Camera-Based Misalignment Detection and Hardware Validation for EV Wireless Charging Systems

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***Abstract*—This paper addresses misalignment issues in wireless EV charging, which most of the time results in a non-ideal alignment of the vehicle with the charging pad, thus introducing inefficiencies in power transfer. A careful analysis conducts a detailed study regarding the effects of misalignment on coil voltage, current, and power using a distance-dependent prototype. Real-time positional differences are identified and analyzed using an AI-based alignment correction module implemented with OpenCV, which provides precise measurements of misalignment along the x and y axes. These insights help optimize alignment to enhance system efficiency. Experimental results demonstrate that even small improvements in alignment significantly boost power transfer efficiency, emphasizing the importance of accurate positioning. Validating the potential of the prototype in improving charging efficiency under varying alignment conditions makes the research findings sensible.**

***Index Terms*—Wireless Charging, Misalignment Correction, Transmitter, Receiver, Electric Vehicle.**

I. Introduction

Transportation contributes a significant portion to the global emission of air pollutants, which is why sustainable transportation has been one of the world's most prominent goals for several years. Electric vehicles (EVs) are a revolutionary invention for both the present and the future, offering a sustainable alternative to internal combustion engine (ICE) vehicles. Studies show a rapid increase in EV usage, highlighting their potential to revolutionize transportation systems. The process of refueling EVs differs significantly from that of ICE vehicles. EVs require electricity, which is supplied through charging stations that vary in speed from slow home chargers to high-speed public chargers. However, charging an EV often takes longer than refueling an ICE vehicle, with times ranging from 30 minutes at fast chargers to several hours at standard chargers. Additionally, it also presents challenges such as the inconvenience of physically connecting and disconnecting cables, exposure to wear and tear, and potential safety hazards in wet or dirty environments. Additionally, the availability of charging infrastructure and the time required for manual plug-in processes can hinder user convenience.

Wireless charging systems (WCS) address these issues by enabling contactless power transfer through inductively coupled coils, eliminating the need for cables. This not only enhances user convenience but also improves durability, safety, and reliability, particularly in adverse environmental conditions. An intelligent, sustainable energy environment can be produced [1] by combining renewable energy, EVs, WCS, and the Internet of Things (IoT). Real-time optimization is made possible by IoT, which also improves wireless charging efficiency and synchronizes EV charging with the availability of renewable energy. However, WCS charging [2] convenience comes with a number of challenges.

WCS transfers [3] energy without cables, using electromagnetic induction. This primary coil is usually embedded in a charging pad or station. The primary coil induces an EMF in the secondary coil when an EV secondary soil is positioned on its receiver and approaches the charging pad with a magnetic field. This induced EMF generates a current, which charges the vehicle's battery. The induced current [4] converts the energy to the charging of the car's battery. The efficiency of this power transfer relies heavily on the alignment of the coils and the distance between them, known as the air gap. The EV battery will reduce the need for heavy, large-capacity, and costly batteries by the usage of Dynamiccharging [5]. This technology is the dynamic inductive-type wireless power transfer, which transmits power wirelessly from an AC/DC supply. A standalone DC-DC full-bridge converter meets the battery requirements at the receiving end. This method also decreases the harmonics and switching losses using an LCL compensating network. A primary coil connected to a power source generates a changing magnetic field in a typical wireless power transmission system. Due to the misalignment between the charging pad and the vehicle coil, problems and increased power loss arise. Charging distance is also limited, requiring precise positioning, often proving to be challenging without advanced alignment technologies. Understanding the misalignment problem in wireless charging is crucial for developing practical solutions to improve tolerance, ensuring consistent and efficient power transfer despite positional deviations between the transmitting and receiving coils.

The study in [6] examines how hybrid topologies can increase the tolerance for misalignment in a wireless charging system for electric vehicles allows efficient and reliable power transfer, independent of the precise alignment between the sending and receiving coils. The performance of two independent receiver configurations in a system of wireless battery charging is studied in [7], in order to compare how well they pass on the power. The equivalent circuit configuration in first harmonic approximation used to design the WPT (wireless power transfer) charge parameter are discussed in [8]. IWPT is the most widely adopted approach for wireless charging, particularly [9] in high-power applications. With its compact form, improved misalignment [10] tolerance, and 93.5% EV charging efficiency, the 3HCC pad improves IPT. Precise alignment minimizes losses and optimizes energy transfer. To fix misalignment, the system moves the charging pad or car coils. It is weak along the Z-axis but best along the X-axis, then the Y-axis. The change in mutual inductance stays under 20% for a misalignment of 160 mm in the X-axis, 120 mm in the Y-axis, and 100 mm in the Z-axis. A flexible charging pad with a new alignment system must be used to support all of the different EV models which require a different charging need. This system automatically aligns with each vehicle's receiver coil using omnidirectional motion, sensors, and control algorithms based on microcontrollers. By examining the distinct sizes, coil locations, and designs of various EVs [11], misalignment problems can be resolved and automated, adaptive alignment techniques in the x, y, and z axes can be developed. This method reduces energy waste, ensures good power transfer [12], and provides a smooth experience for the users. The use of isolated DC-DC converters for dynamic wireless power transfer aims at changing [13] the way EV charging is done by allowing continuous, efficient, and safe power transfer even when cars are moving. Coupled wireless charging systems for electric vehicles apply magnetic resonant coupling to optimize the transfer of energy, automate the process of charging, and make way for sophisticated infrastructure: this improves efficiency, flexibility, and alignment tolerance, thus transferring power over longer distances while also reducing operational costs, which diminishes the decrease in efficiency with separation [14]. In addition the AI based detection algorithms could be used in solving the power transfer issues [15].

Misalignment along the X, Y, and Z axes and angular deflection can significantly reduce mutual inductance and thus decrease the efficiency of energy transfer. Available coupling structures, such as the SP-DDP and the coupling scheme of double layers, resist some deviations in alignment but are sensitive to their tolerance degree as well as magnitude in terms of energy losses, mainly at dynamic or time-varying conditions. Moreover, understanding the behaviour of wireless energy transmission systems and the effect of misalingment needs a detailed study. Sensors and algorithms have already been seen to be applicable for the purpose of alignment; however, integration with a fully automated alignment system is still lacking, combining omnidirectional motion, sensor fusion, and machine learning to enhance coil positioning in real time. The new system would adapt itself to various models of EV and varying environmental conditions and, thereby, ensure maximum energy transfer efficiency and reliability. This could greatly improve the feasibility and scalability of wireless EV charging technologies.

Section 2 explains the methodology of coil alignment detection and efficiency calculation in prototype. Section 3 consists of the simulation, result, and analysis. Section 5 concludes the discussion.

II. Suggested Mechanism for Accurate Coil Aligning

To understand the impact of the problem and for further analysis a software based representation is done using Python in Section A and the same has been validated using hardware which is further discussed in Section B.

A. Misalignment Detection and Adjustment Software Framework

This Python script uses OpenCV to detect a circular object in a video stream that represents a coil and computes the distance and misalignment between the center of the camera and the center of the detected coil as shown in Figure 1. It thus allows for real-time alignment adjustments to maximize coupling efficiency in a wireless charging system. A live video feed is captured with the default camera by using cv2.VideoCapture(0). Each frame from the video will be processed in a loop until the user exits. The function find_circle_center identifies the coil's center within each frame, likely using techniques such as grayscale conversion, edge detection (e.g., Canny), and Hough Circle Transform or contour detection. In case of finding a circle, the script will calculate the position of the center.

Additionally, x-axis and y-axis misalignments (x_move, y_move) are calculated as the horizontal and vertical differences between the centers. For visual convenience, the script overlays the found positions on the frame: a red circle marks the center of the camera, and a green circle marks the center of the coil. The calculated distance and misalignment values are also displayed as text. This setup enables the real-time monitoring of misalignment, providing actionable feedback in the adjustment of the coil position to improve alignment, which means that power transfer efficiency within the charging system is maximized. The user may interrupt the process by hitting the "q" key and release resources and close all OpenCV windows.

This effectively combines image processing techniques and mathematical calculations to detect circular objects in a video stream, calculate their distance from a reference point (camera center), and determine the relative movement required to center the object. The code demonstrates a practical application of computer vision and image processing concepts, offering insights into object tracking and distance estimation in real-time scenarios.

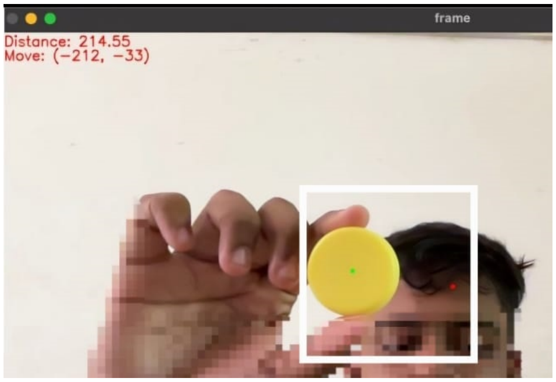

Fig. 1. Output Result of the Open CV module

B. Hardware Architecture for analyzing the misalignment

This system design helps in understanding the misalignment level between the primary and secondary coils to measure power transfer in wireless EV charging. A prototype system has been designed with one part as the primary coil embedded in a charging pad and the other as the secondary coil acting as the receiver for the EV as shown in Figure 2. The system also has an alignment mechanism that may be used to adjust the primary coil in the x, y directions and Height (H) to effectively rectify any misalignment.

A systematic variation of horizontal distance in x and y direction is measured and the absolute difference in distance is calculate as D. The horizontal distance D between the coils are varied at discrete intervals, such as 10 mm steps, will be used to evaluate performance. Key parameters about transmitter coil voltage, current, and power as well as about receiver coil voltage, current, and power are measured at each step in order to determine the influence of distance and misalignment on efficiency in the transfer of energy.

This will incorporate a feedback control mechanism through sensors and microcontrollers to monitor the state of misalignment and adjust the coil positions in real time. The data gathered may be analyzed on mutual inductance variation and energy loss, hence ensuring optimal alignment to maximize efficiency. This is a structured way of approaching the issue and resolution of misalignment that can pave the way for more reliable and efficient solutions on wireless EV charging.

This system aims to solve misalignment issues in wireless EV charging by developing an alignment mechanism between the primary and secondary coils for efficient power transfer. A prototype system design consists of a primary coil embedded in a charging pad and a receiver part that is an emulation of the EV secondary coil. The automated alignment mechanism of the proposed system is capable of adjusting the position of the primary coil in the x, y, and z axes so that misalignment can be counteracted.

The proposed experimental setup integrates hardware and software testing for wirelessly transmitted energy efficiency. It is made up of a stand supporting a primary coil to transmit energy, a secondary coil for pickup, and a microcontroller-most likely to be NodeMCU or ESP8266-for control as well as data acquisition. The measurement tools include a multimeter and sensors for fundamental parameters such as voltage and current. A light bulb serves to be the load used to assess the transfer of power. The circuit employs DC power supply and interconnections utilizing breadboards and jumper wires.

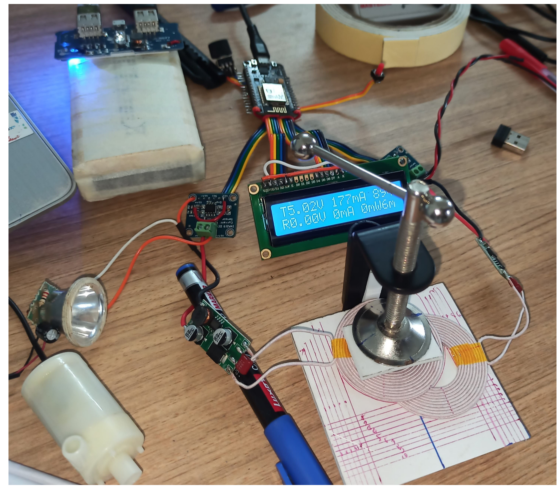

Fig. 2. Design of the EV wireless charging system with ESP8266 NodeMCU

On the software side, tools like Arduino IDE or similar platforms have been likely used to program the microcontroller, while data visualization and real-time graph plotting are managed on a laptop, possibly using Python or MATLAB. This combination allows for systematic testing of the performance of wireless power transfer, including efficiency and alignment under varying conditions.

The system described integrates IoT elements using NodeMCU, ESP8266/ESP32 microcontrollers, sensors, and real-time data visualization. Voltage and current sensors monitor power transfer efficiency; the microcontroller collects and processes this data. Feedback control adjusts the position of the primary coil dynamically to correct misalignment. Although not explicitly stated, IoT principles are implied by features such as data acquisition and visualization using tools like MATLAB or Python, which may involve local wireless communication. The system integrates hardware, such as sensors and actuators, and software, such as the Arduino IDE, to enable real-time operation. Add to that, for fully leveraging IoT, one could include cloud connectivity for remote monitoring, mobile dashboards for control, and predictive analytics in the setup. The complete setup now would transform into an 'all-in-one' IoT-enabled solution for efficient and autonomous wireless EV charging alignment.

III. RESULT ANALYSIS

The result analysis focuses on the efficiency and performance of the WIPT under varying alignment and distance conditions. Specific parameters, such as transmitter and receiver coil voltages and currents, as well as output power, are measured systematically at discrete vertical distance intervals as shown in Figure 3. Trends in mutual inductance, energy transfer efficiency, and power losses are hence identified from the data generated.

Displacement and displacement of windings strongly impact performance, and the most efficient scenario occurs with precise alignment and a minimum air gap. The use of a light bulb as a load gives a real-world representation to the efficiency of power delivered. Graphical analysis of the relationship between distance, alignment, and power transfer should have been generated via tools such as MATLAB or Python. The derived results give insight into the importance of alignment in wireless EV charging and validate the necessity of automated alignment mechanisms for consistent energy transfer.

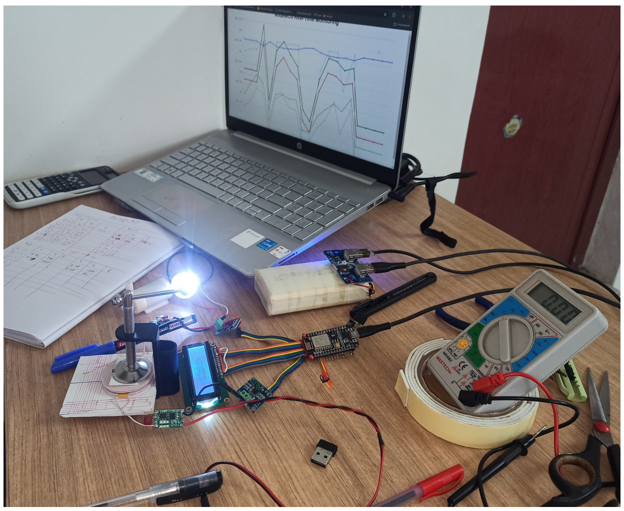

Fig. 3. Working model of the wireless charger prototype

Measurements are made with systematic variation of the vertical distance (D) between the coils at every discrete interval of 0 mm, 3 mm, 6 mm, 7 mm, and 10 mm and above 10. All the following parameters at each distance are recorded: "Distance(D) [mm], Transmitter Coil Voltage(V), Transmitter Coil Current(mA) , Transmitter Coil Power(mW) , Receiver Coil Voltage(V) , Receiver Coil Current(mA), Receiver Coil Power(mW)" and tabulated as shown in Table 1-4. The parameter variations of voltage, current, power and efficiency are plotted as shown in Figure 4-7.

The distance between the primary and secondary coils is critical in determining the efficiency of the wireless power transfer. When the distance between the coils is H = 0 mm and 3 mm, mutual inductance is strong, ensuring high transfer efficiency in power with minimal energy loss.

That is, at such distances, close proximity is achieved that ensures that energy is transferred efficiently between the coils by a magnetic field that is optimally coupled. This suggests that there should be a minimum air gap between coils to have highly efficient wireless charging systems. If one is focused on precise alignment and optimal spacing, the system can then consistently perform and minimize the losses in power. These findings hold promise for improving wireless charging technologies, especially for applications such as electric vehicles where efficiency is critical.

Table 1 Measurement of Voltage, current and Power at H=0mm

Distance (D) [mm]	Transmitter Coil Voltage (V)	Transmitter Coil Current (mA)	Transmitter Coil Power (mW)	Receiver Coil Voltage (V)	Receiver Coil Current (mA)	Receiver Coil Power (mW)
0	4.96	343	1704.88	4.36	158	688.88
1.41	4.93	342	1687.26	4.44	164	728.16
2.82	4.95	318	1578.10	4.26	133	566.58
4.24	4.92	401	1975.92	5.09	122	621.98
5.65	4.87	467	2277.49	5.08	143	726.44
6.40	4.90	412	2018.80	3.78	119	450.42
7.07	4.98	268	1330.64	1.03	53	54.59
8.48	5.02	194	974.88	0	0	0

Table 2 Measurement of Voltage, current and Power at H=3mm

Distance (D) [mm]	Transmitter Coil Voltage (V)	Transmitter Coil Current (mA)	Transmitter Coil Power (mW)	Receiver Coil Voltage (V)	Receiver Coil Current (mA)	Receiver Coil Power (mW)
0	4.92	398	1953.36	5.08	170	863.60
1.41	4.92	395	1946.40	5.09	172	875.48
2.82	4.91	397	1946.07	5.09	144	733.44
4.24	4.88	446	2172.08	5.08	157	797.96
5.65	4.91	398	1957.08	3.87	107	413.49
7.07	4.96	281	1395.36	2.05	96	196.80
8.48	5.02	178	892.36	0	0	0

Table 3 Measurement of Voltage, current and Power at H=6mm

Distance (D) [mm]	Transmitter Coil Voltage (V)	Transmitter Coil Current (mA)	Transmitter Coil Power (mW)	Receiver Coil Voltage (V)	Receiver Coil Current (mA)	Receiver Coil Power (mW)
0	4.88	457	2223.76	4.94	148	731.12
1.41	4.90	424	2076.60	4.07	120	488.40
2.82	4.93	366	1802.38	3.44	88	302.72
4.24	4.96	306	1514.56	2.50	127	317.50
5.65	5.01	205	1025.05	0	0	0

The efficiency of wireless power transfer was consequently lowered to about 6 mm and 7 mm distances due to weak magnetic coupling from the primary to the secondary coils. With increased separation, mutual inductance is reduced, causing the magnetic field interaction to decrease in strength.

Table 4 Measurement of Voltage, current and Power at H=7mm

Distance (D) [mm]	Transmitter Coil Voltage (V)	Transmitter Coil Current (mA)	Transmitter Coil Power (mW)	Receiver Coil Voltage (V)	Receiver Coil Current (mA)	Receiver Coil Power (mW)
0	4.94	335	1653.90	2.63	117	308.91
1.41	4.95	315	1554.25	2.22	102	226.44
2.82	4.98	267	1332.66	1.33	68	90.44
4.24	5.00	236	1180.00	0.40	42	16.80
5.68	5.02	180	903.60	0	0	0

In systems of wireless charging, increased distance between the primary and secondary coils leads to greater losses in energy due to increased inductance and reduced transfer efficiency in power. This would represent the sensitivity of such systems toward coil alignment and spacing. The weakened magnetic coupling at larger air gaps especially underlines the need to keep the separation between the coils as minimal as possible. Thus, optimal efficiency will be realized and power losses minimized as the air gap is eradicated, and alignment will be more accurate. These results highlight the importance of furthering alignment mechanisms and optimizing coil designs in order to raise the performance of wireless charging technologies.

The main point to ensure is that the coils are aligned precisely and at appropriate distances, especially to increase system efficiency with minimum power loss at higher separations. When the height and distance increases further increases the power loss level. For distances greater than H = 10 mm, no energy transfer takes place. This is due to the attenuation of the magnetic field strength, which becomes weak to generate usable electromotive force (EMF) in the second coil. This implies that at 3 mm distances, the system is at its best efficiency point. The system displays a performance efficiency of 44.96%. Efficiency goes down with the increase in distance. When the distance increases, then beyond this value, it is seen at 10 mm that energy transfer is nullified because there is a great depletion. These results indicate that proper alignment of the coils and optimal distance between them are essential for efficient wireless charging.

Table 5 Measurement of Voltage, current and Power at H=10mm

Distance (D) [mm]	Transmitter Coil Voltage (V)	Transmitter Coil Current (mA)	Transmitter Coil Power (mW)	Receiver Coil Voltage (V)	Receiver Coil Current (mA)	Receiver Coil Power (mW)
0	4.97	283	1407.31	1.30	62	80.60
1.41	4.98	267	1330.26	1.04	57	59.28
2.82	4.99	233	1162.67	0.20	35	7.00
4.24	5.01	192	961.92	0	0	0

A. Analyzing Graphs for Different Heights in Wireless Power Transfer

From the graphs of voltage (V), current (mA), power (mW), and efficiency, it is evident that the performance of the system relies more on the difference in height between the primary and secondary coils. At shorter distances, like H = 0 mm and 3 mm, the graphs show strong mutual inductance with maximum values of voltage and current for optimized power transfer. It shows a peak efficiency curve within these heights with minimal energy losses and strongly coupled magnetic.

For H = 6 mm and 7 mm, the curves show a clear drop in system performance with distance increase. The lower voltage and current levels are attributed to weaker magnetic coupling. The efficiency of power transfer greatly falls.

This is also reflected in the graph of efficiency, where the steep fall hints at increased energy losses when the coils are spaced further apart. In the graphs of voltage, current, and power, a flat or close to zero value exists when H is at 10 mm and more, meaning that the system fails to transfer power.

The efficiency graph also tends toward a zero value, revealing the inability of the magnetic field to induce adequate

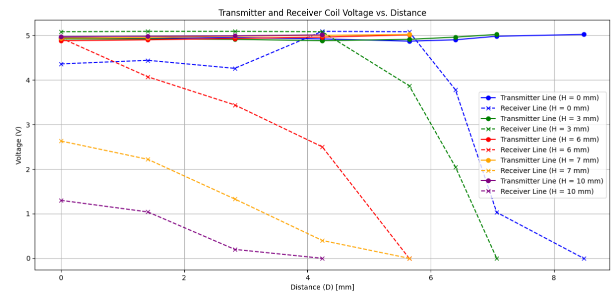

Fig. 4. Graph of Primary and secondary coil voltage(v) with Various Height

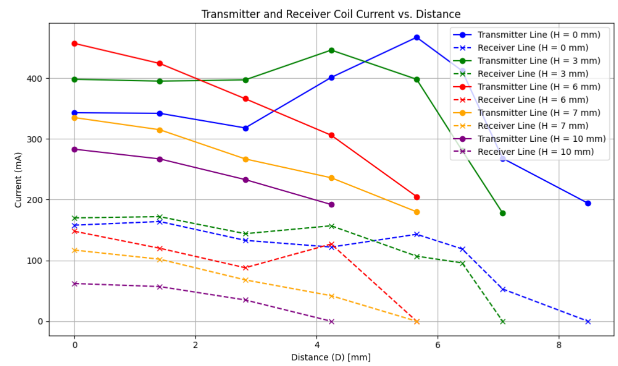

Fig. 5. Graph of Primary and secondary coil current(mA) with Various Height

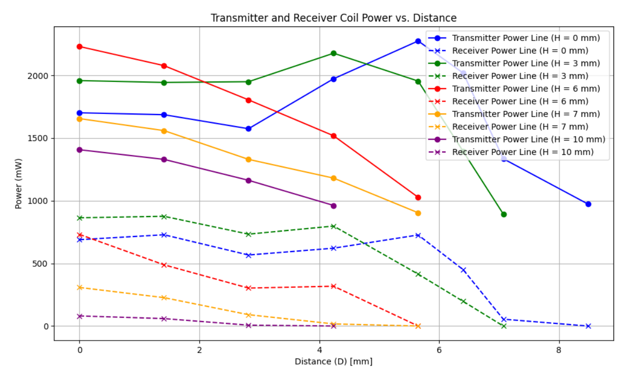

Fig. 6. Graph of Primary and secondary coil power(mW) with varous Height

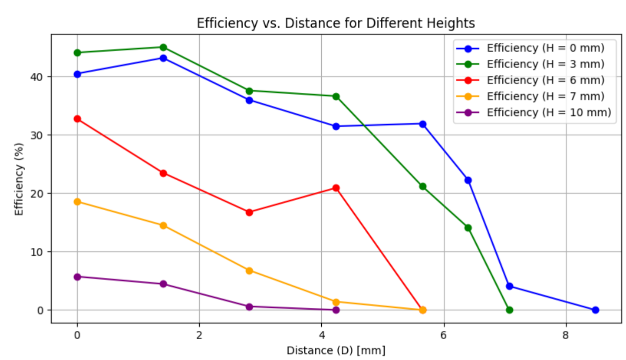

Fig. 7. Graph of efficiency with various Height

EMF for such large separations. These results emphasize the need to keep a gap as small as possible in order to achieve peak performance. The plots essentially represent visual representations of how the system is sensitive to coil alignment and separation, with the performance being visibly depressed at larger separations. Again, this emphasizes the requirement for good mechanisms for precise alignment and, possibly, automated adjustment mechanisms to maximize the energy transfer in a wireless EV charger.

CONCLUSION

The conducted study and experimental setup point out how misalignment issues in the designed wireless EV charging system need to be addressed properly to ensure efficient power transfer. Using systematic evaluation, the relationship between coil alignment and distance of air gap from coil surfaces with power transfer efficiency was investigated. Misalignments of coils and larger separation distances between primary and secondary coils drastically reduce performance while losing significant amounts of power and decreasing charge efficiency.

The practical demonstration of the load by using a light bulb also demonstrated the reliability of the power transfer system under practical conditions. In addition to this graphical representation of the key parameters like voltage, current, and power, it provided more necessity for adaptive and automated solutions in wireless EV charging. This underscores a need for more sophisticated mechanisms of alignment that dynamically shift with changing conditions, providing assurance of power delivery. Lastly, the graphical presentation of such key parameters as voltage, current, and power only highlighted the necessity of yet more adaptive and autonomous systems in wireless EV charging.

The use of OpenCV for x and y direction positional differences embodies the requirement for proper alignment in wireless EV charging. Through finding the centers for the primary and secondary coils and calculating the misalignment, this method assures that precise positioning is essential for achieving maximum efficiency and performance.

This research develops an autonomous alignment system for wireless EV charging, using OpenCV to detect misalignment by calculating positional differences between the primary and secondary coils. The system dynamically adjusts the primary coil in x, y, and height (H) directions, achieving optimal alignment for efficient energy transfer. Results show peak efficiency at 3 mm air gap and show significant drops with increasing separation, highlighting the necessity for minimal air gaps. It addresses misalignment problems to pave the way toward the achievement of advanced, reliable, and user-friendly wireless charging solutions that support the pursuit of sustainable transportation systems through energy efficiency. Accurate positioning in wireless EV charging maximizes efficiency, reduces energy loss, improves system reliability, and increases component lifespan; thus, it becomes crucial to rely on ML-driven alignment technologies like OpenCV for optimal performance.

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