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Design and Simulation of an Electromagnetic Wave-based Electric Vehicle Charging Station

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ABSTRACT

EVs are widely used, as they have become more popular due to sustainability and environmental factors; yet, traditional plug-in-charging infrastructure has numerous disadvantages, such as a long recharge time, poses a threat to user safety, and lacks ease of use. The paper is a modelling and simulation of an electromagnetic wave-based wireless charging station to be used in Electric vehicles. A Series-Series (S-S) inductive resonant coupling system using a topology of 85 kHz was modeled and designed. The mathematical modeling and simulation considered in MATLAB Simulink workspace allowed inclusion of an AC power source, rectifier circuit, transmitter and receiver coils, and a battery load. To determine the effect of circuit parameters on power transfer efficiency, a parametric sweep was carried out to assess the effects of the circuit parameters (inductance, compensation capacitance, mutual inductance, on-resistance diodes, and the distance between the coils) on the power transfer efficiency. The simulation findings indicate that the highest efficiency of 98.22 was achieved when the machine was operating under nominal conditions. Sensitivity and correlation analysis indicate that the primary-side inductance and capacitors of compensation have the most impact on the system performance. These results indicate the efficiency of the suggested model of wireless charging and the possible safety, efficiency, and convenience of EV charging infrastructure integration. Compared to standard research on infrastructure planning or inductive charging design, this paper is a comprehensive efficiency-based parametric and sensitivity analysis of an electromagnetic wave-based EV charging system.

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1. Introduction

The automotive sector is already experiencing a massive change with the focus on electric vehicles (EVs) due to the increasing economic incentives, environmental sustainability campaigns, and the acute environmental issues. EVs offer a cleaner alternative to conventional vehicles with an internal combustion engine, which cause a substantial amount of CO_2 emissions in the global environment, particularly as the level of concern over climate change and the emission of greenhouse gases grows [1]. This change is not simply the necessity to address the challenge of environmental problems, but it is also in line with the overall sustainability, such as the necessity to reduce the dependence on fossil fuels, improve the quality of the air, and the necessity to introduce renewable energy sources into the transport systems. Besides the positive environmental changes associated with EVs, there are various economic gains that these vehicles bring to the developing nations. The reduced number of cars in the city will alleviate traffic jams, promote well-rounded lifestyles, and decrease consumption of imported fossil fuels that are rather costly, particularly in areas where EVs are widely used. Another impact of the EV industry on economic growth is the creation of employment in the renewable energy and EV production plants. The continuous development of battery technology, charging stations, and intelligent grids also improves the performance of EVs and makes them more popular.

Difficulties like short charging duration are being overcome by the fast-charging technology, which makes the technology more practical in daily life. Charging infrastructure is actively developed via government programs as the European Union green deal or the Fast Charging Initiative in Germany, and multiple federal and state laws in the US. As an example, China has proactively encouraged the use of EVs using subsidies, incentives, and major investments in EV charging stations. Although the sales of EVs are concentrated in China, Europe, and the US, the developing countries such as Southeast Asia and Brazil are undergoing a significant increase in the EVs adoption, which is a global trend [2]. This is a positive development in transportation that is friendly to the environment and introduces possibilities of research and innovations in EVs.

Electromagnetic wave-based charging technology is a new technology that is used as a charging method of the EV, which uses wireless power transfer (WPT) to improve the convenience and efficiency of energy transfer. This technology involves electromagnetic fields that are used to conduct the electrical energy of a transmitter to a receiver without the use of physical connectors. With the rise in popularity of EVs, the constraints of the conventional plug-in charging stations are already evident, and thus, the development of the charging infrastructure needs improvement. The traditional plug-in charging systems are also characterized by a number of disadvantages that the electromagnetic wave-based charging solutions resolve. With the traditional charging, the user has to connect wires, a tedious task. Wireless charging creates better satisfaction for customers by removing the use of cables and autonomous charging when the vehicle passes close to charging stations. The physical links employed in the plug-in charging may deteriorate with time, whereas the electromagnetic wave-based charging lowers the maintenance cost associated with the infrastructure, as it eliminates mechanical interfaces.

Exposed wires and connectors are dangerous in wired charging systems, which is not the case with the wireless charging system. Wireless charging minimizes the threats of electric leakages or short circuits and offers greater safety in charging and sustainable cities development. An important benefit of the use of electromagnetic waves is the so-called dynamic charging, charging vehicles on the move. Specifically, it comes in handy with public transport, buses, and trains, which necessitate fewer frequent stops to recharge them. Despite the extensive research on wireless power transfer (WPT) technologies as electric vehicle (EV) chargers, the research conducted to date is largely limited to planning infrastructure, comparative studies of qualitative systems, or even to the overall efficiency analysis of inductive charging systems. Conversely, this research paper gives an elaborate modeling and simulation of an electromagnetic wave-based EV charging station through a resonant inductive coupling method with Series-Series (S-S) compensation topology.

Novelty of this piece of work is that it employs in-depth efficiency-focused analysis, entailing parametric sweeping, sensitivity analysis, and correlation analysis to estimate the role of significant resonant components and system operational conditions in determining system performance. This study, as it identifies the most important parameters clearly contributing to power transfer efficiency, gives more insight into the optimization and design of high-efficiency wireless EV charging systems. Although there has been increased attention on wireless power transfer technology of electric vehicle (EV) charging, the experimentally determined effects of main resonant system parameters on charging efficiency have not been comprehensively studied. Specifically, no analytical results exist on the relationship between a variation of components and efficiency performance in electromagnetic wave-based EV charging systems. To fill this gap, this research attempts to answer the following research questions:

i. Is it possible to use an electromagnetic wave-based wireless charging system based on resonant inductive coupling and get high power transfer efficiency that can be used in charging EVs?

ii. What are the effects of major circuit parameters like inductance, compensating capacitance, mutual inductance, diode on-resistance, and coil separation distance on the overall charging efficiency?

iii. What are the system parameters that exert the most substantial effect on efficiency in terms of sensitivity analysis and correlation analysis?

iv. Does the proposed system perform within acceptable levels of performance in the nominal operating conditions?

The structure of this paper is as follows: Section 2 presents a review of relevant literature on EV charging technologies and related works. Section 3 details the methodology used for designing and simulating the electromagnetic wave-based charging station. Section 4 presents the results and a discussion of the findings. Finally, Section 5 concludes the paper and provides recommendations for future work.

2. Literature Review

The mass adoption of electric vehicles (EVs) is now being obstructed by a number of circumstances, such as the fact that it takes a long time to recharge them as opposed to that of refueling typical gasoline-powered vehicles [3]. The restriction highlights the necessity of measures to improve the efficiency and accessibility of EV charging stations. The charging systems in use are mainly based on physical connectors that pass electricity between charging stations and vehicles, with different connector compatibility depending on the model. Moreover, the lack of charging stations evenly across the country, wherein urban centers are better-equipped than rural ones, may cause range anxiety among EV drivers and remind potential users of the reason why they should not replace fossil fuel-powered cars with the EV [4]. The charging techniques through cables require proximity and, therefore, are limited in regard to their station location in congested regions and compatibility. Public confidence is further diminished by safety issues that include electric shock or overheating in systems with high voltages. Little has been done in exploring the potential of electromagnetic charging in enhancing the efficiency of energy transfer, solving the issue of safety, and addressing the issue of distance constraints. In-depth analysis of real-time efficiency levels, cost of operations, and safety measures is important to have a complete picture of what the technology can and cannot do.

Electric vehicle charging techniques have various characteristics, and can be divided according to the nature of power (AC or DC), physical connection method, or charging speed. AC charging techniques may be single-phase or three-phase. Home and office installations can use single-phase AC charging equipment, which is less costly to obtain, powered by standard electrical outlets with a peak power of 7.4 kW [5]. Charging Three-phase capabilities of up to 22 kW, typically at public charging stations and business premises. In contrast to AC charging, which involves onboard conversion of AC to DC, direct current charging topologies utilize direct current to charge the battery, thus dramatically enhancing the velocity of charging. The Electric vehicle DC charging systems have high power ratings between 50 kW and 150 kW and can be recharged in a short battery in a short time [6]. High-power output Ultra-fast DC chargers have very high-power output, usually up to 350 kW, to be used on long routes, to make electric vehicles able to quickly recharge during long journeys. Battery swap charging is a physical exchange of a used battery of an EV with a charged battery at battery swapping stations, which is a potentially quicker method of charging than conventional charging. The most widespread type of charging electric vehicles, which does not involve any contact, is called conductive charging, in which the charging connector is directly connected to the vehicle inlet, divided by levels of power transmission, which is the foundation of the modern power supply to electric vehicles.

Wireless charging, also called electromagnetic charging systems transform electricity into electromagnetic energy, which is transferred to a charging surface through an induction device on the car [7]. The system makes use of the inductive and resonant magnetic coupling, which is convenient without the use of cables. Inductive charging involves a charging pad (transmitter) and receiver coil in the vehicle body, which is positioned in the parking lots, garages, and built into the roads and rail tracks to charge dynamically. Resonant inductive charging employs resonance to essentially permit the transfer of energy between tuned coils functioning at the same resonant frequency to enhance performance at a greater distance and with the freedom to align coils [8]. Capacitive wireless charging involves the employment of capacitor plates as receivers and transmitters in the transfer of energy over an electric field, as opposed to a magnetic field. Dynamic wireless charging induces energy to an electric car as it moves over embedded charging infrastructure, which is compatible with electric buses, highways, and urban EVs. Radio frequency (RF) wireless charging provides power to a receiver, which in turn converts the energy into electrical energy, especially in low-power devices, including wearables and smartwatches [9]. Multi-receiver Magnetic resonance coupling charges multiple receiver coils at one transmitter coil, to serve common spaces and charge a large number of devices simultaneously. The essential elements of the electromagnetic charging system are the transmitter coil, where the alternating magnetic field is produced, and the coil that is mounted in the vehicle to absorb the electromagnetic field [10]. The energy transmission is controlled by power electronics such as rectifiers and power converters, and the control system measures the performance of the charging and optimizes the coil alignment. The communication system allows wireless communication between the electric vehicle and the charging station to authenticate and control the energy [11].

Charging stations based on electromagnetic waves are convenient and easy to use since drivers do not need to use physical cords to charge their cars; they simply park over a charging pad [12]. Electric vehicles can also recharge as they travel, thus providing a solution to range anxiety and large batteries. The technologies also have significant aesthetic and urban design benefits, which can be effortlessly incorporated into the existing urban environments and enable the shift towards the solutions offered by smart cities. The proposed electromagnetic wave-charging stations fulfill the international objectives concerning environmental protection, complementing the smart grid technologies to facilitate the two-way energy flows, reduce the reliance upon the non-renewable sources, and allow influencing the energy consumption dynamically.

The literature by Ahmad *et al*. [1] offers a detailed analysis of wireless-based EV charging technology and compares it to conductive-based technology. The article by Sun *et al*. [13] is an extensive discussion of Electric vehicles' WPT technologies, including technological development, use, and the issues of fixed and dynamic wireless charging. The suggested wireless charging system of electric cars by Khutwad and Gaur [14] eliminates the drawbacks, risks, and cost of the traditional cable charging. The article by Ou *et al*. [15] examines how on-road wireless charging affects the locational marginal prices in the power market and the mobility of EVs. Elnail *et al*. [16] address the electromagnetic field and core loss of the WPT system of EV, whereby a developed lumped circuit model is used to evaluate the correlation of relative permeability, coupling coefficient, core thickness, as well as core loss. According to Baroi *et al*. [17], electric cars are required, and the wireless charging system has many advantages, which are premised on inductive coupling and MATLAB/Simulink simulation with SS (Series-Series) compensation topology. Sultanbek [18] examines the opportunities of WPT in plug-less EV charging, including the problem of coil alignment and human error. A suggested SSWCS uses resonant inductive coupling and a fingerprint-based method of coil alignment. Machura and Li [19] address the concept of WPT as an alternative to the conventional charging and discuss coil design, compensating topologies, and new materials, and discuss the economic analysis of the repercussions of WPT regarding potential grid impacts, promises, and problems.

Recent research has looked at EV charging infrastructure through the prism of smart grid and planning. An extensive survey of optimal placement of charging stations in smart grids reveals that infrastructure must be deployed in a coordinated manner, but it does not involve modeling of electromagnetic power transfer or optimization of efficiency [20, 21]. Equally, a close examination of EV charging infrastructure, standards, policies, and Indian market aggregators underlines regulatory issues and deployment issues as opposed to the performance of the wireless charging systems [22]. Smart algorithm-based planning of EV charging stations has been investigated in the case of metropolitan areas, with a primary emphasis on the location and demand prediction of the stations. Also, EV chargers have been studied to incorporate capacitors and V2G applications to improve grid stability [23]. Nevertheless, these studies mostly ignore electromagnetic and resonant properties of wireless charging systems, which highlights the necessity to employ more specific modeling and efficiency-oriented research, which is offered in this work.

3. Methodology

To evaluate the performance of an electromagnetic wave-based charging station system, a model was developed using Simulink to simulate power flow, efficiency, and coupling distance. The system was simulated under a variety of conditions to assess the effects of varying components (such as capacitors and inductors) on system power losses and power transfer efficiency.

3.1. System Modelling

The system was designed based on requirements to ensure optimum performance and efficiency, with the main criterion of efficiently handling EV battery charging while maintaining dependable and steady energy transfer, as shown in Fig. (**1**). The operating frequency of 85 kHz was chosen to comply with standards for wireless EV charging and promote conformity and regulatory compliance. The design also prioritized minimizing coil losses to increase the power transfer efficiency overall.

Based on the reviewed literature, resonant inductive coupling was selected as the charging topology for the station due to its magnet-coupled resonant coils, which increase power transfer efficiency and maintain performance at moderate sizes, providing good energy transfer over reasonable separation distances. Series-Series (S-S) topology was chosen for its electrical properties that benefit wireless power transfer efficiency. The S-S compensation improves the power factor, decreasing reactive power losses and increasing system efficiency, ensuring the transmitter and receiver coils are at resonance frequencies.

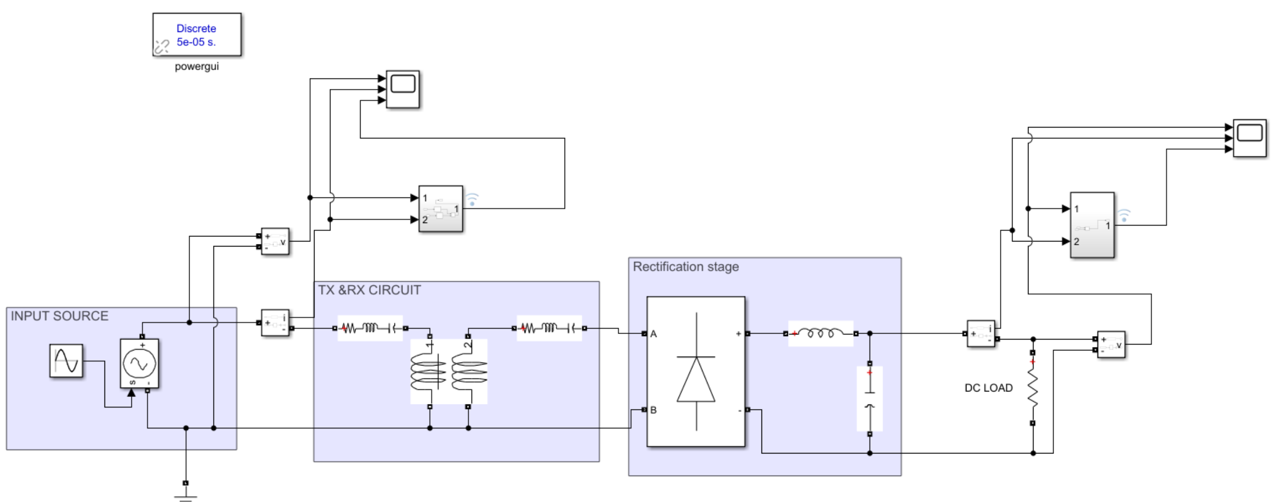

Figure 1: Model of an electromagnetic wave-based wireless charging system for electric vehicles.

3.2. System Mathematical Model

The mathematical model included an input source, where the 240V, 50Hz Sine wave is supplied to a controlled voltage source. The amount of power transferred in the resonant inductive coupling system is governed by Faraday's Law of Electromagnetic Induction, where the power transferred is given by Equation 1, the mutual inductance of the transmitter and receiver mechanical coil (L_M).

$$l_M = K \times \sqrt{l_1 \times l_2} \quad (1)$$

The model also includes a rectification and load stage, where the receiver coil captures the HF AC voltage, which is then rectified using a full-bridge rectifier. A converter is used to step this up to 400 V DC for battery charging, with the battery represented as an equivalent resistive load as given in Equation 2.

$$V_{DC} = {}^{2}/_{\pi} \times V_{PEAK} \quad (2)$$

The system's performance was measured by conducting power assessments throughout the charging procedure at different times. Power measurements at each stage depended on mathematical formulas for Input Power (P_{IN}) given in Equation 3, Rectified Power (P_{DC}), and Load Power (P_{Load}) given in Equation 4, with efficiency obtained to determine the ratio of output power to input power using Equation 5.

$$P_{DC} = V_{DC} \times I_{DC} \quad (3)$$

$$P_{load} = P_{DC} \times \eta_{BOOST} \quad (4)$$

$$\eta_{SYS} = \frac{P_{IN}}{P_{load}} \times 100 \quad (5)$$

The system's descriptive block diagram in Fig. (**2**) explains the system model.

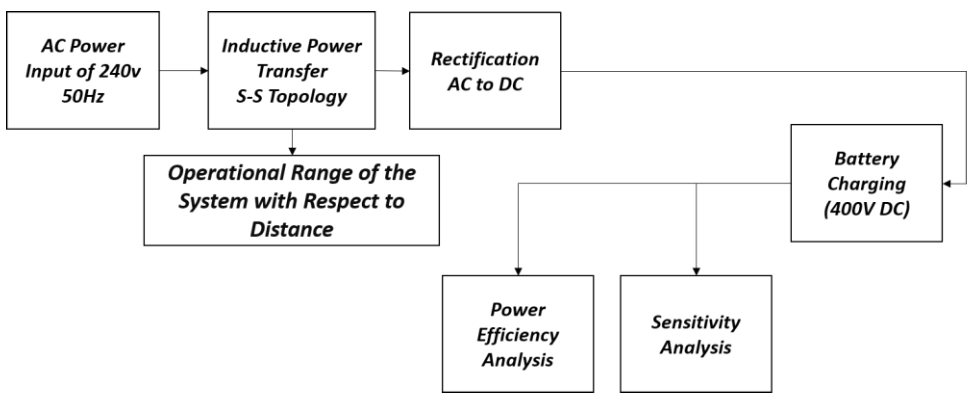

Figure 2: Block diagram of the system's model.

3.3. System's Parameters

The system model parameters in Table **1** define the components utilized in simulating the electromagnetic wave-based wireless charging system. These parameters were categorized based on their respective functional blocks, including the input source, rectification stage, high-frequency inverter, transmitter and receiver coils, secondary rectification stage, and battery storage system.

3.4. Operational Range of the System

The operational performance of the system is significantly influenced by the coupling coefficient between the transmitter and receiver coils. As the separation distance increases, the coupling coefficient decreases exponentially, reducing the efficiency of power transfer. Since the charging current supplied to the battery is directly dependent on the power transferred, a lower coupling coefficient results in a lower charging current. This charging time becomes inversely proportional to the square of the coupling coefficient. To evaluate this, a range of operating distances was established.

3.5. Sensitivity and Correlation Analysis

Certain critical parameters and modifications influence the wireless charging station's reliability in system operations. A sensitivity analysis was carried out to evaluate the major components that affect the system. The analysis was performed using MATLAB Simulink through the parameter sweep technique execution, which was used to optimize the system's model design. Correlation analysis was carried out to understand the relationship that exists between major components of the system model, using the Pearson product-moment correlation coefficient (x,y) to assess the linear relationship between two continuous variables.

Table 1: System parameters.

Component	Parameter	Value	Unit
Input Source	Peak Voltage	240√2	V
	Frequency	50	Hz
Transmitter (Tx) Filters	Resistor-1	0.25	Ω
	Inductor-1	47.8	μH
	Capacitor-1	22	μF
Receiver (Rx) Filters	Resistor-1	0.25	Ω
	Inductor-2	4.78	μH
	Capacitor-2	2.2	mF
Mutual Inductance Block	Winding 1 Resistance	1	mΩ
	Winding 1 Inductance	250	μH
	Winding 2 Resistance	1	mΩ
	Winding 2 Inductance	500	μH
	Mutual Impedance Resistance	10	mΩ
	Mutual Impedance Inductance	340	μH
Rectification	Diode On-state Resistance	1	mΩ
	Diode Voltage Drop	0.7	V
	Filtering Capacitor	1	mF
	Filtering Inductor	3.5	μH
Battery Storage System	Resistive Load	4.85	Ω

Table 2: Range of operating distances.

Distance (cm)	Distance (m)	Coupling Coefficient (k)	Mutual Inductance (M) (μH)
2.89	0.0289	0.45	38.45
4.11	0.0411	0.35	29.91
4.95	0.0495	0.30	25.64
6.88	0.0688	0.22	18.80
9.78	0.0978	0.15	12.82
16.17	0.1617	0.08	6.83
26.46	0.2646	0.04	3.42

4. Results and Discussion

The simulation results of the electromagnetic wave-based wireless charging system for EVs are presented and discussed in this section. The system, designed using integrated stages for rapid inversions, energy transfer via mutually coupled magnet fields, and AC-to-DC conversion for battery charging. Simulations aimed to determine system behavior under various scenarios and conditions, focusing on efficiency, waveform stability, and energy transfer. System performance was measured by monitoring input and output voltage and current, input and output power, as shown in Fig. (**3**-**4**), power loss, and efficiency reaching 98.22%.

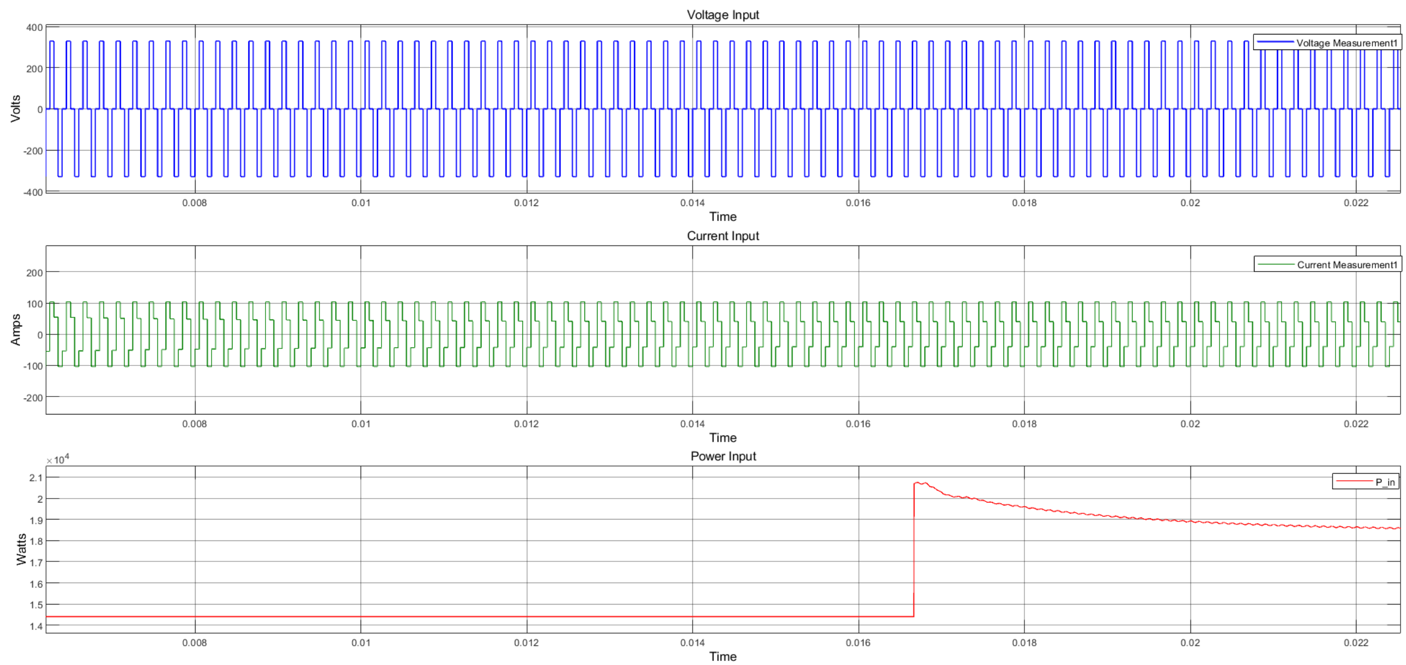

Figure 3: Systems voltage, current, and power input.

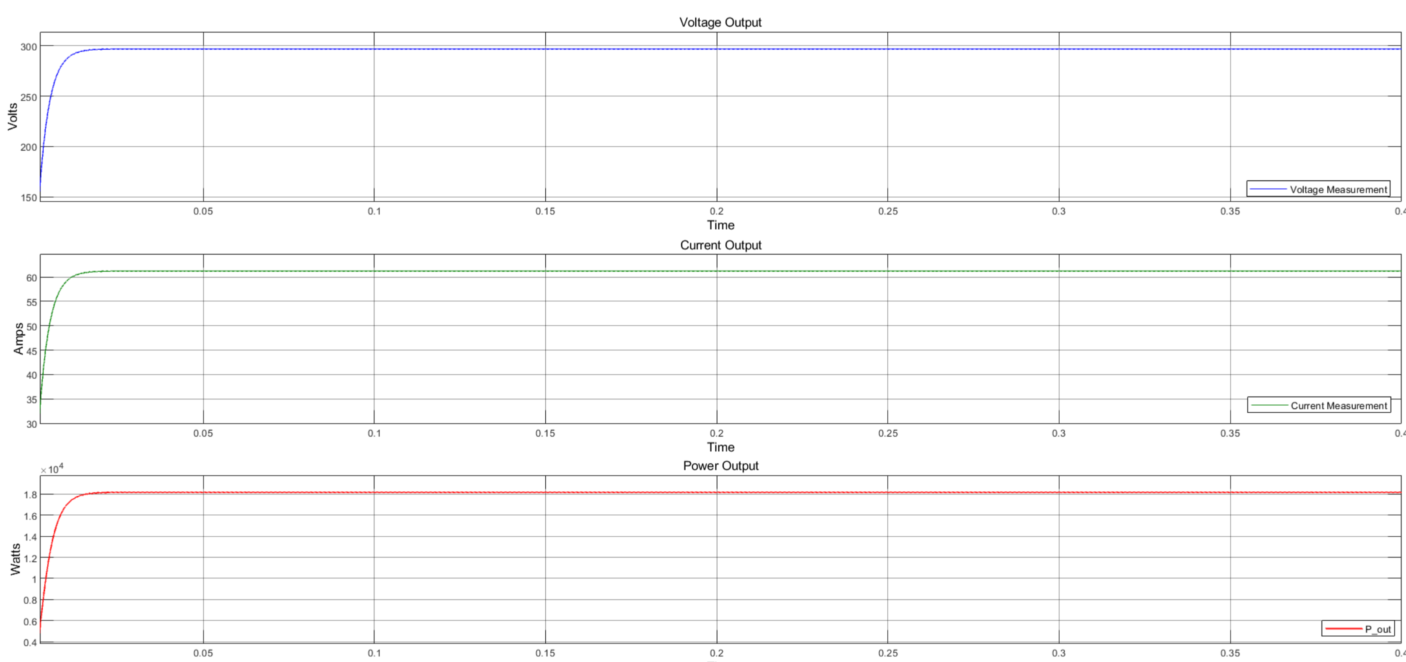

Figure 4: Systems voltage, current, and power output.

This high efficiency indicates optimal system performance under nominal settings, with minimal coil losses, efficient switching, and reduced energy loss through radiation across the air gap. This system's performance is ideal when all parts are perfectly tuned for any situation where safety and high efficiency are needed. The input and output voltage, current, and power are shown in Table **3**.

Table 3: System input and output values.

Parameter	Value
Input Voltage, V_{IN}	233 Volts
Input Current, I_{IN}	78.94 Amps
Input Power, P_{IN}	18,393 Watts
Output Voltage, V_{OUT}	296 Volts
Output Current, I_{OUT}	61.03 Amps
Output Power, P_{OUT}	18,065 Watts
Power Loss, P_{LOSS}	328 Watts
Efficiency, η	≈ 98.22%

The simulations were implemented to determine how the system behaves under various scenario-based changes and conditions. When inductors, capacitors, and coil arrangements were improved, more focus was given to how quickly the system worked, how stable its waveforms remained, and how much energy was passed. These insights are crucial for evaluating system performance and validating whether the developed system effectively satisfies its intended purposes.

4.1. Operational Range of the System

Analysis of the operational range revealed that decreasing the distance between coils increases the efficiency of the wireless charging system. Simulations with a separation of 0.02 meters demonstrated fast charging due to strong magnetic couplings. As distance increased, mutual inductance decreased, resulting in lower output and extended charging times. Fig. (**5**) illustrates the variation of power transfer efficiency with respect to coil separation distance. It can be observed that the efficiency decreases as the separation distance increases. This behavior is attributed to the reduction in mutual inductance between the transmitter and receiver coils as the air gap widens, leading to weaker electromagnetic coupling. The maximum efficiency of 98.22% is achieved at the nominal separation distance, indicating the optimal operating region of the proposed system. This result confirms the suitability of the resonant inductive coupling approach for short-range wireless EV charging applications.

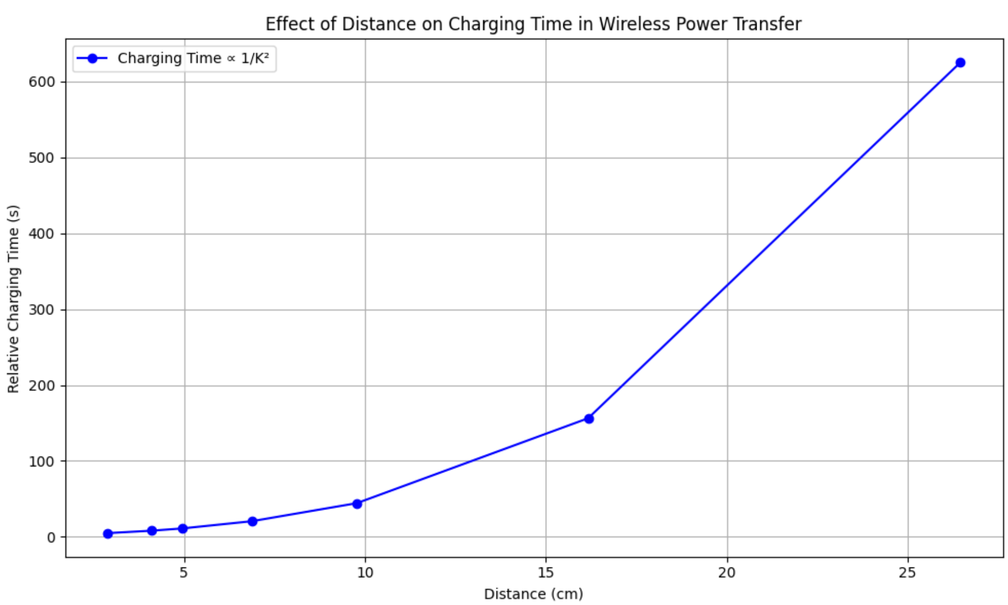

Figure 5: Plot showing the relationship between charging time and coil separation distance.

4.2. Sensitivity and Correlation Analysis

Sensitivity analysis evaluated the system's ability to cope with variations in component values caused by manufacturing issues, aging, and heat. The tornado chart in Fig. (**6**) depicts the sensitivity analysis of key system parameters on power transfer efficiency. It is observed that the primary-side inductance and compensation capacitors exhibit the highest sensitivity indices, indicating their dominant influence on system performance. In contrast, the diode on-resistance shows a comparatively lower impact. This result provides valuable design insight by identifying the parameters that require strict control during system implementation. Minimal effects were observed for magnetizing inductance (L_M) and diode on-resistance (Ron), suggesting system flexibility, summarized in Table **4**.

Table 4: Summary of efficiency deviation.

Parameter	Efficiency Deviation (%)
C_1	±4.8
C_2	±4.3
C_3	±3.9
L_1	±3.1
L_2	±2.8
L_3	±1.4
L_M	±0.5
Diode R_{ON}	±0.2

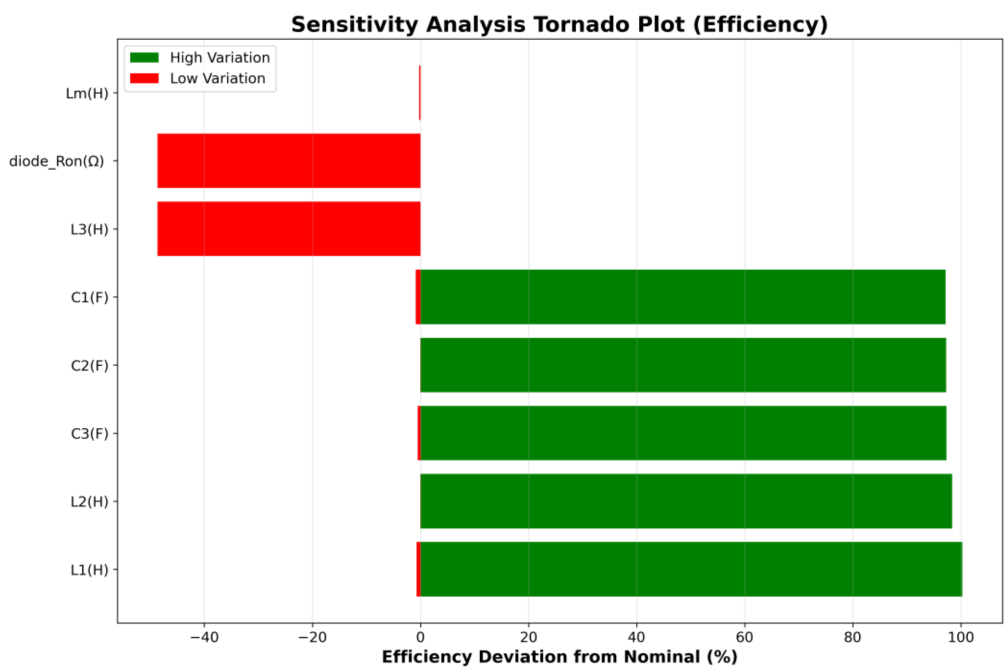

Figure 6: Tornado plot of efficiency deviation (%) due to parameter variation.

Correlation analysis demonstrated how certain system parameters affect its efficiency and the relationships between the system's different parameters. Correlation coefficients, formed from a heatmap, revealed a dataset containing synthetic representations of crucial circuit components. Pearson correlation coefficients for all model parameters were found and compared to the efficiency for each case, as shown in Fig. (**7**), which shows the correlation coefficients between system parameters and charging efficiency. Strong positive correlations are observed for compensation capacitance and mutual inductance, confirming their direct influence on efficiency enhancement. These findings are consistent with the sensitivity analysis results, reinforcing the reliability of the proposed analytical approach.

High values in C_1 and C_2 had a significant negative impact on system efficiency, while inductors were linked to a moderately negative correlation. Diode R_{ON} and L_M had minimal effect, with correlation values close to zero. These findings indicate:

i. C_1, C_2, and L_1 have strong influences on the system's efficiency, which must be handled with priority whenever the system is being optimised or designed.

ii. When two system parameters have weak links, they can be more flexible on their tolerance values and cost less, while still meeting the set standards.

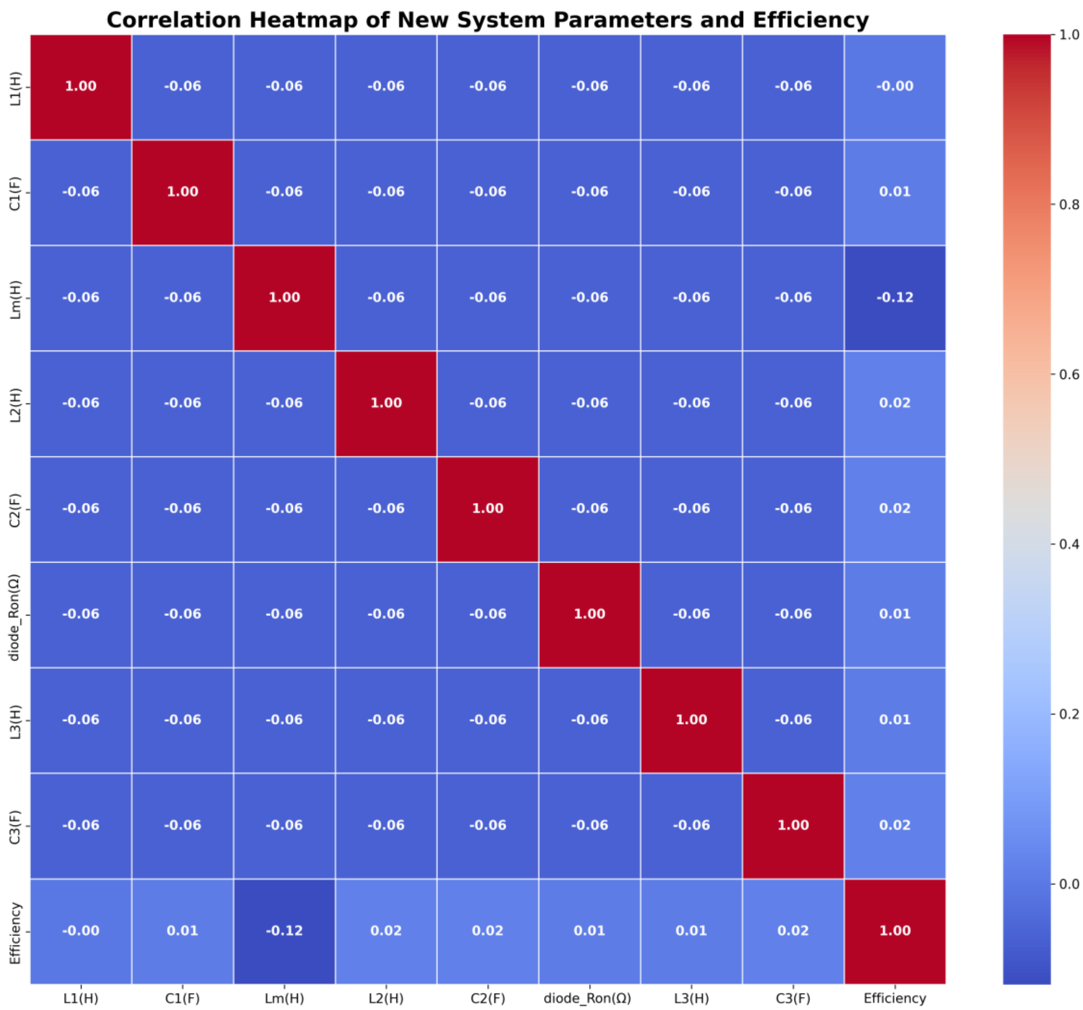

Figure 7: Correlation matrix of parameter influence on system efficiency.

4.3. Power Analysis

A power analysis was performed to assess the effect of changes in the major resonant and non-resonant as regards the nature of power transfer in the suggested electromagnetic wave-based EV charging system. The Fig. (**8**-**15**) show the change in input power, output power, and power loss in response to changes in each of the system parameters individually between set points -100% and +100%. These findings distinctly reveal the fact that various components affect system performance in different ways, with different physical mechanisms that lead to a different level of deviation of power.

Fig. (**8**) and (**9**) show the impact of the changes in the primary and secondary compensation capacitors (C1 and C2), respectively. It is noted that variations of the nominal values of capacitance lead to substantial losses in the power produced and high-power loss. This phenomenon is explained by resonant detuning of the Series-Series compensated network, which interferes with impedance matching between the transmitter and receiver coils. The over-compensation or under-compensation changes the resonant frequency compared to the operating frequency (85 kHz) and results in increased circulating reactive power and decreased transfer of real power. Such a high sensitivity proves that compensation capacitors are considered to be one of the most important parameters that determine the efficiency of the system, which is also consistent with the results of other research that has been conducted on resonant inductive wireless power transfer systems previously. However, the change of the filter capacitor C3 (Fig. **10**) has a more moderate effect on power transfer. Excessive capacitance raises the input current required and the losses incurred due to over-filtering, but too little capacitance causes a smaller DC voltage to appear at the output. C3, in contrast to C1 and C2, is less likely to influence resonance formation and much more likely to influence secondary-side power conditioning. This trend is similar to the results reported earlier that output-side filtering parts have a major effect on voltage ripple and transient response, but not steady-state power transfer.

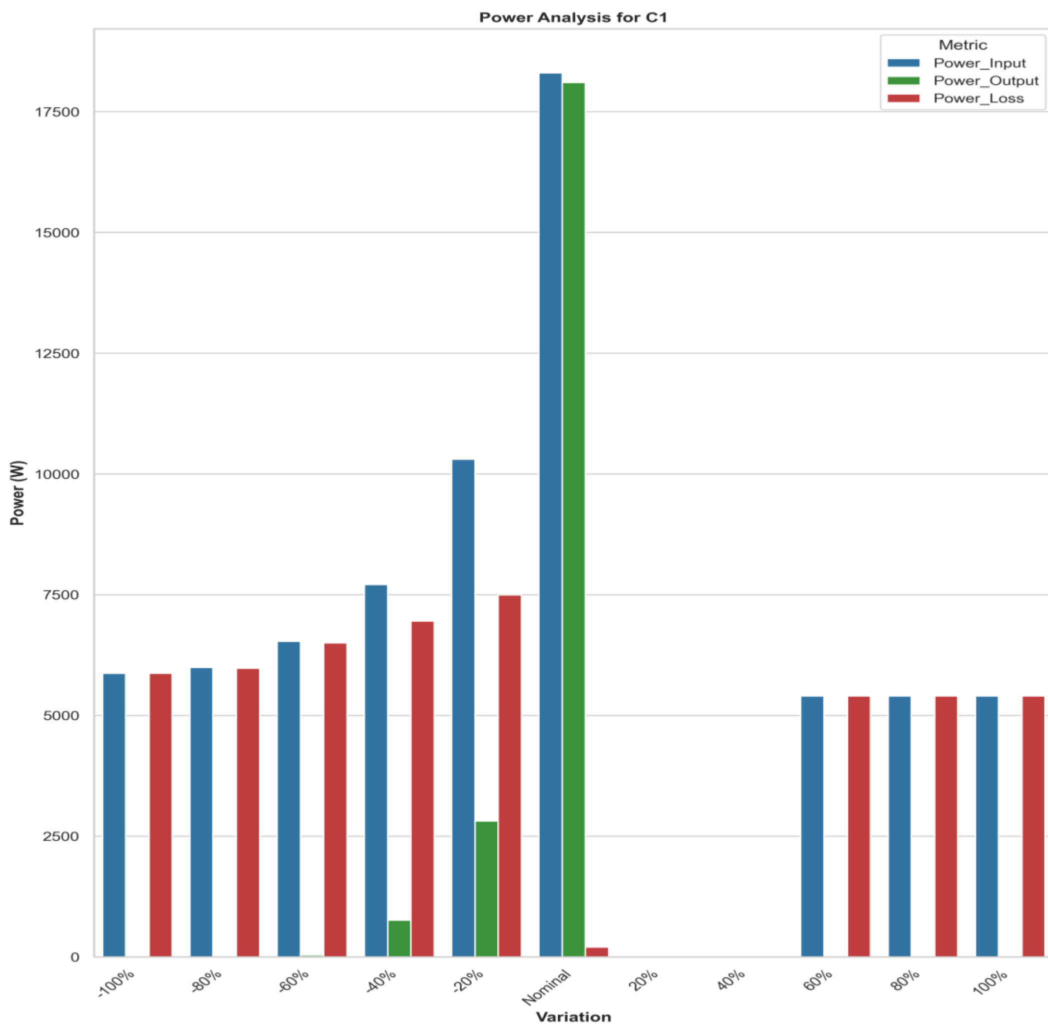

Figure 8: Power analysis for C1.

Fig. (**11**-**13**) show the effect of inductive factors. Changes in the transmitter and receiver inductances (L1 and L2) cause measurably decreasing output power with an increase in inductance. An increase in the inductance values causes leakage reactance and decreases the effective magnetic coupling, thus diminishing the mutual exchange of energy between coils. On the other hand, the resonance stability is compromised by extremely low values of inductance. The influence of L1 is a little higher as compared to L2, showing the primary-side magnetic field dominating as the major influence on creating desired coupling. The observations are in line with resonant inductive charging theory, where the primary-side inductance has a very strong influence on the strengths of the magnetic fields and the efficiency of the coupling. Filter inductor L3 (Fig. **14**) has little effect on steady-state power levels but has an effect on the smoothness and stability of output power. Reduction in L3 causes mainly ripple attenuation as opposed to power magnitude, which confirms that L3 is a secondary factor in power transfer optimization. This is the reason why it has a low sensitivity level relative to resonant inductors and capacitors.

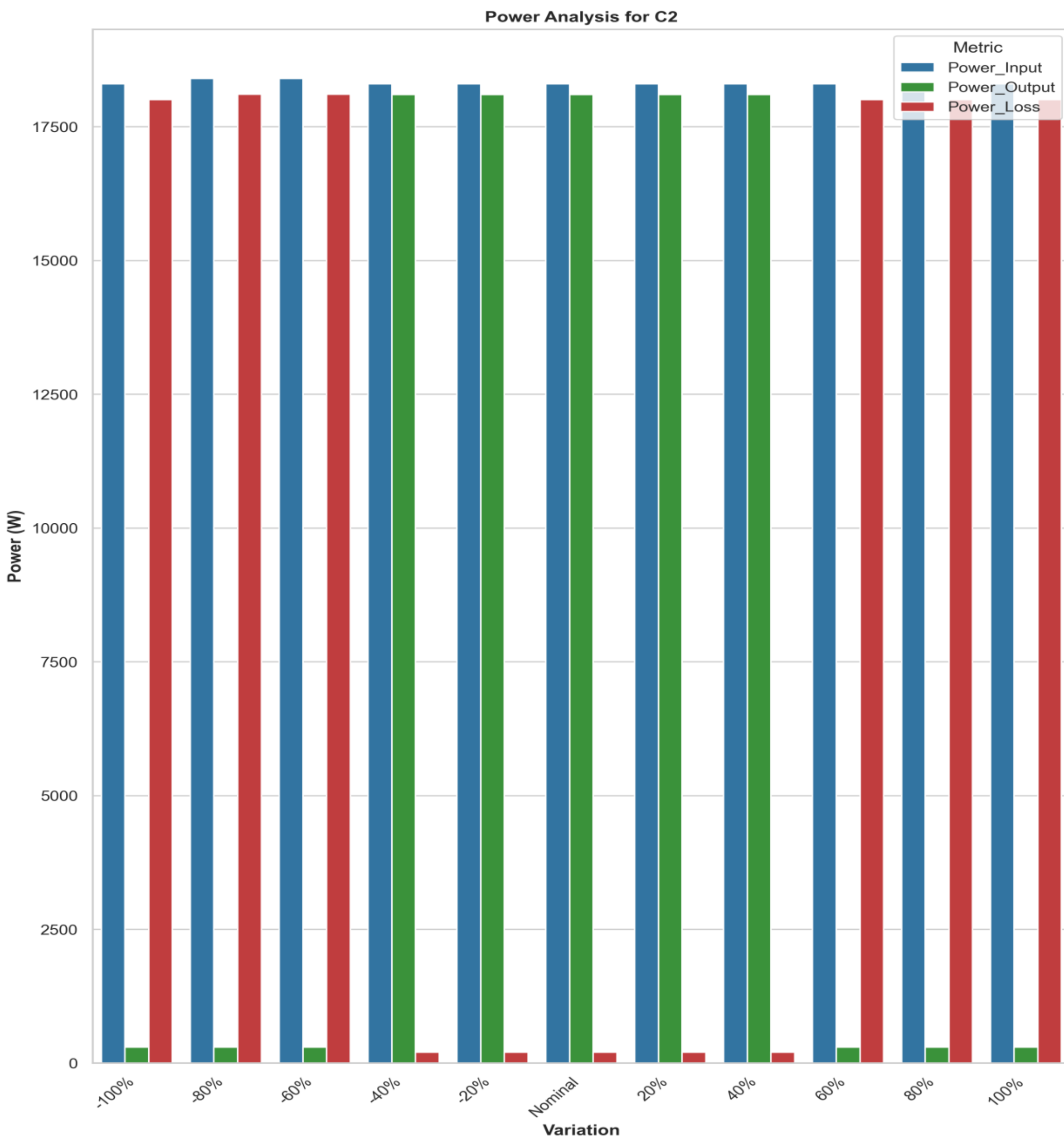

Figure 9: Power analysis for C2.

Fig. (**15**) shows the impact of diode on-resistance (RON), where the change creates insignificant changes in output power and power loss. This implies that conduction losses in the rectification step are considered to be quite small when compared to resonant and coupling losses at the chosen operating frequency. Accordingly, differences in magnetizing inductance (LM) in Fig. (**16**) do not cause significant power transfer changes and thus indicate that the system is tolerant of reasonable magnetic parameter bases. These findings indicate that parasitic factors that are non-resonant play minimal roles in system efficiency when operating under nominal operating conditions.

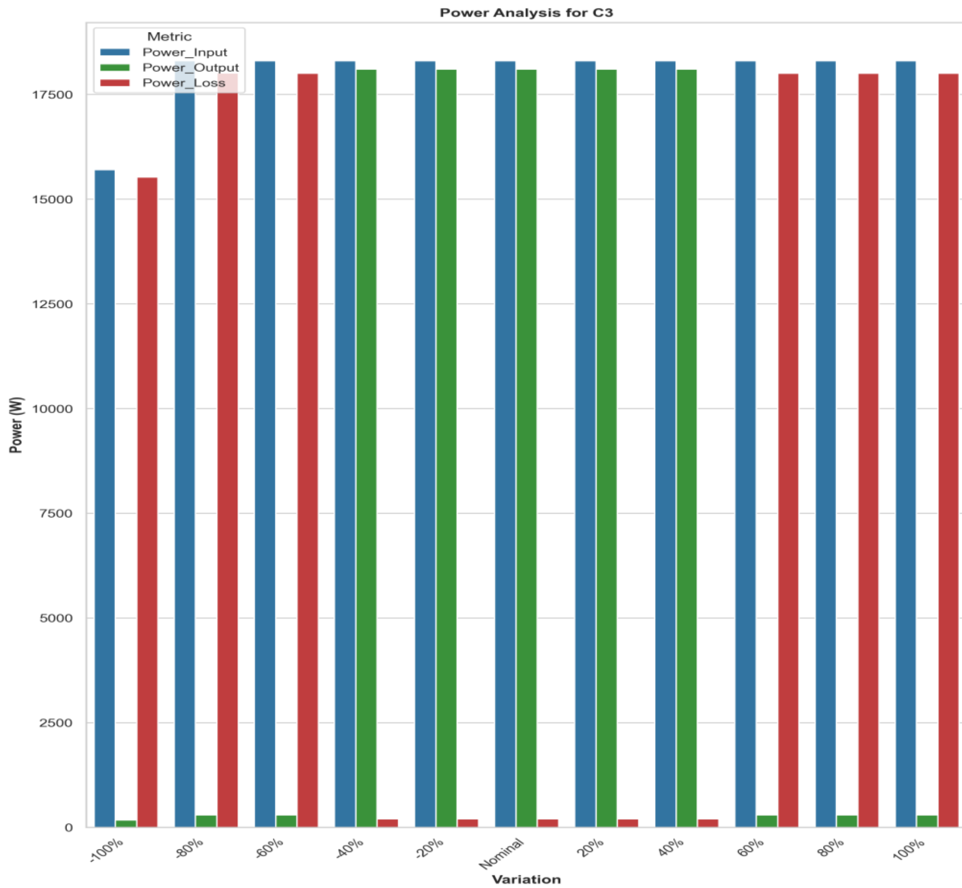

Figure 10: Power analysis for C3.

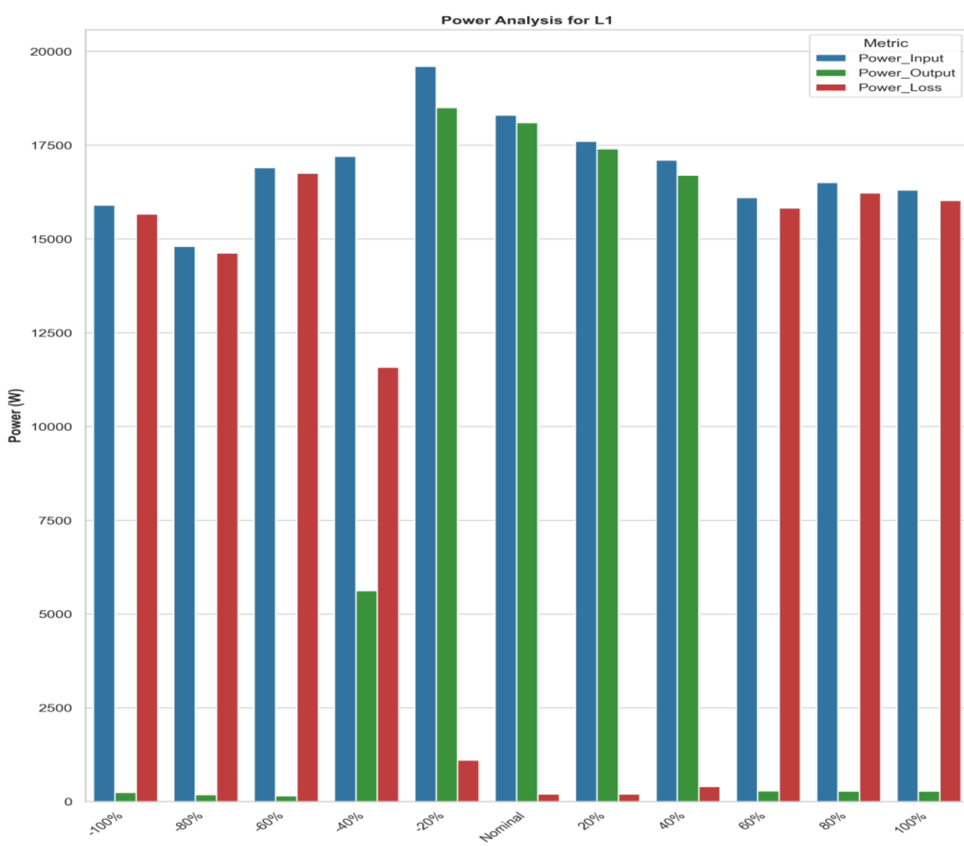

Figure 11: Power analysis for L1.

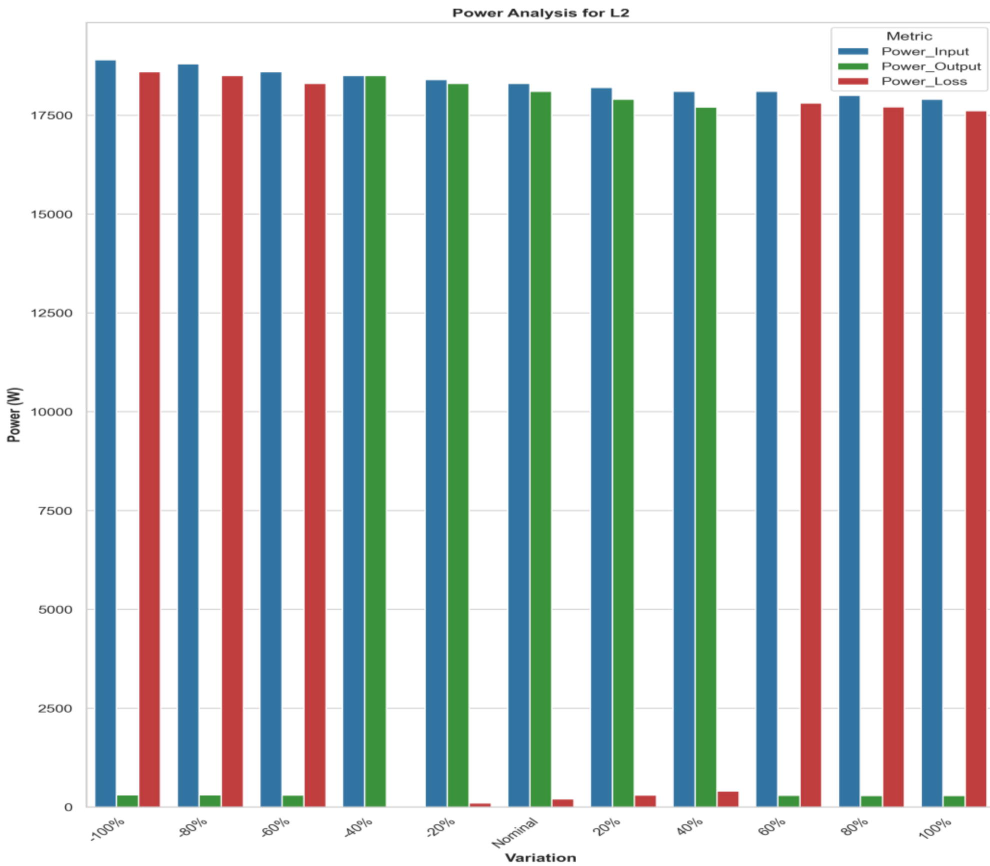

Figure 12: Power analysis for L2.

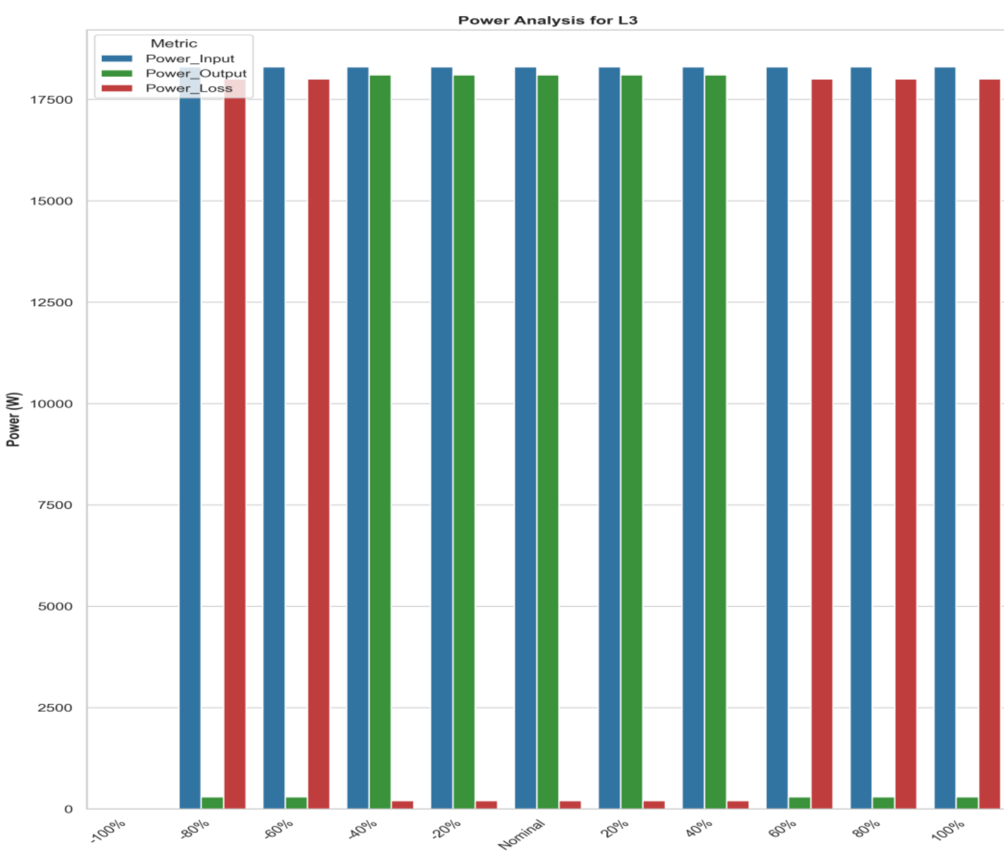

Figure 13: Power analysis for L3.

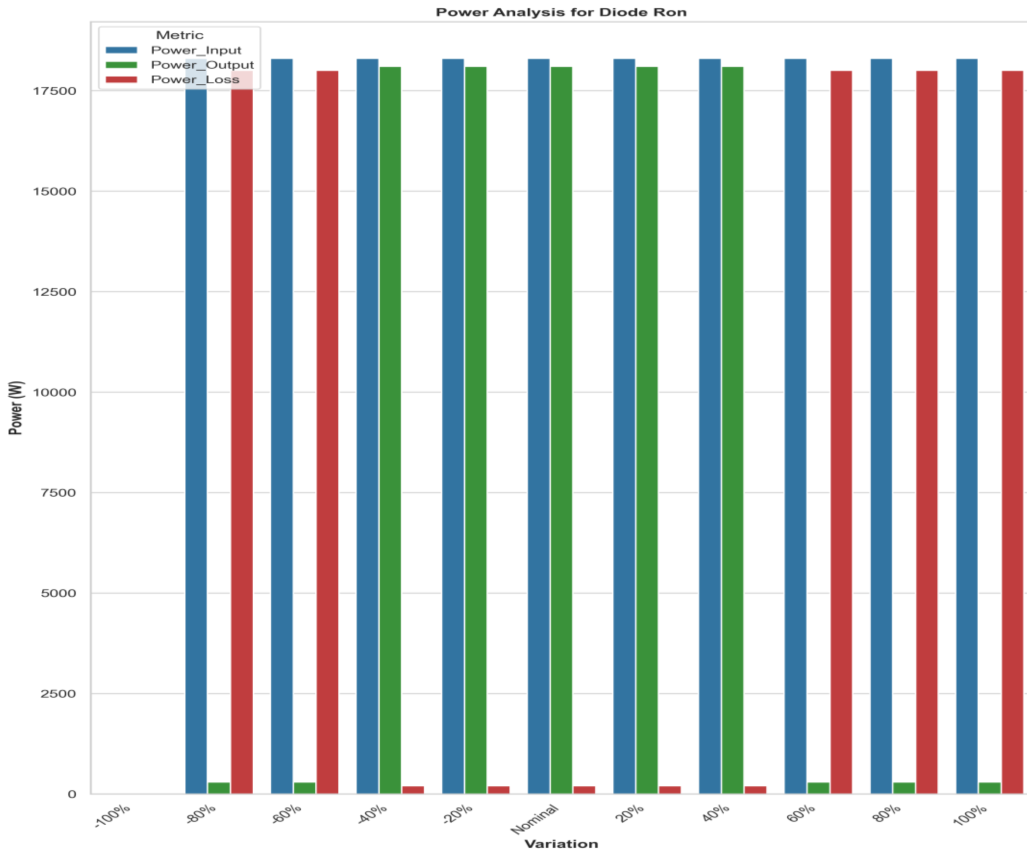

Figure 14: Power analysis for R_{on}.

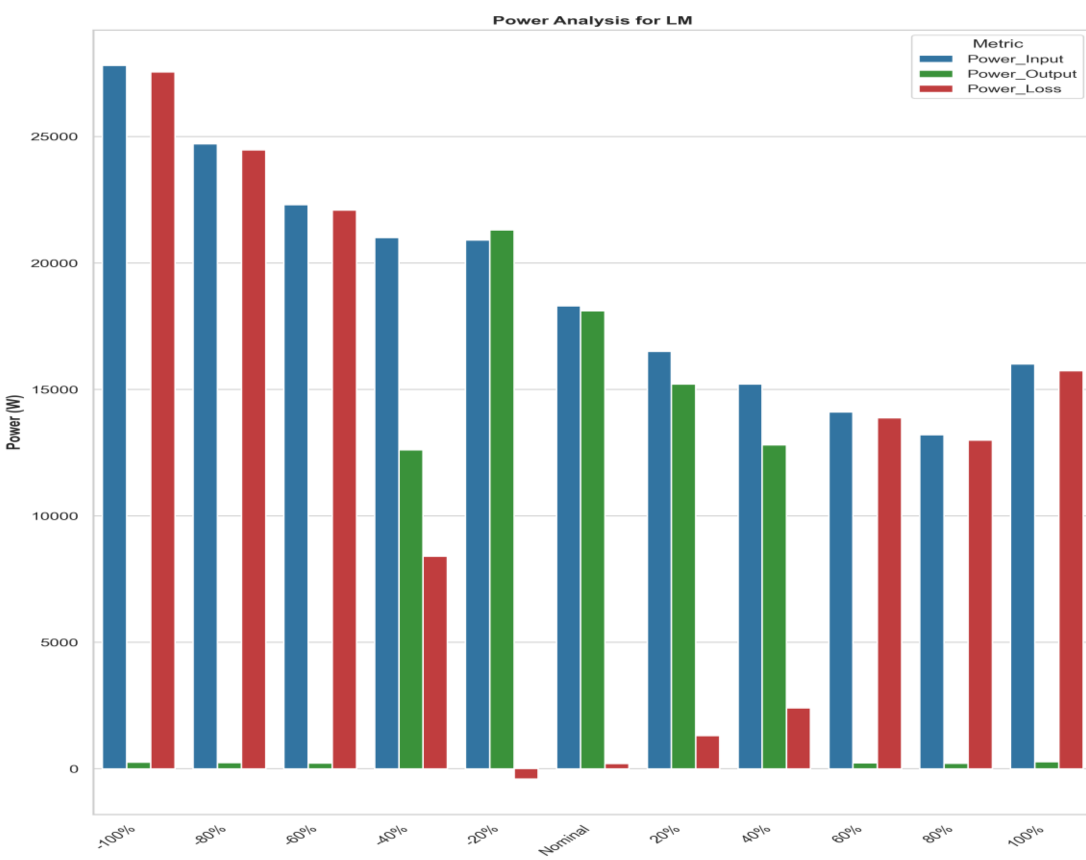

Figure 15: Power analysis for L_M.

The comparative evaluation between Fig. (**8**-**15**) indicates clearly that most power transfer behavior is due to compensation capacitors (C1 and C2), primary inductance (L1), and secondary to rectifier and filtering elements. On balance, it has been demonstrated in the power analysis that the proposed system can be highly efficient when the resonant parameters are properly tuned, but can be robust with respect to the changes in non-critical components. These findings confirm the technical reliability of the system design and practical information on component tolerance that may be used in real-world EV wireless charging implementations.

5. Conclusion

Simulation results demonstrated that the proposed system achieved a maximum power transfer efficiency of 98.22% under nominal operating conditions at an operating frequency of 85 kHz. At this point of operation, the system gives the output power of 18.07 kW against an input power of 18.39 kW, thus representing a total power loss of just 328 W. The voltage and current at the receiver side were 296 V and 61.03 A, respectively, and this proves that the system is able to support practical EV battery charging requirements at medium-power charging ranges. The parametric, sensitivity, and correlation analyses all indicate that resonant components are predominant in the system performance. Specifically, the efficiency deviations of up to ±4.8 were caused by changes in the compensation capacitors (C1 and C2) and ±3.1 deviations due to the variation in the primary-side inductance (L1). Conversely, non-resonant components like diode on-resistance and magnetizing inductance caused insignificant modifications in efficiency of $< -0.5\%$ and a demonstration of significant robustness of the suggested system to parasitic losses. The quantitative confirmation of these findings is that the most crucial design requirement of high-efficiency wireless EV charging systems is the precise resonance tuning.

The analysis of operational range also showed that the power transfer efficiency is strongly affected by the separation distance of coils. Strong magnetic coupling makes transfer of energy rapid and highly efficient at short air gaps (less than 0.05 m). The separation between two electrodes reduces mutual inductance, resulting in a slight decrease in output power. The behavior validates the appropriateness of the proposed resonant inductive coupling architecture to use in the context of static wireless charging, including residential garages, parking lots, taxi ranks, and fleet depots, where the controlled alignment and short separation distances can be achieved. Practically, the findings present a number of major benefits of deployment. The efficiency with low power loss in the simulations translates to lesser thermal stress, enhanced safety, and less energy wastage as compared to the conventional plug-in charging systems. The exhibited ability to withstand the changes in non-critical parameters also makes production easier and the cost of the system less appealing to the design appealing to practical application.

Moreover, the covered connectors also improve user safety and minimize maintenance needs, especially in outdoor and public charging locations. On the whole, this research offers a technically valid and quantitatively validated design and optimization scheme of the electromagnetic wave-based EV charging stations. The findings fill the gap between theoretical models of wireless power transfer and real-world applications of EV charging and the relevance of the proposed system to future systems of sustainable transportation. The future work will be aimed at experimental hardware validation of the suggested model, optimization of the geometry of the coil to increase the toleration of misalignment, and an analysis of the electromagnetic field exposure to confirm adherence to the global safety measures. Moreover, the extension of the system to dynamic wireless charging cases and the connection with smart grid and vehicle-to-grid (V2G) systems will also contribute to the further applicability of the system in intelligent transportation networks of the next generation.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

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