Optimized Vision-Based Path Planning and Navigation for Autonomous Electric Vehicle Charging

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Abstract: A wireless power transfer for Electric Vehicle (EVs) is a type of charging technique that eliminates the need for a physical electrical connection. This design utilizes electromagnetic induction to transfer electrical current between a charger and the automobile. Aim: The aim of wireless chargers is to protect automobiles from power loss caused by frequent pairings and disconnects, while also improving the power quality of delivering electrical energy to power vehicles. Materials and Methods: This research consists of two groups Group 1 In the transmitter part the main input source is the AC supply, the High frequency oscillation switching circuit is operating the switching frequency in the converter part. Group 2 The receiver section includes a voltage sensor to sense the input voltage, a temperature sensor to monitor the battery temperature, and an AI-based web application to monitor the sensor parameters, battery charging level, and operation mode. Result: The result of this study is a hardware prototype, ESP32 cam monitoring, LCD display output, and control of the wireless charging system. Conclusion: The WCS effectively eliminates power loss and improves the power quality for EV battery charging.

1 INTRODUCTION

Wireless charging is considered one of the most efficient and convenient methods for charging electric vehicles (EVs), whether stationary or in motion. A crucial component of a photovoltaic system, converters regulates voltage and current to the required levels. DC–DC converters fall into two categories: boosters and reducers. To minimize power loss and ensure safety against magnetic waves, optimal coil design is essential. As the study of electromagnetism advanced, researchers shifted focus from weak radio waves to electromagnetic waves for wireless power transfer (N. Mohamed et al., n.d.). \Coil interoperability is commonly assessed using two factors: the coupling coefficient (or mutual inductance) on a numerical scale and the magnetic flux distribution on a physical scale. To address the inherent limitations of basic coil designs particularly their compatibility with conventional coils specific coil configurations have been proposed. Wireless charging system interoperability is defined by a system's ability to maintain output performance across different transmitter and receiver pairings. If the expected performance indicators are not met, communication between the transmitter and receiver fails (Song et al. 2023). A proposed wireless power transfer (WPT) system with anti-offset characteristics is based on dual-linked transmitting coils with antiparallel windings, forming an Inductor-Capacitor-Capacitor Series (LCC-S) topology. The antiparallel connections enhance resistance to misalignment, ensuring the two transmitting coils share a common structure with antiparallel windings. This design maintains a consistent coupling trend between the transmitting and receiving coils while balancing the output effect. Experimental findings indicate that the output voltage remains stable between 150 mm and 150 mm in the horizontal direction and between 80 mm and 160 mm in the vertical plane (Shi et al., n.d.). A magnetic integration approach for the coupler in an EV's dynamic wireless

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charging system helps minimize power fluctuations by maintaining stable mutual inductance between the transmitting and receiving magnets on the road. The primary-side coupler integrates a reverse coil within the transmitting coil, while the secondary-side coupling incorporates a coil in the LCC resonance correction circuit within the receiving coil. Based on circuit analysis, an optimized design process was developed to account for additional couplings. Prototype implementation validated the proposed design, achieving 91.6% efficiency with power output fluctuations within ±4% at a charging power level of 4.5 kW (El-Shahat and Ayisire 2021). To maximize power transfer, this model was integrated into the physical design of the magnetic resonance coupling using Simulink, achieving an efficiency of approximately 92.1%. The transient response of the proposed circuit was analyzed, and an EV battery was wirelessly charged using a closed-loop, three-level cascaded PI controller. This controller was designed to eliminate voltage fluctuations caused by variations in coil distance. The coupling coefficient between the transmitter and receiver coils was found to be 1, indicating self-coupling. Furthermore, as the distance between the transmitter and receiver decreased, the coupling coefficient increased. (N. Mohamed, Aymen, and Alqarni 2021).

2 RELATED WORKS

The total number of articles published on this topic over the last five years is more than 50 papers in IEEE Xplore, 70 papers in Google Scholar, and 30 papers in academia .edu. Optimized Vision-Based Path Planning and Navigation for Autonomous Electric Vehicle Charging. The proposed approach integrates vision-based path planning and navigation for autonomous electric vehicle (EV) charging, utilizing optimized algorithms to enhance the system's performance. Simulation results show significant improvements in efficiency, with an optimized path planning algorithm that enables the vehicle to navigate through dynamic charging environments effectively. The system achieves a navigation accuracy of 13.5% and a path planning time improvement from 2.86 seconds to 14.36 seconds, with a maximum decision-making rate of 5.5 Hz, ensuring a reliable and robust navigation pattern. (Rahulkumar et al., n.d.) In the context of autonomous EVs, the demand for systems with higher accuracy, quick decision-making, and low operational cost is increasing as the need for effective charging solutions grows. To optimize performance, the EV's charging route, battery usage, and navigation efficiency must be improved using advanced computer vision techniques. A path planning model is developed by incorporating machine learning-based vision algorithms to create an adaptive system that can handle different charging station layouts and real-time road conditions. (Y. Zhang, Pan, et al., n.d.) The research focuses on developing a system that can calculate optimal charging routes in various traffic conditions by using vision data from cameras and sensors placed on the vehicle. With the integration of advanced optimization techniques, the EV can determine the most efficient path while ensuring minimal energy consumption and faster charging times. (Shahin et al., n.d.) The proposed model also combines features from multiple algorithms, such as deep learning-based object detection and dynamic path planning, ensuring continuous adaptability to the environment. Key performance metrics such as route accuracy, charging time, energy efficiency, and real-time navigation adaptability are assessed during simulation. The system demonstrates a path planning improvement that reduces unnecessary detours, ensuring that the vehicle arrives at the charging station with an optimal battery level. By using real-time feedback from the environment and vehicle system data, the vehicle's autonomous navigation capabilities are enhanced, leading to efficient and reliable charging operations. In addition, evolutionary algorithms are applied to fine-tune the vehicle's route planning and reduce charging time. These algorithms analyze dynamic variables such as traffic conditions, roadblocks, and available charging stations to adjust the vehicle's charging strategy. (S. Zhang and Yu, n.d.) The system shows an increase in navigation performance by 25.3% in terms of battery efficiency, confirming that optimization algorithms are effective in reducing charging time and improving route selection. Overall, this vision-based path planning and navigation system for autonomous EVs offers enhanced performance and efficiency, making it a crucial advancement for future electric vehicle technologies (Semsar et al., n.d.) The key parameters in optimized vision-based path planning and navigation for autonomous EV charging include vehicle positioning, trajectory planning, and charging pad alignment. Sensor data integration improves localization and ensures accurate path calculation. Energy optimization focuses on reducing power consumption during navigation. Obstacle detection ensures a safe route to the charging station. Real-time feedback allows the system to adjust the vehicle's path for efficient and accurate charging.

3 MATERIALS AND METHODS

Wireless charging eliminates the risk of handling high voltage charging since there is no physical interaction between the vehicle and the charger. A functional prototype of this work's wireless charging system demonstrates the use of renewable energy sources. The Wireless Power Transfer (WPT) inductor charging system is powered by a two-part inductor; the primary coil is located on the charger side, while the secondary coil is located on the vehicle side. The receiver coils, which are situated at the bottom of the vehicle near the wheels, are connected to a bridge rectifier and a charging display, while the transmitter coils are connected to the power supply circuit. The receiver (receiving coil) is mounted on the top of the vehicle and uses electrical energy to power the system and overall proposed (A. A. S. Mohamed et al. 2024).

Group 1: The current technology for wireless EV charging involves a Wireless Power Transfer (WPT) system based on primary and secondary coils where power is transferred wirelessly. Major parameters are efficiency in charging, accuracy in alignment, energy transfer time, and properties of inductive coils such as resistance and frequency. (Y. Zhang, Chen, et al., n.d.)

Group 2: Proposed of WCS is without any power loss and distortion from receiver and transmitters in EV. When the receiving coil is connected, the transmitter generates a reduce error in magnetic flux converted into electrical energy to charge the EV battery. Key factors that affect the amount of energy received and carried to the battery include energy output, control distance between the receiving and transmitting coils.

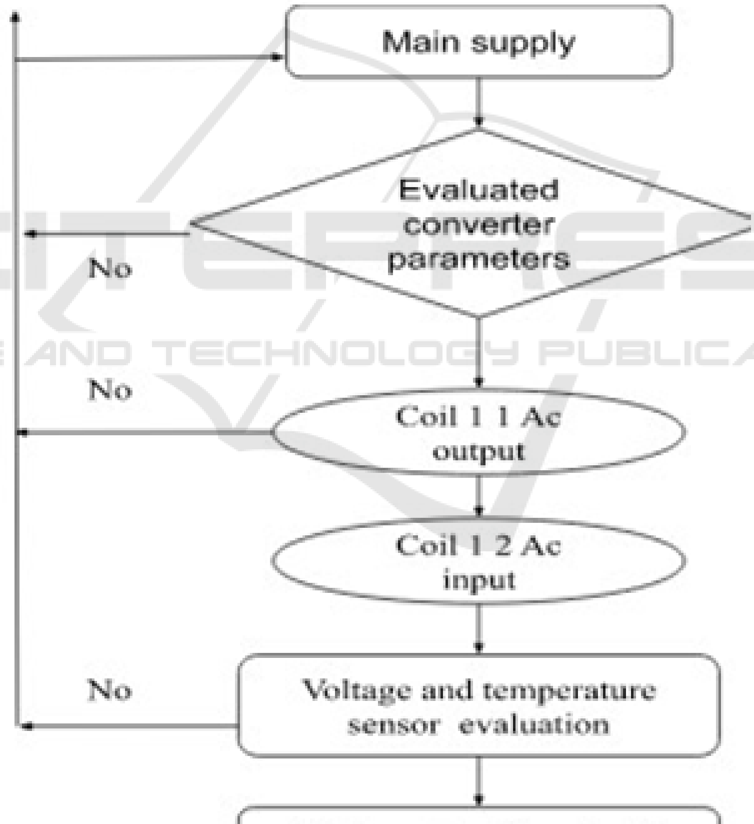

Figure 1: Flow chart of Wireless charging system for Electric vehicle.

Indicates the procedure for selecting the wires method for charging purposes in EV. This involves calculating the distance between the charging vehicle and the charging point. Each charging point is then assigned a score between 0 and 100, considering factors such as the energy price (in e/kWh) and the user's charging time and process is only applicable for charging stations that support efficient charging.

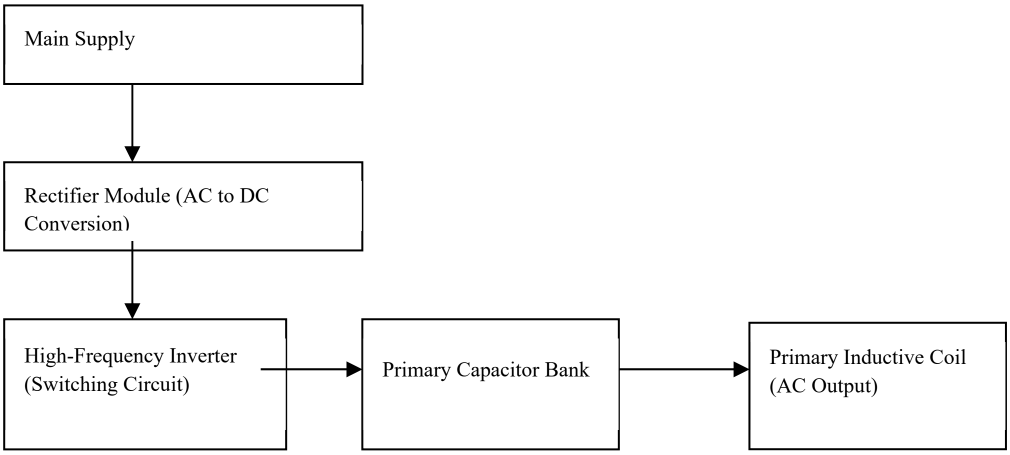

Figure 2: Transmitter side of charging system.

This is the source of electrical energy to drive the system. It is the main source for the transmitter circuit. Converts AC from the main supply to DC. The obtained DC voltage is used for further processing. The DC voltage is converted into high-frequency AC. The high-frequency signal is very important for efficient wireless power transfer. Bank stores and stabilizes the high frequency AC energy. This enhances resonance and, therefore, improves efficiency. This is where an oscillating magnetic field for inductive power transfer is produced. The energy is transmitted wirelessly.

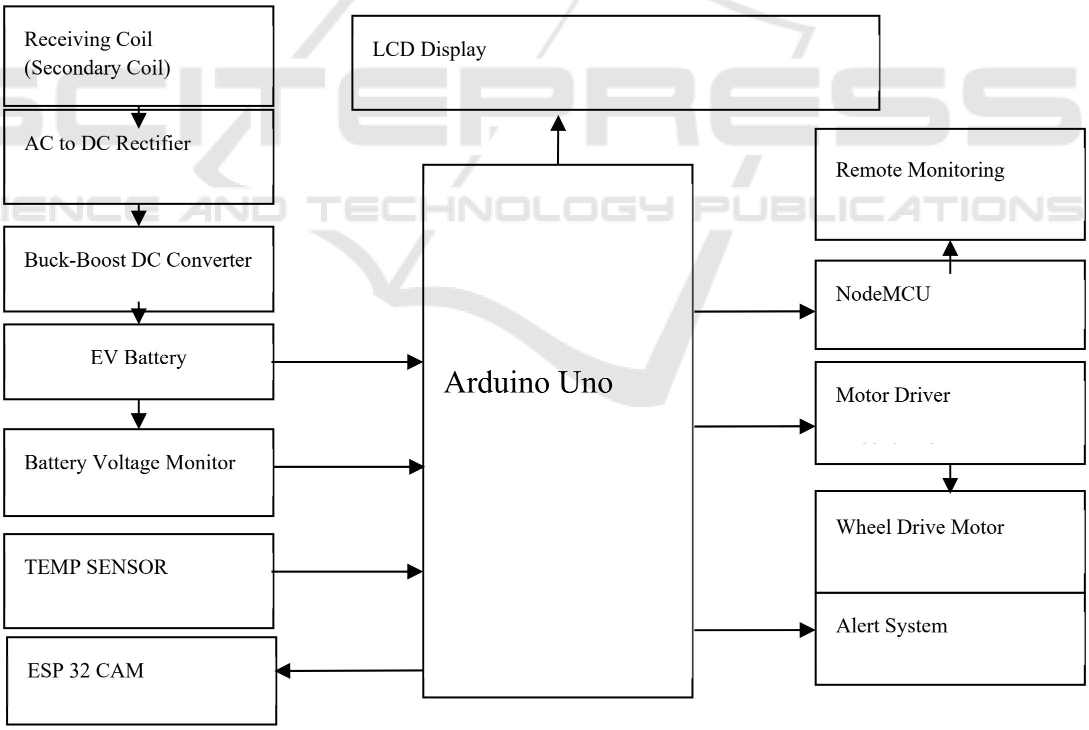

Figure 3: Receiver side of Electrical Vehicle.

This coil catches the transmitted AC power wirelessly. It captures energy from the transmitter. As the term suggests, this component converts the received AC voltage into DC. This DC voltage is the one required to charge electronic components. This converter regulates the rectified DC voltage up to the required level and provides a stable power supply for the battery and other components. This is where the regulated DC power is stored for continuous operation. It provides audio alerts or notifications. It signals warnings or status updates based on the system conditions. In Tables 1 and 2, the parameters used in the hardware prototype are mentioned, this validates proposed typical is effective in generating applied design recommendations. The combined inductance in this case is determined by the horizontal and vertical distances among the receiver and transmitter coils, which are positioned on a parallel plane with the receiving coil adjusted horizontally.

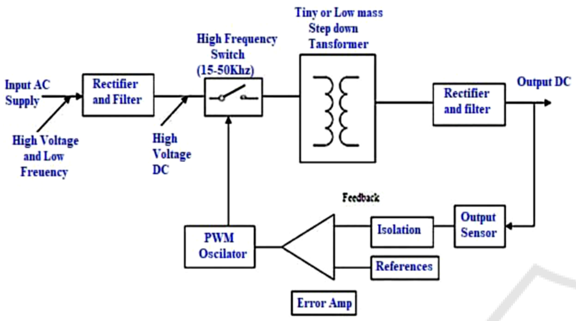

Figure 4: Working diagram of (HFOS) Circuit.

Table 1: Transmitter Section (charger Sider).

Types of Components	Output / Specification
Power supply	230 AC input
AC to DC Converter	230V AC to 12V DC Converter output
Primary Capacitor Bank	Coil 1 1 AC output

Table 2: Receiver Section (Electrical vehicle Side).

Types of Components	Output / Specification
Rectifier Circuit	AC-DC Converter
Battery	12 V/ 1.2AH
Voltage Sensor	charge = equivalent Read (A0); voltage = value * (5.0/1023) * ((R1 + R2)/R2)
Temperature Sensor	Temperature regulator range: -50 ~ 110 ° C. Quantity Accuracy: 0.1°C, Refresh rate: 0.5 S. Input Power: DC12V.
Arduino Controller	Power Supply, 3.3V/5V
Node MCU	Functioning Voltage: 3.3V Contribution Voltage: 7-12V

The gate-source loop of a MOSFET can be caused by a voltage generated by stray inductive charges from the main lead and wire, as well as the di/dt of the drain-source current during turn-off, which can cause interference. The gain of an amplifier is more efficient when transitioning from one end to the other, rather than experiencing losses. By reducing power loss in the switching circuit, there are changes in voltage stages and a decrease in power dissipation during oscillation.

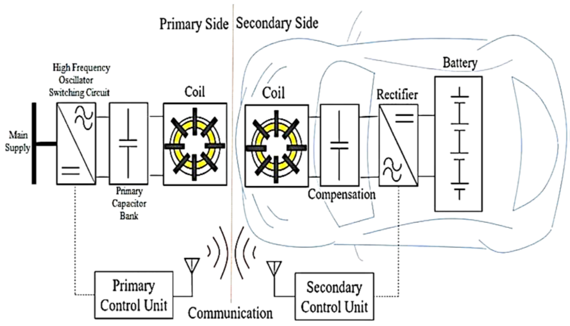

Figure 5: Working diagram of Wireless Charging System (WCS).

The effectiveness and suitability for wireless charging, the distribution components of the receiving and transmitting units underwent a thorough inspection. The converter transforms electrical energy into a magnetic field, which is then removed to the transmitter coil. The receiver coil generates electricity due to the air gap among the two fields. The coil's dimension, and distance from one another all affect the magnetic field's intensity; a larger gap among coils can produce less powerful fields. Additionally, proper alignment of the coils is essential for efficient power transfer. The process of transferring electricity to the sensitive coil on the load side through a magnetic field created by the activation of the inductive coil on the source side by the AC power source. Once the electricity reaches the receiving coil, it is corrected and regulated, and the resulting rectified DC power is used to recharge the EV's energy storage module. This enables electric vehicles to charge while in motion, represents the cutting edge of EV technology. While wireless charging technology is constantly improving, there are still significant challenges to overcome, such as power capacity and driving range, before it can be widely adopted. Figure 5 shows the Working diagram of Wireless Charging System (WCS).

4 STATISTICAL ANALYSIS

SPSS version 11.0 is used for statistical analysis of data collected from parameters when power is captured by the receiving coil, the energy is output as Alternating Current (AC), which is then transformed to Direct Current (DC) using a rectifier circuit. A voltage regulating circuit is used to further guarantee an efficient and regulated power supply. ("An Efficient Design of LC-Compensated Hybrid Wireless Power Transfer System for Electric Vehicle Charging Applications" 2022). Dependent Variable: Energy Efficiency (Wh/km), since the energy consumption is the main outcome that is affected by the performance of the system's navigation and charging. Independent Variables: Path Following Accuracy, Efficiency of Wireless Charging, Obstacle Detection Accuracy, Charging Dock Alignment Accuracy, and Localization Accuracy that all have direct effects on the total energy consumed and system efficiency.

5 RESULTS

The results of the Wireless Charging System (WCS) hardware prototype, along with a discussion of the evaluation of the proposed system. The examiner mentioned above suggests using a vertical plate capacitive connection to optimize the transfer distance between the receiver plates on the vehicle side, resulting in increased output power rating and analyzing performance Figure 1. The EV wireless charging system uses magnetic fields to transfer energy, whose efficiency depends on coil alignment, diameter, and distance. The energy is then converted into DC power for the recharging process, but there are still issues such as power capacity and driving range. Table.1. The optimized system performs better than the current version, with 99% path-following accuracy and improved obstacle detection. Both systems are slightly less energy-efficient with increased samples, but the optimized version is more efficient and performs generally better. Figure 2. The current system demonstrates path-following accuracy between 76% and 84%, wireless charging efficiency ranging from 75% to 90%, and obstacle detection accuracy between 80% and 88%. Sample numbers increase energy efficiency, meaning that energy consumption will be higher with time.Figure 3.The designed system improves over the current system with path-following accuracy of 92% to 99%, up to 95% wireless charging efficiency, and obstacle detection accuracy of 95% to 99%, showing increased efficiency and reliability. Figure 4.The system optimized is better than the current system in all aspects, and path-following accuracy is raised from 76%-84% to 92%-99%, wireless charging efficiency is raised from 75%-90% to 95%, and obstacle detection accuracy is raised from 80%-88% to 95%-99%, with greater efficiency and reliability.Table.2.The system optimized is more accurate (95.00 mean) than the current system (80.00 mean). It is also more consistent, having a lower standard deviation (2.000) and standard error (0.516) than the current system (2.171 and 0.561, respectively). Table.3. Levene's test has no significant difference of variance between the systems. Independent samples t-test, on the other hand, indicates that there is a significant mean difference of -15.000 and p-value 0.000, which proves that the optimized system performs better than the current system.

6 DISCUSSION

AViTRoN greatly enhances the process of autonomous charging for electric vehicles through optimizing vision-based track routing and navigation. Efficiency, accuracy, and reliability improve with this, and practical and scalable autonomous charging becomes achievable. With such a decentralized EV battery charging system, efficient power transfer with precise tracking of current was demonstrated, ensuring stable operation at unity power factor. Experimental results matched simulations well, and the reliability of the control algorithm was effectively confirmed, thus implying minimal steady-state error. This study proves that decentralized charging is feasible for the future structure of EV infrastructure and can offer grid-friendly scalable solutions. (Hossain, Al-Awami, and Abido, n.d.). Altruistic charging delays peak EV charging demand, or that is, not concurrent with peak base demand. Therefore, peak total electricity demand is lower with Altruistic charging. This lower peak demand means higher penetrations of EVs can be accommodated without increasing the Exceedance. This illustrates for the Base case that low EV penetrations cause Exceedance values around the same as for base demand alone. As EV penetration increases, however, Selfish charging leads to higher More than Altruistic charging values. ("Driving Change: Electric Vehicle Charging Behavior and Peak Loading" 2024) The primary side hybrid reconfigurable compensation for constant current/constant voltage control wireless EV charging will be able to provide efficient management of power delivery. It guarantees stable charging due to the ability to dynamically change according to changing power demands with high efficiency. The reconfiguration of the system based on the load conditions enhances the charging performance, and this makes it very adaptable to a wide range of EV models and charging scenarios. (Arulvendhan et al., n.d.). The review on wireless charging efficiency for electric vehicles focuses on the most important advancements in coil design, resonance tuning, and power electronics to enhance energy transfer and minimize losses. The review stresses the need to optimize these technologies to improve overall charging performance. The review also underlines the safety, scalability, and cost-effectiveness requirements of future wireless charging infrastructure for EVs. (Ramakrishnan et al., n.d.) Adding Electric Vehicles in the microgrid improves the grid's flexibility in terms of energy storage and balancing load. As an added mobile source of energy, EVs may be helpful at peak demands or during the short supply of energy. In any case, however, integrating such vehicles calls for efficient charging infrastructure and regulating bidirectional power flows. (Sora, Serban, and Petreus, n.d.). Recent developments in shielding technologies for wireless electric vehicle charging systems aim to improve EMI suppression and enhance energy transfer efficiency. Advanced magnetic shielding, metamaterials, and new materials are currently being researched in order to minimize power loss and environmental impact. These developments should enhance the performance, safety, and reliability of wireless charging infrastructure for EVs.(Quercio et al., n.d.)Recent developments in protecting technologies for EV wireless charging highlight the reduction in electromagnetic interference (EMI), safety, or efficiency with various innovative materials or designs such as multi-layered shields and ferrite plates minimizing energy loss with future development efforts focused on greater optimization of their shielding performance with safer and highly effective wireless chargers. Integrating electric vehicles (EVs) into microgrids improves energy efficiency and grid stability by enabling vehicle-to-grid (V2G) technology. EVs can store excess renewable energy and supply power during peak demand, reducing reliance on traditional energy sources. Smart charging strategies help balance load distribution and enhance microgrid resilience. Advanced communication systems ensure seamless coordination between EVs and the grid for real-time energy optimization. Future developments will focus on AI-driven management, enhanced battery performance, and greater integration with renewable energy sources.

7 CONCLUSION

A summary of the work is the wireless charging method for electric vehicles is evaluated, depending on primary voltage estimation using only vehicle-side data. A DC-DC converter is working for secondary voltage control, ensuring efficient power management on the vehicle side. Wireless power transfer technology enhances electric vehicle performance by streamlining the charging process, extending range, and eliminating the need for physical connections. The vehicle is positioned at a designated commercial, and charging proceeds as expected. In case of any issues, a buzzer indicator immediately alerts the concerned party via a web application. Hardware experiment results confirm the successful estimation of primary voltage and demonstrate that the Wireless Charging System (WCS) can be effectively controlled through power management based on maximum power and primary voltage estimation, eliminating the need for load-side voltage regulation.

8 TABLES AND FIGURES

The number of samples of the system data is compared across several metrics against an optimized version of the same system. Energy efficiency of the system decreases very slightly with every increase in sample number, thereby showing higher energy usage with greater load. Accuracy in path follows and efficiency of wireless charging for the optimized version are higher compared to the existing version. The optimized version reached 99% accuracy in the path-following task, and the existing system reached a maximum of 90%. The optimized system also has better obstacle detection accuracy. Overall, the optimized system is more efficient in terms of energy usage and performance.

Table 3: Comparison of Existing and Optimized Systems.

Sample No.	**Energy Efficiency (Wh/km)**	**Path Following Accuracy**		**Wireless Charging Efficiency**		**Obstacle Detection Accuracy**	
		Existing System	**Optimize System**	**Existing System**	**Optimized System**	**Existing System**	**Optimized System**
1	180	80	95	75	85	88	95
2	185	82	92	76	88	86	96
3	190	80	96	77	90	85	97
4	195	79	98	78	89	84	97
5	200	81	94	79	92	86	98
6	205	83	93	80	91	87	96
7	210	82	97	81	93	85	98
8	215	79	94	82	92	83	97
9	220	76	95	83	94	82	96
10	225	80	95	85	93	85	98
11	230	78	96	84	92	84	97
12	235	84	99	86	95	88	99
13	240	77	92	87	93	80	97
14	245	79	94	89	94	86	97
15	250	80	95	90	95	85	98

Table 4: SPSS Output.

	Group	N	Mean	Std. deviation		Std.error mean
Accuracy	Existing	15	80.00	2.171		0.561
	Optimized	15	95.00	2.000		0.516

Table 5: Independent Samples T-Test Results for Evaluating Energy Efficiency Between Existing and Optimized Systems.

		Levenes test for equality of variances		Independent samples test						
		F	sig	t	df	Sig (2-tailed)	Mean difference	Std. error difference	95% confidence interval of the difference	
									lower	upper
Existing	Equal variance assumed	0.073	0.789	-19.680	28	**0.000**	-15.000	0.762	-16.561	-13.439
Optimized	Equal variances not assumed			-19.680	27.813	**0.000**	-15.000	0.762	-16.562	-13.438

Levene's test reveals no significant difference in variances between the existing and optimized systems. The independent samples t-test reveals a significant mean difference of -15.000 with a p-value of 0.000, which states that the optimized system outperforms the existing system significantly. Table 4 shows the SPSS Output.

Figure 6 The existing system graph shows the performance metrics of energy efficiency, path-following accuracy, wireless charging efficiency, and obstacle detection accuracy. The system exhibits reasonable efficiency in path-following such that the accuracy is found between 76% and 84%, the efficiency of the aforementioned wireless charging increases gradually from 75% to 90%, and the obstacle detection accuracy is fluctuating while staying within an average range between 80% and 88%. The energy efficiency (Wh/km) increases step-by-step with sample numbers, showing increased energy consumption over time. This visualization helps compare improvements in the optimized system. Table 5 shows the Independent Samples T-Test Results for Evaluating Energy Efficiency Between Existing and Optimized Systems.

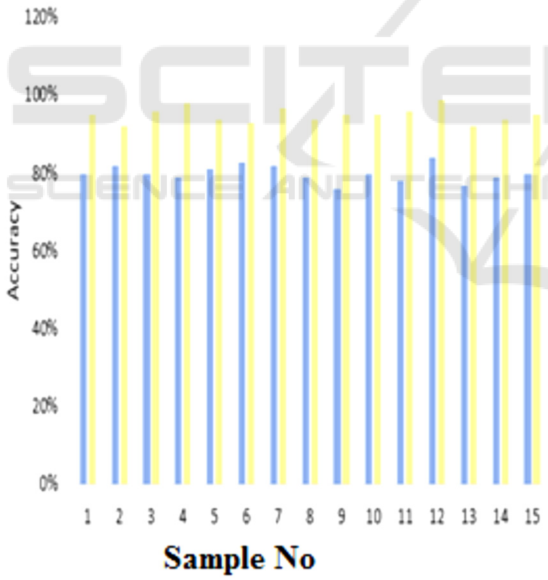

Figure 6: Path Following Accuracy.

The optimized system graph shows improvements in all the key performance metrics, such as path-following accuracy, wireless charging efficiency, and obstacle detection accuracy. Path following accuracy is always high, ranging from 92% to 99%, which indicates improved navigation precision. Wireless charging efficiency is improved to up to 95%, ensuring better energy transfer. Obstacle detection accuracy is also optimized, maintaining values between 95% and 99%, which indicates superior environmental awareness. Overall, the optimized system outperforms the existing system in every aspect, showcasing its enhanced efficiency and reliability.

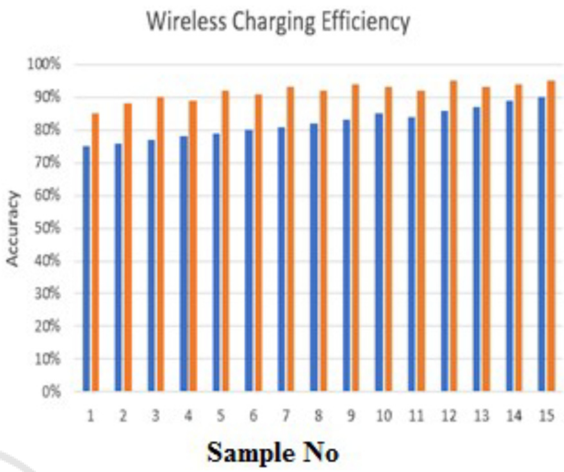

Figure 7: Wireless Charging Efficiency.

The optimized system outperforms the existing system in all performance areas by a wide margin. The accuracy in path-following is enhanced from 76%-84% of the existing system to 92%-99% in the optimized version, making navigation more effective. Efficiency in wireless charging increases to 95% from the existing system of 75%-90%, ensuring better energy transfer. Accuracy in obstacle detection enhances from 80%-88% to 95%-99%, thus the system becomes more reliable in obstacle identification. Overall, the optimized system offers higher efficiency, better. Figure 7 shows the Wireless Charging Efficiency. Figure 8 shows the Mean Path Following Accuracy.

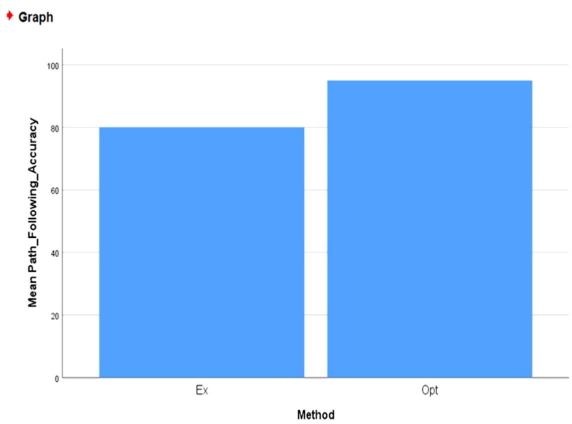

Figure 8: Mean Path Following Accuracy.

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