from the perspective of the recipient. 5.A polarizing pad that allows little leakage flux to occur. 6.Plenty of space to charge. 7. Improved resistance to horizontal and vertical misalignment. 8.To operate the DDQ pad, two power converters are needed.
Bipolar	1. Increased compatibility with a lower threshold for misalignment. 2. A multi-step control scheme; two power converters are required to operate the bipolar pad. 3. A complicated control approach typically used on both the transmitter and receiver sides, with a strong influence of k and shielding.	Quadrapule	1. A highly interoperable control method including complexity. 2. Kind of polarizing pad has a lower leakage flux and a greater misalignment tolerance. 3. Both the transmitter and the receiver often use advanced control methods.
Flux pipe	4.A polarizing pad with a medium flux leakage has a higher shielding effect. 5.The medium-charge zone has a low misalignment threshold. 6.Deficiency in compatibility. 7.Useful both for sending and receiving signals.	Tri-polar	4.a broad charging zone is achieved by using polarizing pads on the receiver as well as the transmitter sides, which usually have a low leakage flux. 5.Very good compatibility with other systems. 6.Greater ability to withstand misalignment. 7.Reduced protective effect.

1.2 Research motivation

With dynamic charging, electric vehicles can be topped up while on the go, greatly extending their range and doing away with the need to pull over for charging. On long-distance trips, when drivers could be away from charging facilities for days at a time, this technology really shines. Electric cars may also find a home in public and commercial transportation systems that use dynamic charging, as these vehicles often adhere to predetermined routes and make numerous stops [18]. Typical deep-well capacitive systems use resonant inductive power transfer to move current from underground primary coils to an EV's secondary coil at the vehicle's undercarriage, with an air gap that's proportional to the vehicle's height above ground. To reduce downtime and increase efficiency, charging pads may be integrated into the road infrastructure [19]. This allows these vehicles to be charged continually while they are in operation. But before dynamic charging catches on, a few things have to be ironed out. Installation costs, charging efficiency, and pedestrian and driver safety are a few of these factors. Dynamic charging technology is a thrilling step toward a greener transportation system, despite these obstacles.

EV researchers have long sought to perfect wireless power transfer systems that are both dependable and efficient. The problem of angular misalignment among the coils of the transmitter and the receiver is one of the primary obstacles encountered by such systems. Imperfect power transmission due to angular misalignment may reduce system efficiency and even harm the electric vehicle's battery. Current WPT systems often fail to sufficiently handle this matter, resulting in a significant decrease in power transfer effectiveness. For maximum efficiency in power transmission and the system as a whole, a solution is urgently required that can detect and compensate for angular misalignment. This article's major contribution was summed up as:

- Adding CC and CV charging methods to the 500W WPT charging device for the low-cost electric scooter that was built.
- Ansys-Maxwell Finite Element Analysis tools were used to analyze the performance of a WPT system with angular misalignment.
- Create and deploy a tracking system to fix WPT charging for electric vehicles that suffers from angular misalignment which achieves a high misalignment tolerance.

Here is the breakdown of the article: Section II introduces the fundamentals of a WPT system and how it works, as well as the proposed CC-CV-based WPT. We talk about WPT's simulation analysis in Section III. The difficulties caused by WPT coils' angular misalignment are not the only ones that the suggested solution takes into account in Section IV. A strategic method to reducing misalignment problems when parking two-wheelers utilizing hardware configuration is shown in Section V, which focuses on employing angular motion for aligning the coils.

2 Related work

Improve the stability and efficiency of the system's output power using a vision-based misalignment detection approach, as recommended by the authors of [20]. To begin, theoretical correlations were constructed among system efficiency, output power, and mutual inductance. Secondly, ANSYS Maxwell was used to model and simulate the interaction between the misalignment and the mutual inductance. Third, the correct misalignments were obtained online by using image recognition of the ground guideline to find the transmitter coil. The obtained misalignments allow for the accurate and speedy regulation of the output power to the required value. In conclusion, the experimental findings demonstrate that the suggested technique outperforms the typical discrete proportional-integral control method in precisely acquiring coil misalignments and promptly regulating the system output power.

While analytical and experimental research in the [21] literature indicate the concept's empirical validity, the problem of misalignment has not been thoroughly investigated. In V2V systems, the inductive coils must be precisely aligned in order to achieve optimum power transmission. Significant energy losses occur as a result of lateral misalignment when the coils deviate from their correct alignment. Furthermore, there has been insufficient progress in developing controllers that effectively handle the issue of V2V misalignment. The authors of that paper suggest fixing V2V-DWC systems' misalignment problems by creating an ANFIS, an adaptable fuzzy logic controller based on neural networks. In order to assess how well each controller performs at different levels of LTM, they compare the standard fuzzy logic controller with the suggested ANFIS controller. They use MATLAB/Simulink simulations and augment them with experimental testing to assess the suggested ANFIS controller's performance. When it comes to solving the problem of V2V misalignment, the findings show that the suggested ANFIS controller is better than the FLC in both experimental and simulation settings.

The authors of [22] put forth a novel approach to SDWPDT, or simultaneous dynamic wireless energy and information transmission. As the receiver moves, its location determines whether the power and data transmission channels are turned on or off. Coupling coils and metal shield plates produce an electric field with a high frequency that carries data, while coupling coils also produce a magnetic field with a relatively low frequency that carries power. That keeps the power and data transmission lines from interfering with each other too much. To start, without a direct electrical wire-based connection, power-to-data interference may be significantly minimized. The second point is that the data transfer channel's impact on the power link's power loss is negligible. Furthermore, closed-loop control may be more easily established with the use of real-time communication. That system ensures that the power output remains constant during the dynamic movement, regardless of changes in the load or input voltage. The experimental results based on the prototype in the lab confirm that the strategy is feasible.

A highly interoperable, communication-free optimum frequency control solution for the autonomous guided vehicle's dynamic wireless charging system is suggested by the experimenters of the [23] study. The location of the receiver (Rx) may be tracked in real-time by regularly measuring the main winding currents. Transmitters that are firmly coupled to the Rx can then be turned on for power transfer. A suggested optimum frequency control strategy for zero-phase-angle is meant to enhance the efficiency of the system. The principal side reactive power is quickly eliminated using a proportional-integral loop. The location and appropriate frequency tuning may be finished in 10 ms, according to the experimental findings. Even in the most extreme circumstances, the out-phase can be kept within 3. 57°, while the system transfer effectiveness can be enhanced to 11. 1%. Various shaped Rxs are used as case studies in tests, while the same efficiency is confirmed. High interoperability is shown by the findings. The suggested control technique yielded a dependable and environmentally friendly system that did not need any auxiliary position sensors or bidirectional communication.

In order to control the output voltage of the DWCS for EVs without model priori knowledge, the researchers in [24] concentrated on that topic. While the DWCS offers a potential answer to the range anxiety problem, the prolonged charging time and restricted energy storage capacity have prevented the broad deployment of EVs. A model-free composite disturbance rejection control system is developed for the control circuit of a DWCS in that paper. That scheme is intended to offer electric vehicles with a steady and uninterrupted energy source. To be more precise, the charging circuit's unknown lumped disturbance is estimated using an adaptive extending state observer. In order to provide the DWCS with the required duty cycle signal, an MFC law that relies on switching gain was developed. Afterwards, a rule for identifying online parameters is formulated in order to retrieve the unidentified control input gain. Not only that, but the suggested approach may recover the DWCS's unknown control input gain, uncertainties in the circuit, and external disturbances all at once, without analyzing or establishing the system mathematical model. All of the state error signals are shown to be confined by stability analysis. In conclusion, the suggested MFC system for the DWCS using constant output voltage control is successful, as shown by both experimental and computational findings.

In order to enhance the anti-misalignment capabilities of a DWC system, the authors of [25] suggested a main-auxiliary cooperative receiving coil (MA-coil) that has a reduced space occupancy rate with a simple control based on the time-sharing working concept. The design of the MA-coil's structure with circuit topology is the first step. The two auxiliary coils, denoted as A-coils, are symmetrically positioned on each side of the main coil, and they are linked in reverse series. Second, the time-sharing working concept is used to determine the MA-output coil's performance in the y-direction. As soon as side shift happens, the A-coil automatically increases the output power. Lastly, the optimal ratio of coil widths w _M and w _A is established. In that scenario, they simulate the MA-coil and a square coil to evaluate their anti-misalignment performance and effective side shift range. As a last step, they construct an experimental prototype to test the suggested structure's viability. The findings of that test are generally in line with those of the theoretical analysis. Compared to the square coil, the MA-coil has a 20% better anti-misalignment capacity.

Table 2. System comparison analysis

References	Simulation model	Description	Methods / Objectives
Ref [20]	ANSYS Maxwell	Vision-Based Misalignment Detection	system efficiency, output power, and mutual inductance
Ref [21]	MATLAB/Simulink simulations	Fixing V2V-DWC systems' misalignment problems	ANFIS, an Adaptable Fuzzy logic

Ref [22]	ANSYS Maxwell	Simultaneous Dynamic Wireless Energy And Information Transmission	Coupling coils and metal shield plates
Ref [23]	ANSYS Maxwell	Communication-Free Optimum Frequency Control	Optimum frequency control strategy for zero-phase-angle is meant to enhance the efficiency of the system
Ref [24]	MATLAB/Simulink simulations	DWCS with the required duty cycle signal	All of the state error signals are shown to be confined by stability analysis
Ref [25]	ANSYS Maxwell	Main-auxiliary cooperative receiving coil (MA-coil) that has a reduced space occupancy rate	Optimal ratio of coil widths w _M and w _A is established. MA-coil and a square coil to evaluate their anti-misalignment performance

3 Dynamic system model

Two coils for mutual coupling and a bridge rectifier circuit featuring a capacitive filter that serves to convert incoming high-frequency AC current to DC, that is safe for battery charging, make up a WPT system.A high-frequency inverter is responsible for boosting the main current's frequency. Typical DWC systems use resonant inductive power transfer to move current from underground primary coils to an EV's secondary coil at the vehicle's undercarriage, with an air gap that's proportional to the vehicle's height above ground.

A comprehensive bridge design with four SiC-MOSFETs—silicon carbide metal oxide semiconductor field-effect transistors—makes up the inverter. Inverters used to employ silicon-insulated gate bipolar transistors, but MOSFETs are slowly but surely displacing them because of how much better they work in commercial and industrial settings with their lightning-fast switching speeds. The switching speed and reverse voltage blocking capacity of IGBTs are lower than those of MOSFETs. For WPT systems operating within the frequency range of around 80 to 210 kHz, which is required by SAE requirements for systems rated under 3. 7 kW, MOSFETs are the best choice due to their lowest switching loss at about 100 kHz. Inverters for low-powered autonomous cars or very slow-moving EVs are therefore best designed using MOSFETs. When comparing MOSFETs to IGBTs, MOSFETs significantly outperform IGBTs in terms of heating capacity, switching losses, along with gate driver loss. Devices made of silicon carbide, such as SiC-MOSFETs, have a very high heat conductivity and may function in applications requiring a wide voltage range. As a result, SiC-MOSFETs are thought to be the best semiconductors for efficient power conversion. A controller must be included in the design of a closed-loop system in order to regulate the system. In a closed-loop control system, a controller that is linked to another controller that only takes derivatives (D-only) is the best option. There are three primary kinds of controllers, and this decision is based on that fact: proportional, integral, and derivative. Other controllers, such PI, PD, and PID controllers, are built upon combinations of these three. The benefits for each of these controllers are distinct from one another. But when working with a complicated system such a WPT system, you need feedback that is precise, reliable, and quick to react to changes. Because it is reliable, accurate, and combines properties of all three controllers, the PID (proportional-integral-derivative) controller is widely employed in most devices. The fact that it's not as fast as the PI controller is its only negative aspect. An ideal use for a PI controller would be in a WPT structure, where a quick reaction is required. The feedback control loop determines the amount of error by comparing the system's output signal to a setpoint value. This setpoint value is regularly modified according to the battery's SoC %. In order to keep the charging current and voltage constant, the PI controller must be able to manage the primary side feedback with little noise sensitivity. Modifications to the main side's input are possible with the use of secondary side data. One option for the main side is to use sinusoidal pulse width modulation control. Pulse width modulation regulates the working frequency of the MOSFET switches, and that in turn generates the input and output voltages needed by the secondary side. This is useful for figuring out if CC or CV charging is better. The controller can only provide feedback if the right control structures and procedures are in place to make use of it.

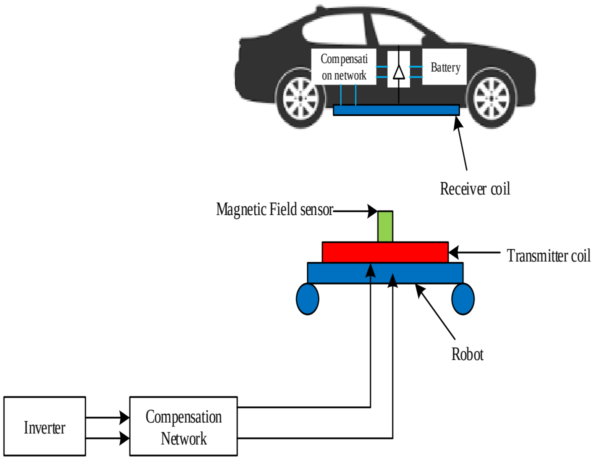

Figure 1: System model

It is significant to determine how the circuit responds to modifications given to it fundamentally determines the effect of various compensation architectures on the effectiveness of a WPT device under misalignment situations. Over time, changes in system efficiency are caused by several characteristics, including operating frequency, load fluctuations, and mutual inductance (which is comparable to the coupling coefficient). Finding out how changes to the mutual inductance affect the power transfer efficiency is the goal of the investigation here. Here we assess the behavior of each compensation topology with respect to changes in mutual inductance, as previously established.

Here we'll go over what LoNgitudinal Misalignment is and how it differs from LTM, as well as how each affects the energy and power delivered in a DWPT system. Obtaining the transmitted power in a lossless as well as well-tuned DWPT system is possible by:

$$P_{\mathrm{out}} = \omega \frac{M^2}{L_2} I^2 Q \qquad (1)$$

The main and secondary compensation circuits' system resonance frequencies are denoted by ʋ, the angle-frequency of the coil current that matches them, the RMS value of the primary current, and the mutual inductance between the two coils is denoted by M. It is clear from (1) that M affects the transmitted power significantly, and M is dependent on both LNM as well as LTM.

3.2 Design objectives of each modules

The aforementioned details the intended uses of several DWC system attributes. Over time, the vehicle's battery life will decrease due to increased use. Hence, location and environmental considerations should be taken into account while determining the DWC system's lifetime. The efficiency and lifespan of the battery may be improved with the help of a dynamic charging system. The architecture of the DWC system makes use of several topologies and configurations to guarantee efficient operation.

After receiving electricity, the EV rectifies and regulates it before sending it to the battery to make up for energy lost while driving and add to the battery's reserve. We may simplify the link between the energy required by the EV, the energy received from DWC, and the EV battery's SoC as:

$$\mathrm{SoC_f} = \mathrm{SoC_i} + \left(\frac{\mathrm{E_{DWC}} - \mathrm{E_{con}}}{\mathrm{E_{max}}}\right) \times 100, \qquad (2)$$

where $\mathrm{SoC_f}$ where $\mathrm{SoC_i}$ is the starting point and $\mathrm{SoC_f}$ are the starting points of the journey, $\mathrm{E_{DWC}}$ is the energy that the dynamic charging device sends to the EV, $\mathrm{E_{con}}$ is the energy that the EV uses during the same trip, while $\mathrm{E_{max}}$ is the maximum capacity of the EV's battery. The effectiveness of the DWCS system, denoted as η_{DWC}, is used to link the received energy, $\mathrm{E_{DWC}}$, to the grid power supply, $\mathrm{P_{In}}$:

$$\mathrm{E_{DWC}} = \int_{\mathbb{C}} \eta_{\mathrm{DWC}} \mathrm{P_{In}}(t)dt, \qquad (3)$$

wherein C is the duration that the electric vehicle's main charging coils provide electricity. Figure 1 shows the various system components that affect the DWC system's efficiency and, by extension, the energy received through the EV. These components include both the primary and the secondary coils' designs, as well as their compensation networks. The coupling efficiency of the inductive link while the vehicle's alignment across the primary coils also plays a role. Further, consideration of battery age, temperature, and other variables influencing energy levels is essential for precise SoC calculation of the EV battery.

3.3 Control structure

Two different methods of battery charging are available with the WPT system. Initially, constant current charging is used when the DC connection is set up between the main along with secondary sides of the system. A battery may be charged using the CV method when there is relative stability between the two sides of the system, meaning the voltages on the primary and secondary sides are almost equal. Therefore, two independent control systems for the charging mechanisms are required to govern the WPT system. A "control structure" and a "control method" are necessary to enable both. By "control structure," we mean a topology that specifies, in relation to its position in the system, which parts of the system are to be governed. A control method is an algorithm that provides instructions or procedures to govern the system. There are four broad categories, each with its own set of subtypes, of control structures used to regulate charging current and voltage. A look at Figure 13 reveals the control structures that are often used for WPT systems. Here are the control structures:

- Inverter control;
- Impedance matching;
- Dual-side active bridge control;
- DC level control.

In contrast to control structure 4, which has two sides, control structure 1 only has one. The most typical control structure for WPT while IPT systems is frequency control or phase shift control, which are used mostly in inverter control. Because of its compact size, minimal number of components, and straightforward design, this approach is ideal. The most common technique is sinusoidal pulse widening modulation since it allows for easy frequency adjustment. Applications with low power consumption and high frequencies are the main ones that use the IM control mechanism. Numerous inductors, capacitors, with relays or switches adorn each side of this structure. To compensate for the primary-side converters' and the loads' impedance mismatch, which reduces the output voltage, the capacitors along with inductors undergo a substantial voltage adjustment. However, the system becomes cumbersome and difficult because of the big configurations of inductors and capacitors, which increases the complexity of control. Because of this, it can't be used in WPT equipment where the load may alter. One way to get around the problems with power transfer systems that only work on one side is to employ dual active bridges, which have the best conduction losses. The main and secondary sides may each have their own control because of features like load transformation, power regulation, as well as reactance compensation. The elimination of the need for a feedback connection between the two parties is a major advantage of DABs. The massive amount of semiconductor components and the system's overall size are its major flaws. A DC-DC converter is located on the main as well as secondary sides of the DC level control mechanism. You may utilize buck, boost, or buck-boost converters. There is no need for a feedback connection in the control mechanisms implemented for this sort of construction since the converters on each side operate autonomously. Both the input voltage and the output voltage are controlled by the converters; the former is located on the main side. Typically, this kind of control is used in a primary-side boost converter before the inverter section with a secondary-side buck-boost converter to modify the output as needed.

3.4 Control Method using ANN

Here, a sensor-free technique is suggested for predicting the LTM value in real-time using DC-link current and vehicle speed observations. The main side of the DWPT device is seen in Fig. 2, and the system variables are listed in Table I. We built a reliable controller for the root-mean-square value of the main coil's current after studying the system's dynamics. Here, we go over the suggested ANN-based method and examine the necessary ANN in detail.

The degree of vehicle's LTM in DWPT devices is estimated in this article using an Artificial Neural Network approach. The region immediately around the main pad's center is where the primary coil can most effectively transmit a large quantity of power. A vehicle's total transmitted energy might be drastically decreased if it is misaligned. With a solid LTM forecast in hand, we can make the necessary adjustments. In this work, we use the LTM estimate to adjust the value of the primary coil's current so that the quantity of energy transmitted to the secondary side remains constant.

To keep efficiency and reliability high in EV charging dynamic wireless power transfer systems, misalignment correction is critical. To reduce the impact of charging pad-to-vehicle receiver coil misalignment during dynamic charging, many methods are used. Some of these mechanical methods center on coil design, whereas others use control systems with sensor feedback; yet others are electrical.

The intricate biological neuronal architectures seen in human cognition serve as the conceptual basis for ANNs. The three main components of an ANN design are the input nodes, the intermediate processing layers, along with the output nodes. To make processing and adaptation easier, these layers provide computational units with weights that may be adjusted. Both the structure and the training procedure have a significant impact on the network's performance. To get the most out of an ANN, you need to choose the right adaptive learning method, layer distribution of neurons, and other critical architectural components. Optimal computing performance is frequently attained by this optimization using methodical trial-and-error methods.

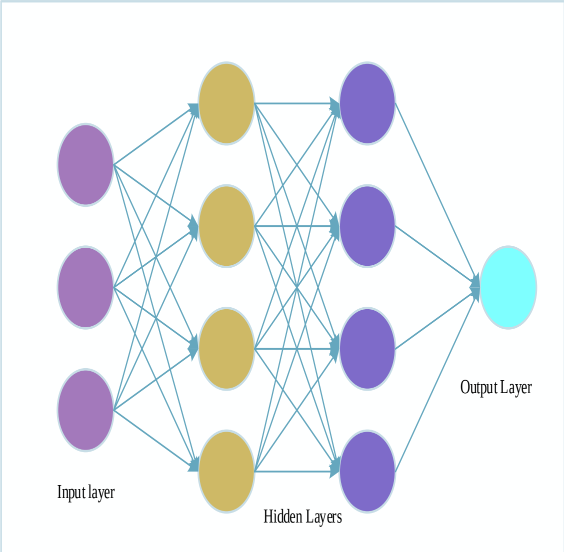

Figure 2: ANN model

As shown in Figure 2, there is a two-step process to build a neural network. The first step is to train the network on a pre-existing dataset; during this phase, the system learns to spot patterns by repeatedly tweaking the weights of its connections in an effort to narrow the gap between their expected and intended outputs. step two occurs when the network performs to expectations; this step involves validating the network using fresh, unexpected input data to evaluate its prediction accuracy and generalizability.

The two primary computing stages that make up the mathematical representation of a neuron are shown by Equations (3) as well as (4). Equation (4) determines the output A_i of the last neuron by applying the activation function $f_2(s)$, and Equation (5) determines the output y_i of the first layer by applying a transfer function $f_1(s)$ to the weighted combination of inputs.

$$y_t = f_1(s) \cdot \{\sum_{t=1}^{N} (x_t \cdot w_t + b)\}$$
$$A_t = f_2(s) \cdot \{\sum_{t=1}^{N} (y_t \cdot w_t + b)\} \quad (4)$$

where x_i, w_i, b, and y_i symbolize the signals that enter the neuron, the synaptic weights that are directly related to those signals, the bias parameter that is usually given a value of either one or one-half, and the signals that leave the neuron, in that order. A neuron's activity level is the outcome of this weighted sum. The transfer function, $f_2(s)$, and the nonlinear hyperbolic tangent activation function, $f_1(s)$, are given by the following equations.

$$f_1(s) = \frac{e^{as} - e^{-as}}{e^{as} + e^{-as}}$$
$$f_2(s) = \beta s \quad (5)$$

α and β represent the profits.

The feedforward backpropagation technique is used in the neural network training procedure until the MSE among the target and actual responses achieves a low value.

In this setup, the DFIG system's reactive and active electricity are controlled by the neural architecture. This method makes use of a pair of separate multilayer perceptron neural networks, one for managing the power supply and the other for managing the load. One neuron makes up the input layer of each MLP, eight neurons make up the hidden layer that uses the hyperbolic tangent sigmoid (tansig) activation function, while finally, one neuron makes up the output layer.

The active power error is fed to the first MLP during training, and the quadrature rotor voltage reference is output by the first MLP. Figure 3 also shows how the second MLP handles the reactive power error and generates the direct rotor voltage reference. Finding a happy medium among model complexity and generalizability led to the adoption of the 1-8-1 MLP structure. An ideal compromise between accuracy and computing efficiency is provided by the hidden layer configuration that was established via empirical testing, while the reference power signal is represented by the single input neuron. The expected control signal for efficient power regulation is provided by the output layer.

Because it can handle positive as well as negative values and guarantees smooth gradient transitions throughout backpropagation, the tansig activation function was used. When contrasted with linear or solely sigmoid-based functions, this improves the learning dynamics of the network, resulting in quicker convergence.

By using a variety of control approaches, we can maximize efficiency and power transmission. The WPT system's inverter receives many signals from the front-end converter. The phase changes and angles of these signals are distinct. For the most part, the phase angle and phase shift are controlled using the sinusoidal pulse width modulation technique. The main side's output remains stable because to the basic duty cycle that is maintained for CC with CV charging. This procedure could be affected by the design of the system as a whole. A voltage source inverter on the main side is often used for frequency and phase control. Changes in the DC-link voltage, switching frequency, or phase shift between the bridge legs are common VSI symptoms. But for low-power uses, these methods are too complicated and costly. A safe charging process and extended battery life are both achieved by using two charging modes simultaneously. The CC charging mode begins by charging the battery to its capacity using a current equal to that capacity. Following the achievement of the charging voltage, the method of charging is changed to CV mode. You may utilize the maximum current in CC mode if the battery is completely dead. The current begins to drop to its lowest point as soon as CV mode is engaged. The aforementioned procedure relies on an analog-to-digital converter to transform the readings from the receiving side's voltage and current sensors. A common method for doing this is by use an ANN controller in conjunction with a PI controller to power the inverter switch drivers.

3.5 Maximum efficiency tracking (MET) control

Like a "loosely coupled" transformer, the main and secondary coils of a dynamic wireless power transfer system are separated by air. This results in the formation of stray heat because some of the main side flux does not connect with the secondary side instead dissipates as leakage flux. The overall efficiency of the system is reduced since this causes voltage dips on the secondary side that creates an elevated series reactance on the primary side. Another factor that impacts the WPT system is the coupling coefficient of the coils and changes in the system load. In a WPT system, the relative positions of the coils affect the coupling coefficient, and changes in the charging status of the vehicle's battery affect the load. For this reason, improving system efficiency necessitates introducing maximum efficiency tracking control. Tuning the secondary side's equivalent load control to an ideal value via impedance conversion is the underlying notion of MET. To put it simply, the goal of impedance conversion is to bring two impedances into harmony. When it comes to electricity, it's all about balancing the load impedance with the driving source's internal impedance. According to the law of maximum power transfer, which is the foundation of this concept, in order to transmit the greatest amount of power from a source to a load, the load's impedance must be equal to the source impedance. The load in a WPT system—the secondary-side equivalent resistance—is driven by the AC source. In order to improve the system's overall efficiency, there are several approaches to do impedance matching or conversion.

A WPT system employs resonant magnetic coupling and two coils to transfer power inductively. What follows is a diagram showing the connection between the coils' mutual inductance M and coupling coefficient k:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{6}$$

where L_1 and L_2 stands for the self-inductances of the main and secondary side coils. Resonance may be established at the transmitting and receiving sides, respectively, to increase the power transfer capacity and decrease the source voltage and load current stress. Currently, there are a number of simple resonant topologies that can meet the aforementioned criteria. Four topologies are available: SS, SP, PS, and PP. Moreover, these topologies include the capacitive compensations. This system's circuit may be driven by a voltage or AC current source. A power source reactance in the SS topology—one of the four basic topologies—is unaffected by the coupling coefficients or load resistance on the side that experiences resonance frequency. To find the resonance frequencies on the receiving and sending sides, one must

$$\omega = \frac{1}{\sqrt{L_n C_n}} \tag{7}$$

where n is either one or two, depending on which side is doing the sending and receiving. Its position is that of a receiver at this frequency. Power reflection to the transmitting side is now nonexistent. Radiation, conduction, along with switching losses in power semiconductors all contribute to the overall power loss in the WPT system, which is influenced by the magnitude of the main and secondary-side resonant currents. To make estimating the WPT system's efficiency easier, we'll treat all losses, denoted by ESRs R1 and R2, as if they were a single entity. The output voltage of a closed-loop system remains constant regardless of changes in the load or coupling factor.

4 Simulation of coils using ansys maxwell

As part of our investigation into a wireless charger for an electric car that can handle misalignment, we used Ansys Maxwell simulation software to simulate the coils shown in Figure 2. With this program, we may define the coils' dimensions in terms of number of turns, both inner and outer diameter, wire size, insulating thickness, as well as material properties, among other things. Magneto static analysis is the method of choice for simulating the coils. Based on the steady-state situation, this sort of analysis permits the computation of the distribution of the magnetic field and other associated parameters. With this program, you may see the distribution of current density in the coils and map the intensity of the magnetic field along certain lines. The model's coils are thin (2 mm), have a diameter of 20 cm, and consist of 25 turns each.

One way to measure the compensation network's efficacy is to find out how efficiently the transmitter and load exchange power. You may simulate the load using an equivalent resistor, even if in actuality it is usually a rectifier, filter, and switched controller. We ran simulations in ANSYS Simplorer® to see how efficient it was. This section's determination of the mutual inductance for simulations was based on the findings obtained earlier in Section 3 using ANSYS Maxwell ^(2005). Based on the Maxwell findings, the main and secondary inductances stay at 59 uH, while the mutual inductance varies due to variations in the relative locations of the coils. The secondary terminals are loaded with a constant resistance. In order to find out how efficient the system is at various frequencies, particularly the resonant frequency, the simulation was run in AC-analysis phase in Simplorer. Finding the ratio of the actual power obtained on the secondary side to the real power delivered on the main side allowed us to determine the efficiency. A comparison of the resonance frequency's consistency was made by plotting the efficiency in the frequency domain.

$$\eta = \frac{P_{\text{Receinel}}}{P_{\text{irmusition}}} \quad (8)$$

We ran simulations for all four fundamental compensation topologies using circular with rectangular coils to look at the general behavior of different combinations of compensation techniques and coil shapes. Next, the secondary coil was subjected to a lateral displacement ranging from 0 to 200 mm, and the system's efficiency was assessed while it was misaligned. For a broad range of misalignment, it is desired that the system maintains its optimum efficiency.

With the use of 3D FEA, it is possible to numerically solve differential equations. This method is comparable to the FDA and is often used in modeling. Critical and difficult is the analytical computation of mutual inductance. Finding the optimal value of mutual inductance is achieved via the use of analytical analysis and finite element analysis (FEA). Table 1 displays the rectangular power pad's receiver and transmitter coil specifications. Ansys Maxwell® 3D is used to verify the rectangular power pad's construction. The medium of wireless power transmission is air. When it comes to coupling coefficient, mutual inductance, self-inductance, as well as magnetic flux, Ansys Maxwell®3D delivers trustworthy figures. This WPT model employs the series-series compensation values derived from the Ansys Maxwell®3D simulation results.

Table 3: Rounded coupler set simulation settings.

Variables	Value
Vertical distance between coils	40 mm
Tx turns	30
Rx turns	30
Current in Rx	15 A
Coil length (Tx and Rx)	150 mm
Coil width (Tx and Rx)	98 mm

In order to examine a wireless charger for an electric car that can accommodate misalignment, the coils in Fig.2 were modeled using Ansys Maxwell simulation software. With this program, we may define the coils' dimensions in terms of number of turns, both inner and outer diameter, wire size, insulation thickness, as well as material properties, among other things. Magneto static analysis is the method of choice for simulating the coils. The steady-state condition may be used to calculate the distribution of the magnetic field and other relevant parameters using this form of analysis. This program allows one to view the magnetic field strength plotted along certain routes and determine the current density variation in the coils. The model's coils are thin (2 mm), have a diameter of 20 cm, and consist of 25 turns each.

4.1 Battery for WPT vehicle

A lithium-ion battery powers the vehicle's design. Here, we'll think about the travel factor and the design of the battery pack for a range of 40 kilometers. With a maximum speed of 40 kmph, the overall range is 40 km.

$$\text{Travel factor} = \frac{\text{Total Range (Travel)}}{\text{Total Speed}} = \frac{40}{40} = 1$$
(9)

The specified travel factor is a constant speed of 40 km/h. Therefore, the necessary power is,

$$\text{Power} \times \text{Travelfactor} = 384 \times 1 = 384 \text{ Wh} \quad (10)$$

Consequently, 384 Wh will be the total power needed. Then there's the matter of the battery pack's efficiency. When it comes to charging and discharging, lithium-ion batteries typically achieve efficiencies of 85-93%. With an efficiency of 85% in mind,

$$\text{Battery pack capacity required} = \frac{\text{Total Power}}{\text{Efficiency}} = \frac{384}{0.85} = 451.74 \text{ Wh} \quad (11)$$

4.2 Power efficiency analysis

The system's efficiency, denoted as η, may be calculated by dividing the power output by the power input.

$$\eta = \frac{P_{out}}{P_{PA} + P_{PB}}. \quad (12)$$

Figure 8 illustrates the relationship between the theoretical through simulated system efficiency and different output powers when θ is set to 0∘ and 90∘. Changing the load resistance with a constant transmitter current change the output power. When the transmitter currents are in phase, the system is more efficient than when the currents are orthogonal, even when the output power is kept constant. Additionally, the system's output power capacity is larger when the transmitter currents are in phase compared to when they are orthogonal.

4.3 Finite element modeling

A well-designed coil as well as matching impedance system is crucial for increasing the system's misalignment tolerance. The success of the system depends on the coil's interoperability, which should be maintained independent of the charging power rate or symmetry of the car. Additionally, it is important that the design adheres to global norms. The system's viability for installation along roadways is dependent on the main cost of infrastructure. How many cars will be able to use the DWC network determines the system's economic feasibility. More people using the technology means less money spent. A study was conducted to examine the current flowing across identical coils and their flux densities with ANSYS Maxwell 3D software. Below, we'll go over the specifics of these scenarios.

Table 4: Changes in coupling coefficient and mutual inductance as a function of vertical misalignment

Coupling coefficient	Mutual inductance (μH)	Vertical Misalignment (cm)
0.264456	19.644530	3
0.239967	15.977210	6
0.183321	14.744385	9
0.158896	12.890334	12
0.125590	19.459978	15
0.091774	7.409443	18
0.080454	9.743997	21

Above, you can see Figure 3 which depicts the coil structure and the flux density area. The 85 kHz resonant frequency was intentionally included in the coil's construction. A current of 10 A was determined to be passing through the coil. In this simulation, a coupling coefficient of 0. 136 was used. The reciprocal inductance was 2. 25 µH, and the self-inductance of the receiver was 16. 84 µH, while the transmitter's self-inductance was 16. 3 µH. We also tried other geometries under the same circumstances.

Table 5: Comparison of different coil structure

Parameters	**Misalignment**	**Interoperability**	**Leakage Flux**	**Coupling Range**	**Efficiency (%)**
Rectangular	Intermediate	Low	Intermediate	Low	85–90
Circular	Poor	Very Low	High	Low	90–95
Hexagonal	Good	Low	Low	Intermediate	>90
DD Coil	Intermediate	Non-interoperable	Poor	Intermediate	>90
DDQ Coil	High	High	Poor	High	90–95

4.4 Training process

The fast-convergent Levenberg-Marquardt backpropagation method was used to train the MLP controllers. Consistent output creation for comparable input values is made possible by the LM method's repeated adjustment of network weights and biases. Neural networks excel in intelligent control systems due to their output approximation capabilities.

One measure that was used for assessment during training was the Mean Square Error (MSE), which is defined as:

$$\mathrm{MSE} = \frac{1}{N}\sum_{t=1}^{N} (D_l(k) - A_t(k))^2 \quad (13)$$

where A_i stands for the real reaction of the network, Di for the desired result, N for the size of the training dataset, and k for the number of iterations.

Table 6: ANN designs and their efficacy for a three-input network

Scenario	Neurons in Hidden Layer 1	Neurons in Hidden Layer 2	MSE	Training Performance	Validation Performance	Test Performance	R
1	6	6	2.30×10^{-3}	3.17×10^{-3}	1.60×10^{-3}	6.73×10^{-1}	0.95556
2	7	7	2.74×10^{-5}	2.92×10^{-5}	1.52×10^{-1}	2.99×10^{-1}	0.91218
3	8	0	1.60×10^{-3}	3.63×10^{-5}	1.40×10^{-3}	4.42×10^{-5}	0.98674
4	**8**	**8**	$\mathbf{1.90 \times 10^{-5}}$	$\mathbf{1.20 \times 10^{-5}}$	$\mathbf{1.20 \times 10^{-5}}$	$\mathbf{4.86 \times 10^{-5}}$	**0.99845**
5	8	9	5.62×10^{-4}	7.64×10^{-4}	3.34×10^{-5}	5.35×10^{-5}	0.98345
6	8	10	1.72×10^{-4}	1.84×10^{-4}	3.21×10^{-5}	7.22×10^{-1}	0.99649
7	9	9	1.29×10^{-4}	1.45×10^{-4}	4.93×10^{-1}	1.63	0.99947
8	10	10	2.64×10^{-5}	2.54×10^{-5}	4.80×10^{-1}	1.39×10^{-1}	0.99937

Table 7: Forward model attributes and metrics

Attribute	Value	Metric	Optimized Value
API Used	PyTorch	Test MSE	0.035456682
Model Architecture	2->21->43->2	MAE I [A]	0.087329255
Activation Function	LeakyReLU	MAE P [kW]	0.031215948
Loss Function	Weighted MSE	Best Validation Loss	0.010697847
Optimizer	Adam	R^2 I [A]	0.946632147
Batch Processing	Yes, batch size = 32	R^2 P [kW]	0.998046945
Early Stopping	Yes, patience = 5000		

Our model's accuracy and resilience were enhanced with each iteration of this development route. By using adaptive optimizers, bespoke loss formulas, and sophisticated activation functions, a systematic refining process that is particular to machining data can be shown. The improved predictive capabilities that resulted from these upgrades paved the way for their successful use in adaptive control and real-time The effectiveness and efficiency of the wireless power transfer system in charging electric cars are brought to light in this examination. Examining the data collected from the prototype system makes it clear that both the receiver and the transmitter coil spacing greatly impacts the power transfer efficiency. The significance of fine-tuning the wireless power transfer system's architecture and settings to achieve maximum efficiency with minimum losses is highlighted by these results. Improved wireless charging methods for electric cars, made possible by more study and development in this field, may provide charging options that are more convenient and efficient. The connection between the computed outcomes and the real-world use of the wireless power transfer device in an EV is the primary focus of this investigation. The system's performance along with its potential for real-world applications are monitoring applications.

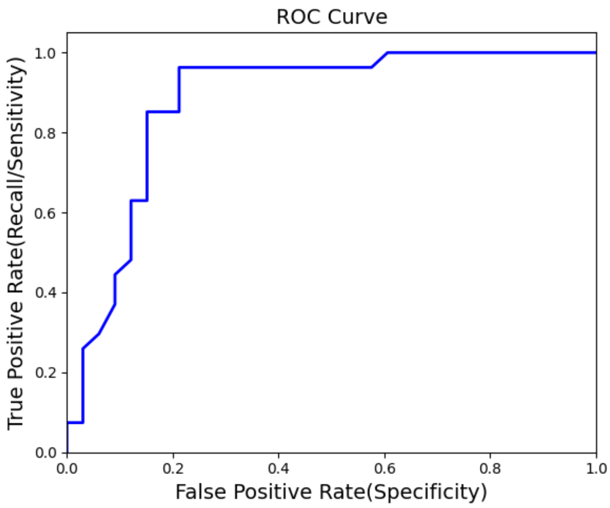

Figure 3: ROC curve

Greatly enhanced by these results. Improving the efficiency of wireless power transmission requires thinking about things like distance, losses, as well as power source. The results of this investigation demonstrate that the wireless power transfer technique is a viable option for supplying electricity to EVs. The examination of the prototype method establishes a strong link between the computed and executed outcomes. Data shown in Table 7 shows that received voltage drops off sharply as distance increases, highlighting the need of close proximity and proper alignment of the transmitter with reception coils.

The wireless power transfer device may be made more efficient by optimizing its design, reducing losses, and taking the power supply into account. This will allow it to be successfully integrated into electric car charging infrastructure.

5 Conclusion

DWPT technology, which does away with the need for actual connections among EVs and charging stations, bodes well for the future of EV charging. Nevertheless, finding methods to improve the efficiency of electricity transmission remains a major challenge, and academics are always seeking answers. Some of the solutions include designing better power electronic circuits, magnetic couplers, compensating capacitance, and control techniques. Modern best practices and state-of-the-art approaches for improving power transfer efficiency have been revealed via the investigation of design procedures and control tactics. Socioeconomic studies have also illuminated the wider implications of DWPT technology, including its potential effects on infrastructure development, EV uptake, and market dynamics. Research into novel magnetic coupler configurations that enhance the alignment tolerance along with power transmission capabilities of DWPT systems. Investigating new materials and geometric forms may help reduce losses and increase overall efficiency. To test the effects of coils that aren't perfectly aligned, engineers created a wireless charging system for EVs that uses inductive technology. Using theoretical research, the Wireless Power Transfer technology examined how angular misalignment affects changes in mutual inductance. A finite element analysis model of a coil with varying axial offset angles was generated using the Ansys-Maxwell FEA modeling program. At the central site, the coupling mechanism created a magnetic field, and the program calculated its magnitude. By keeping the transmission angle constant, the magnetic shield was able to attenuate the external magnetic field while amplifying it inside the coupling mechanism.

The primary component of this alignment process is the axis control method, which was developed with this particular wireless EV charging monitoring system in mind. Here we detail every single step that the suggested algorithm takes to complete its task. To provide the most efficient flow of power, this algorithm is vital in coordinating the transmitter and reception coils. To make sure the charging gadget works well, you have to pay close attention and understand its complex nature. In this part, we'll take a close look at the algorithm's inner workings, exploring all its ins and outs to understand its limits and strengths. In this part, we will thoroughly examine the algorithm in order to understand its inner workings, possibilities, and limits. We will also highlight its importance in the field of electric car wireless charging.

The following areas require more research due to the promising future of this technology:

- A coil design that can be easily reconfigured to provide high coupling coefficients between electric vehicles and chargers under different misalignment conditions;
- Instead of relying on communication among the EV and the charging circuit, future research should focus on developing a new control system that uses system parameters whose changes reflect the misalignment between the charging coils, such as mutual inductance deviations.
- The current research on the thermal failure of the ferrite core used in coil construction is lacking, making it challenging to draw any firm conclusions;
- Dynamic wireless charging offers a promising solution to EV problems, but there are limited studies that take misalignment into account.

References

[1] Zhao, M. , & Miyamoto, T.(2025).LED-Based Optical Wireless Power Transmission for Automatic Tracking and Powering Mobile Object in Real Time. IEEE Access, 13, 33643-33654. DOI:10.1109/ACCESS.2025.3542769

[2] Sivakumar, N. , Charles Raja, S. , Balasundar, C. , & Geethanjali, M.(2024).A Cutting-Edge Deer Hunting Optimized Converter Control (DHOCC) Based Dynamic Wireless IPT System for EV Charging Applications.IEEE Canadian Journal of Electrical and Computer Engineering, 47, 218-225. https://doi.org/10.1109/icjece.2024.3469390

[3] Zhang, M. , Liu, Z. , & Su, H.(2024).Optimal Output Regulation for EV Dynamic Wireless Charging System via Internal Model-Based Control.IEEE Transactions on Industrial Electronics, 71, 13031-13041. DOI:10.1109/TIE.2024.3352158

[4] Zhang, M. , Liu, Z. , & Su, H.(2024).Precise Disturbance Rejection for Dynamic Wireless Charging System of Electric Vehicle Using Internal Model-Based Regulator with Disturbance Observer.IEEE Transactions on Industrial Electronics, 71, 7695-7705. DOI:10.1109/TIE.2023.3314907

[5] Quirós, J. C. , Calvo, Á. L. , Triviño, A. , & Guerrrero, E. V.(2024).Time-domain design for misalignment-tolerant dynamic wireless charging.IET Power Electronics. DOI:10.1049/pel2.12777

[6] Yue, J. , Liu, Z. , & Su, H.(2024).Observer-Based Finite-Time Disturbance Rejection Control for Dynamic Wireless Charging Systems with Constant Output Voltage Regulation.IEEE Transactions on Industrial Electronics, 71, 11398-11407. DOI:10.1109/TIE.2023.3333040

[7] Behnamfar, M. , Olowu, T. O. , Tariq, M. , Debnath, A. , & Sarwat, A. I.(2024).Composite Second-Order Sliding Mode and Backstepping Control for Power Pulsation Suppression in Dynamic Wireless Charging.IEEE Transactions on Industry Applications, 60, 5803-5812. DOI:10.1109/TIA.2024.3398605

[8] Zhang, M. , Zhang, H. , Tao, W. , Yang, Y. , & Sang, Y.(2024).The power control and efficiency optimization strategy of dynamic wireless charging system for multiple electric vehicles.Circuit World. DOI:10.1108/CW-01-2024-0003

[9] Sun, H. , Ma, X. , Hu, R. Q. , & Christensen, R.(2023).Precise Coil Alignment for Dynamic Wireless Charging of Electric Vehicles with RFID Sensing.IEEE Wireless Communications, 32, 182-189. https://doi.org/10.48550/arXiv.2312.12565

[10] Hong, Y. , Wang, J. , Cai, C. , Liu, Q. , Luo, Y. , & Wan, L.(2022).Field Control Method for Coupling Efficiency Improvement of Two-dimensional Dynamic Wireless Charging System with Multiple Transmitter Coils.2022 IEEE 20th Biennial Conference on Electromagnetic Field Computation (CEFC), 1-2. DOI:10.1109/CEFC55061.2022.9940656

[11] Dong, S. , Huang, Z. , Song, B. , & Cui, S.(2024).Inventor Open Circuit Fault Diagnosis Method for Dynamic Wireless Charging System Based on Post-fault Reconstruction of Driving Signal.2024 11th International Forum on Electrical Engineering and Automation (IFEEA), 149-154. DOI:10.1109/IFEEA64237.2024.10878541

[12] Hua, Z. , Chau, K. T. , Pang, H. , & Yang, T.(2023).Dynamic Wireless Charging for Electric Vehicles With Autonomous Frequency Control.IEEE Transactions on Magnetics, 59, 1-5. DOI:10.1109/TMAG.2023.3293793

[13] Guo, Y. , Song, Y. , & Zhao, W.(2023).Sliding-Mode Control Strategy for Dynamic Wireless Charging System with Long Guide Transmitting Coil for EV.2023 IEEE 12th Data Driven Control and Learning Systems Conference (DDCLS), 1708-1714. DOI: 10.1109/DDCLS58216.2023.10166521

[14] Liu, J. , Liu, Z. , & Su, H.(2022).Passivity-Based PI Control for Receiver Side of Dynamic Wireless Charging System in Electric Vehicles.IEEE Transactions on Industrial Electronics, 69, 783-794. DOI:10.1109/TIE.2021.3050350

[15] Yue, J. , Liu, Z. , Zhang, M. , & Su, H.(2025).Cascade ESO-Based Control for Power Converter of Dynamic Wireless EV Charging System Subject to Uncertainty and Sensor Noise.IEEE Transactions on Transportation Electrification, 11, 4598-4608. DOI:10.1109/TTE.2024.3465531

[16] Diep, N. T. , & Trung, N. K.(2022).Transmitting Side Power Control for Dynamic Wireless Charging System of Electric Vehicles.Engineering, Technology & Applied Science Research. DOI:10.48084/etasr.4988

[17] Diep, N. T. , Hiep, T. D. , & Trung, N. K.(2023).Constant Current Charging and Transfer Efficiency Improvements for a Dynamic Wireless Charging System.Engineering, Technology & Applied Science Research. https://doi.org/10.48084/etasr.6315

[18] Wang, C. , Chen, Z. , Zheng, H. , & Yang, Q.(2022).Power control study of dynamic wireless charging system based on resonant point switching.2022 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific), 1-5. https://doi.org/10.3390/wevj16020065

[19] Cao, G. , Wang, X. , Yan, L. , & Jia, Y.(2022).Mode on Power Distribution of a Dynamic Dual Pickup Wireless Charging System for Electric Vehicles.Frontiers in Science and Engineering. DOI:10.54691/fse.v2i6.969

[20] Tian, Y. , Zhu, Z. , Xiang, L. , & Tian, J.(2020).Vision-Based Rapid Power Control for a Dynamic Wireless Power Transfer System of Electric Vehicles.IEEE Access, 8, 78764-78778. DOI:10.1109/ACCESS.2020.2989466

[21] Rahman, M. S. , & Ali, M. H.(2025).Adaptive Neuro Fuzzy Inference System (ANFIS)-Based Control for Solving the Misalignment Problem in Vehicle-to-Vehicle Dynamic Wireless Charging Systems.Electronics. DOI:10.3390/electronics14030507

[22] Li, X. , Zheng, F. , Wang, H. , Sun, Y. , Dai, X. , & Hu, J.(2024).A Simultaneous Power and Data Transfer Method for Dynamic Wireless Charging Electric Vehicles.IEEE Journal of Emerging and Selected Topics in Power Electronics, 12, 328-340. DOI:10.1109/JESTPE.2023.3323473

[23] Chen, K. , Ouyang, Y. , Yang, X. , Cheung, N. C. , Cheng, E. K. , & Pan, J.(2024).A High-Interoperability Optimal Frequency Control Method for the AGV Dynamic Wireless Charging Systems Without Communication.IEEE Transactions on Power Electronics, 39, 3797-3808. DOI: 10.1109/TPEL.2023.3335945

[24] Yue, J. , Liu, Z. , & Su, H.(2024).Model-Free Composite Disturbance Rejection Control for Dynamic Wireless Charging System Based on Online Parameter Identification.IEEE Transactions on Industrial Electronics, 71, 7777-7785. DOI:10.1109/TIE.2023.3317869

[25] Li, Z. , Yang, X. , Ma, J. , Ban, M. , & Liu, Y.(2023).Design and research of high misalignment tolerant magnetic couplers for dynamic wireless charging systems.Journal of Power Electronics, 24, 492-502. DOI:10.1007/s43236-023-00739-4