

Article

Novel Electrical Modeling, Design and Comparative Control Techniques for Wireless Electric Vehicle Battery Charging

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Abstract: Dynamic wireless power systems are an effective way to supply electric vehicles (EVs) with the required power while moving and to overcome the problems of low mileage and extensive charging times. This paper targets modeling and control for future dynamic wireless charging using magnetic resonance coupling because of the latter's efficiency. We present a 3D model of transmitter and receiver coils for EV charging with magnetic resonance wireless power developed using ANSYS Maxwell. This model was incorporated into the physical design of the magnetic resonance coupling using ANSYS Simpler in order to optimize the power. The estimated efficiency was around 92.1%. The transient analysis of the proposed circuit was investigated. A closed-loop three-level cascaded PI controller- was utilized for wireless charging of an EV battery. The controller was designed to eliminate the voltage variation resulting from the variation in the space existing between coils. A single-level PI controller was used to benchmark the proposed system's performance. Furthermore, solar-powered wireless power transfer with a maximum power point tracker was used to simulate the wireless charging of an electric vehicle. The simulation results indicated that the EV battery could be charged with a regulated power of 12 V and 5 A through wireless power transfer. Fuzzy logic and neuro-fuzzy controllers were employed for more robustness in the performance of the output. The neuro-fuzzy controller showed the best performance in comparison with the other designs. All the proposed systems were checked and validated using the OPAL Real-Time simulator. The stability analysis of the DC–DC converter inside the closed-loop system was investigated.



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1. Introduction

Wireless power transfer has been used since it was invented by Nikola Tesla [1]. Magnetic resonance power transfer is favored due to its high efficiency and ability to charge even with large spaces separating the coils [2–4]. A wireless power transfer (WPT) system is typically composed of a transmitter coil, a storage device, a receiver coil, an electric source, controllers, a matching circuit and sensors [5,6]. There are two main types of topologies, referred to as compensation topologies, to interface the WPT coils: series-series (SS) and parallel-series (PS) [7]. To enhance the maximum efficiency of the transfer, for the PS topology, a secondary-side inductor–capacitor–capacitor (LCC) impedance-matching circuit can be used [8,9]. Other studies have proposed ways to increase the efficiency of wireless power charging systems with experimental verification and analysis [10,11]. To reduce system loss, one study devised a transmitter including a technique to turn it on or off while the EV is moving [12], and an optimal receiver design resulted in a 50% higher power transfer efficiency [13]. There is a critical need for research addressing ways to respond to the necessities of electromagnetic safety [14–16] and pollution [17], which, in some cases, results from the high power transferred wirelessly between the coils. Wireless

power technology was thus extended as a key to removing the charging threats related to plug-in EVs and cable-associated problems [18]. Additionally, MPPT control embedded in wireless transfer systems with solar power arrays can enhance the power gained in a noticeable way [19]. As well as the abovementioned advantages of the dynamic wireless charging technique, there are issues that must be solved and obstacles overcome to enhance the overall performance.

These problems can be summarized as an insufficient understanding of the effect of motion on the magnetic field [20]. The energy delivered on the rail path can be lowered by employing an efficient coupling technique, thus making the system more stable and efficient [21,22]. To obtain increased stability and reduce power losses, a soft switching technique (SWT) is generally employed. This can be achieved by using a control method with a double closed-loop [23]. The primary challenge posed by the proposed technique is the movement of the receiver coil due to the changing load. This can be resolved by using a high-level control to enhance the efficiency of the power transfer [24–26]. Moreover, with the intention of improving its action, the shape of the transmitter coil can be designed to be circular or rectangular [27,28]. Some of the preliminary results of these investigations are reported in [29–32].

This study investigated several problems. (a) We explored how to design a modern wireless EV charging system that enables dynamic wireless electric vehicle charging “on the go” while addressing the following issues: transmission of electrical energy without the use of conductors or wires; an efficient means of power transfer from one place to another through space; safe, convenient and reliable power transmission; the desire for a clean and safe environment; the fast-growing market for electric vehicles. (b) We aimed to provide a reliable solution for the related issues concerning plug-in electric vehicles, such as low mileage, extensive charging times, cable-related problems and battery-size problems. (c) We investigated how to overcome the problem of unstable output during the dynamic charging process by using different control techniques to eliminate the variation in voltage resulting from the varied spacing existing between the transmitter and receiving coils and enhance the robustness of the dynamic wireless power transfer system. (d) Finally, we studied and investigated the applicability of using PV generation and MPPT to track the maximum power from the PV array.

To address the described problems and provide answers to our research question related to wireless electric vehicle charging “on the go”, this study utilized modern electrical modeling, an accumulative enhancement design approach and comparative control techniques for optimal wireless electric vehicle battery charging. The research team decided on magnetic resonance coupling, among other techniques, due to its ability to transfer power efficiently without the use of cables and increase the efficiency of wirelessly transferring energy [33–37]. The effectiveness of the wireless-based resonance charging system was thus investigated through simulation results. The simulation results showed the effects of parameters such as the inductor, capacitor, load and coupling coefficient on efficiency. The energy transfer efficiency depends on the operating frequency, coupling factor and other circuit components. The results showed that the energy transfer efficiency of the resonance-based wireless energy transfer system could reach a maximum of 92.1%. Additionally, we demonstrate that the dynamic wireless power system is one of the most effective solutions as it can supply energy to the electric vehicle while moving. This system could be utilized underneath roads as fixed power tracks to transfer power wirelessly as the vehicles move on the roads [38–42].

This technique can not only improve the attraction of electric vehicles for potential investors but may also lead to improved sustainability in electric vehicle energy. For instance, the vehicle-to-grid idea enhances the distribution of the generated energy, which can be raised to another level with wireless power transfer in electric vehicles. The research team developed a proper solution for unstable output during the dynamic charging process by using different control techniques and taking into consideration the utilization of the average PV generation, which would not be related to the location where high efficiency is

achieved. To achieve this goal, a design for dynamic wireless power transfer was developed to ensure charging when the vehicle is in motion. This was undertaken by developing a three-level PI controller to eliminate the variation in voltage resulting from the varied spacing existing between the transmitter and receiving coils. Additionally, a fuzzy logic controller was used to enhance the stability of the voltage and current delivered to the battery. Then, a neuro-fuzzy controller was used to enhance the robustness of the dynamic wireless power transfer system. MPPT was used to track the maximum voltage and current from the PV array, along with other electronic power converters for impedance-matching purposes. A comparison between different control techniques and validation using real-time simulator equipment were undertaken to ensure the most robust control. Stability analysis of the closed-loop system was carried out and the system was found to be asymptotically stable for most validation purposes. However, more research and investigations are needed, especially with regard to the distance and angle between the Tx and Rx receivers, as has been proposed for future experimental work by the authors and other teams.

The rest of the paper is ordered as follows. In Sections 2 and 3, the proposed approaches are presented. In Section 4, the other simulation models are discussed along with the results. Then, the validation and stability analysis are described in Sections 5 and 6, respectively. A discussion of the findings is presented in Section 7, and Section 8 presents the work's limitations and proposed future work. The various procedures are illustrated in Figure 1.

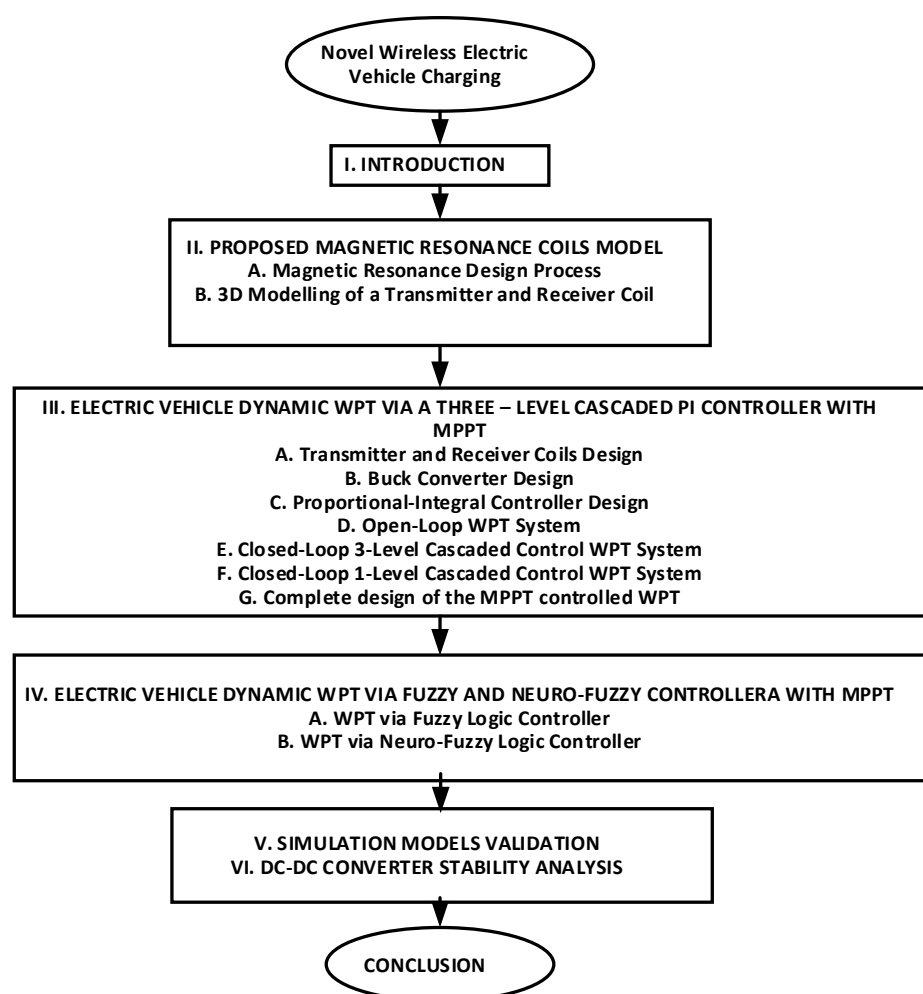


Figure 1. Overall flowchart of procedures.

2. Proposed Magnetic Resonance Coil Model

Magnetic induction functions through a transmitting coil that creates a magnetic field and a receiver coil inside the magnetic field that induces a current in the coils. The resonance improves efficiency significantly by conducting the electromagnetic field to the receiver resonating at a corresponding frequency [43], and in this way increasing the charging distance compared to other approaches, making it a respectable candidate for future developments. The primary coil of the magnetic resonance coupling circuit is utilized as a transmitting coil underneath the ground and the secondary coil. Wireless electric power transfer takes place between the coil beneath the ground and the one straddling the framework of the EV. To transfer power efficiently, resonant compensation is utilized to reduce the inductance leakage and improve the coupling [44]. The key compensation constructions for the magnetic resonant WPT technique are PP, SS and PS-SP systems [45,46].

2.1. Magnetic Resonance Design Process

The series resonance circuit includes an inductor, capacitor and resistor. Therefore, it is referred to as a series RLC circuit. The RLC impedance Z is measured in ohms using Equation (1):

$$Z = R + j\omega L + \frac{1}{j\omega C} \quad (1)$$

where R is the resistance in ohms and ω is the angular frequency in rad/sec. However, L is the inductor in henrys (H) and C is the capacitance in farads (F).

Resonance happens when the mean electromagnetic energy stored in the inductor (W_m) is equivalent to the mean electric energy deposited in the capacitor (W_e) [4,47]:

$$W_m = \frac{1}{4}|I|^2 L \quad (2)$$

$$W_e = \frac{1}{4}|I|^2 \frac{1}{\omega^2 C} \quad (3)$$

At resonance, $W_e = W_m$ and $Z_{in} = R$, resulting in the resonance frequency as shown in Equation (4):

$$\omega_o = \frac{1}{\sqrt{LC}} \quad (4)$$

The quality factor (Q) is the quantity of the losses that ensue in a resonant circuit and it is calculated as follows:

$$Q = \omega_o \frac{\text{stored energy in } L \text{ and } C}{\text{average power dissipated}} = \omega_o \frac{W_m + W_e}{P_{loss}} \quad (5)$$

where P_{loss} is the power that the resistor R disintegrates [4,46]:

$$Power_{loss} = \frac{1}{2}|I|^2 R \quad (6)$$

At resonance,

$$Q = \omega_o \frac{2W_e}{P_{loss}} = \omega_o \frac{2 \cdot \frac{1}{4}|I|^2 L}{\frac{1}{2}|I|^2 R} = \frac{\omega_o L}{R} \quad (7)$$

$$Q = \omega_o \frac{2W_m}{P_{loss}} = \omega_o \frac{2 \cdot \frac{1}{4}|I|^2 \frac{1}{\omega_o^2 C}}{\frac{1}{2}|I|^2 R} = \frac{1}{\omega_o RC} \quad (8)$$

Equivalent circuit for magnetic resonance is shown in Figure 2. For parallel resonance, energy is stored in the inductor and capacitor. At resonance, the whole reactive power is equivalent to zero:

$$Z_{in} = \left(\frac{1}{R} + j\omega C + \frac{1}{j\omega L} \right)^{-1} \quad (9)$$

$$P_{loss} = \frac{1}{2} \frac{|V|^2}{R} \quad (10)$$

$$W_m = \frac{|V|^2}{4\omega^2 L} \quad (11)$$

$$W_e = \frac{1}{4} |V|^2 C \quad (12)$$

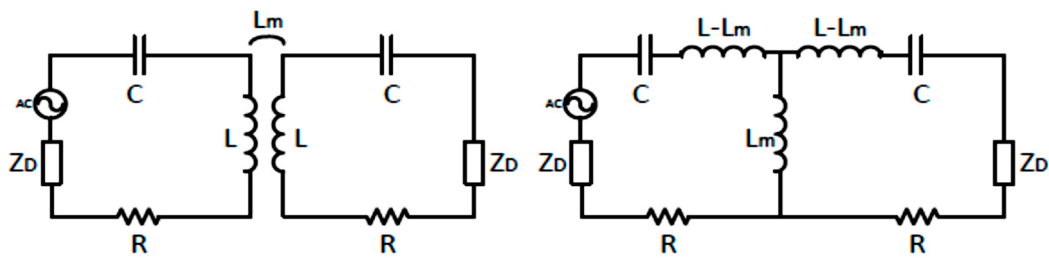


Figure 2. Equivalent circuit for magnetic resonance.

At resonance, $W_e = W_m$ and $Z_{in} = R$:

$$\omega_o = \frac{1}{\sqrt{LC}} \quad (13)$$

$$Q = \omega_o \frac{2W_m}{P_{loss}} = \omega_o \frac{2 \cdot \frac{1}{4} |V|^2 \frac{1}{\omega_o^2 L}}{\frac{1}{2} \frac{|V|^2}{R}} = \frac{R}{\omega_o L} \quad (14)$$

$$Q = \omega_o \frac{2W_e}{P_{loss}} = \omega_o \frac{2 \cdot \frac{1}{4} |V|^2 C}{\frac{1}{2} \frac{|V|^2}{R}} = \omega_o RC \quad (15)$$

As shown in the circuit above [48], at resonance the reactance is equivalent to zero, as in Equation (16). However, the coupling coefficient K can be evaluated:

$$\frac{1}{\omega L_m} + \frac{2}{\omega(L - L_m) - \frac{1}{\omega C}} = 0 \quad (16)$$

$$W_m = \frac{\omega_o}{\sqrt{1+k}} = \frac{1}{(\sqrt{L + L_m}) + C} \quad (17)$$

$$W_e = \frac{\omega_o}{\sqrt{1-k}} = \frac{1}{(\sqrt{L - L_m}) + C} \quad (18)$$

$$K = \frac{L_m}{L} = \frac{w_e^2 - w_m^2}{w_e^2 + w_m^2} \quad (19)$$

The efficiency was calculated by using the reflection and transmission coefficients in Equations (20) and (21), respectively [4,46]:

$$\eta_{11} = S_{11}^2 \times 100\% \quad (20)$$

$$\eta_{21} = S_{21}^2 \times 100\% \quad (21)$$

where S_{11} is the reflection coefficient and S_{21} is the transmission coefficient, which can be evaluated using Equation (22) [46]:

$$S_{21}^2 = \frac{2jL_m Z_o \omega}{L_m^2 \omega^2 - \left(\omega L - \frac{1}{\omega C}\right)^2 + 2jZ_o \left(\omega L - \frac{1}{\omega C}\right) + Z_o^2} \quad (22)$$

The power loss was calculated using Equations (6) and (10). However, the efficiency was calculated using Equations (20)–(22). The 3D coils were modeled and designed based on the efficiency testing described in [46] in order for the misalignment ratio and the air gap ratio to be within the range of 0:0.25 and thus obtain an efficiency of around 90% or more. Additionally, we considered the theoretical and experimental results described in [46], where efficiency is treated as a function of wireless power transfer distance, in order to keep the efficiency at around or more than 90% with respect to the coupling coefficient and the wireless power distance. The results achieved were obtained after many trials in which these factors were adjusted in ANSYS Maxwell and Simplorer by altering the circuit components until the optimal efficiency value was reached. Figure 3 shows the effect of coupling coefficient (K) variation with respect to the efficiency and frequency.

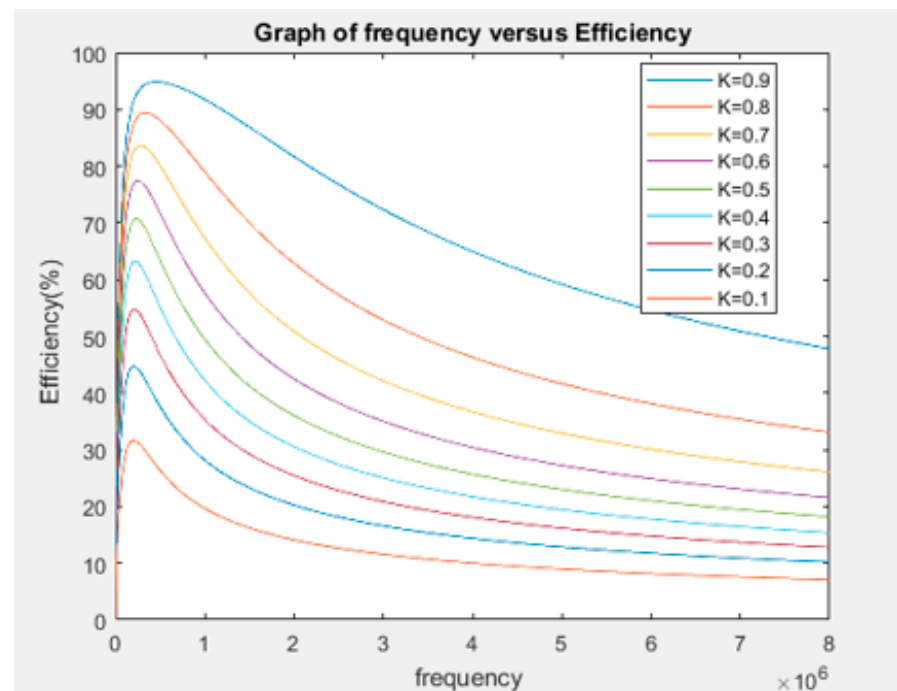


Figure 3. Effect of varying the coupling coefficient with respect to efficiency and frequency.

2.2. Three-Dimensional Modeling of Transmitting and Receiving Coils

The 3D modeling of the transmitter and receiving coils was completed using ANSYS Maxwell software. The two coils were made of copper and separated by distances of 100 mm. A translucent quadrilateral plate was positioned in between the transmitting and receiving coils to seize the magnetic field that is produced between the coils. Two lids were linked to the transmitter and receiver respectively for current excitation. The lids were composed of copper of 500 mm in length and 1 mm in thickness. A section measuring 1000 mm³ and comprised of air was where the simulations would happen. The solution devised in ANSYS Maxwell involved forming a limit for the placements of the two coils. Figure 4 shows the design of the transmitter and receiver coils.

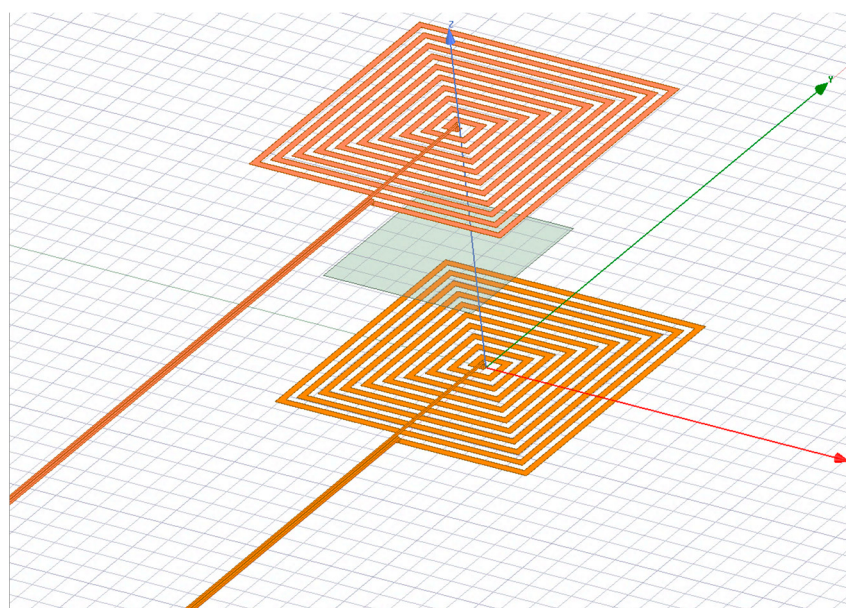


Figure 4. Design of the transmitter and receiver coils.

Table 1 lists the properties of the coil and the rectangular plate.

Table 1. Properties of the coil and the rectangular plate.

Properties of the Coil				
Name	Value	Unit	Evaluated Value	Description
Version	2.0			
X pos	0	mm	0 mm	X position of a start point
Y pos	0	mm	0 mm	Y position of a start point
Distance	6	mm	6 mm	Distance between turns
Turns	10			Number of turns
Width	3	mm	3 mm	The width of the spiral coil
Thickness	3	mil	3 mil	The thickness of the spiral coil
Properties of the Rectangular Plate				
Name	Value	Unit	Evaluated Value	
Command	Create rectangle			
Coordinate system	Global			
Position	50, 0, 70	mm	50 mm, 0 mm, 70 mm	
Axis	Z			
X size	−70	mm	−70 mm	
Y size	−70	mm	−70 mm	

Figure 5 displays the transmitter coil and the receiver coil in ANSYS Maxwell, along with the coils' magnetic fields. The two coils had equivalent sizes in order to bounce a better coupling coefficient. In Figure 4, it can be seen that the magnetic field between the two coils will be reduced as the distance between them increases. The coupling coefficient of the transmitter and receiver coils is 1 since it is self-coupling. It was found that the coupling coefficient between the transmitter and the receiver would increase as the space between them becomes smaller and smaller. From Figure 6, it is obvious that the quantity of mutual inductance between the transmitter and the receiver coils will undergo a little alteration since each is the summation of its self-inductance and the mutual inductance of the other coil. When the other coil moves closer due to the definition of the track of the excitation current, the rate is altered a little because there is still some flux.

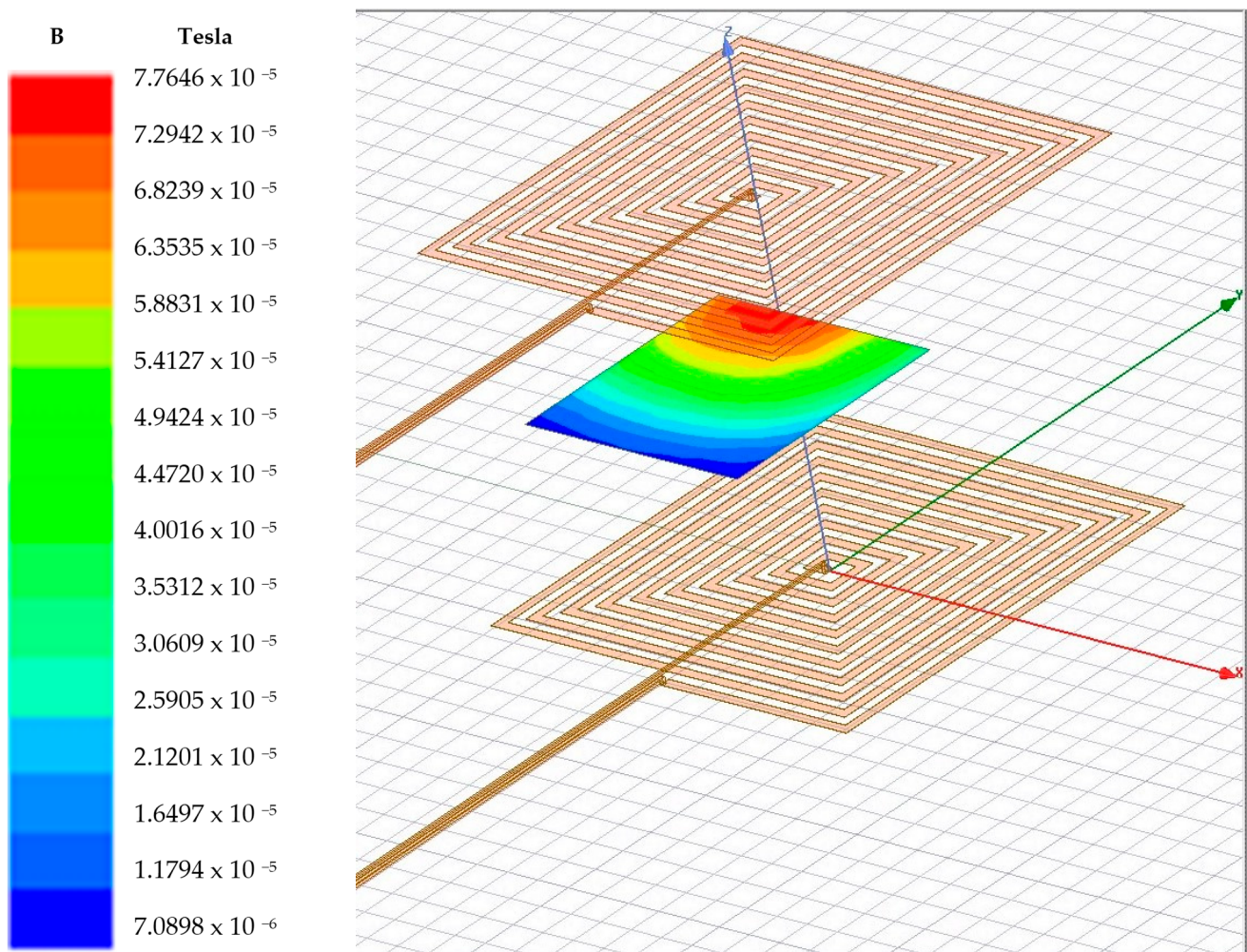


Figure 5. Magnetic field between the transmitting and receiving coils.

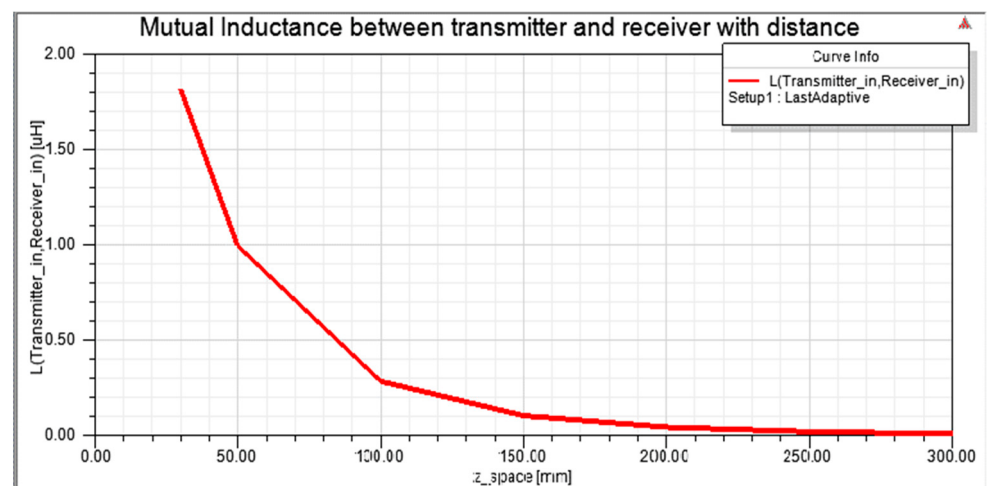


Figure 6. Mutual inductance between transmitter and receiver coils.

The design of the system circuit was developed in ANSYS Simplorer, including the design of the transmitter and receiver spirals from ANSYS Maxwell. The implemented Maxwell design included the dynamic inductance data about the coils' construction, which exported into the Simplorer as L parameters. At the transmitting side, in order to obtain maximum power transported to the transmitter, the resonance capacitor was linked in

series with the inductor, thus maximizing the current flowing through the inductor of the coil. At the receiving side, the capacitor was linked in parallel with the inductor in order to maximize the voltage drop in the load resistor. To identify the efficiency of the system, an AC examination was undertaken with a starting frequency of 1 kHz and a stopping frequency of 1 MHz. Figure 6 displays the whole system of the magnetic resonance WPT circuit planned in Maxwell and Simplorer. The circuit contains a power source, transmitting coil, rectifier, inverter, receiving coil and EV battery as a load.

Figure 7 shows that the maximum transfer efficiency would reach around 92.1248% at a resonance frequency of 0.3542 MHz with spacing equaling 100 mm. The space between the coils was adjusted around this number in ANSYS, with a coupling coefficient around 0.9. After careful investigation of the circuit's components and many trials, the values mentioned in Table 2 were chosen to achieve the desired efficiency.

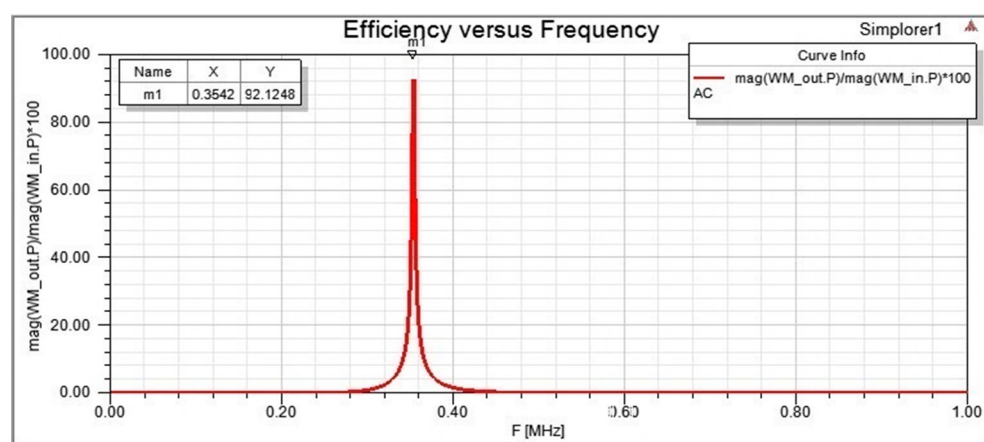


Figure 7. System efficiency and frequency from ANSYS Simplorer.

Table 2. The circuit components values.

C_1	900 μF
C_2	7 μF
R_1	7.1 $\text{m}\Omega$
R_2	4 $\text{m}\Omega$
C_{tx}	1.6 μF
C_{rx}	4.7 μF

From Figure 8, the maximum transfer efficiency could be estimated to reach approximately 92.1% at a resonance frequency of around 0.35 MHz under the constraints of the required spacing. This indicates that the magnetic resonance method is a very efficient means of transferring power wirelessly over a mid-range distance compared to other wireless techniques. The 3D rectangular plot helped in estimating the transfer efficiency of the coils, and not the whole system, with respect to the spacing between the coils and their operating frequency. The transient analysis was undertaken to facilitate the frequency analysis of the system. Below are the values for the setup.

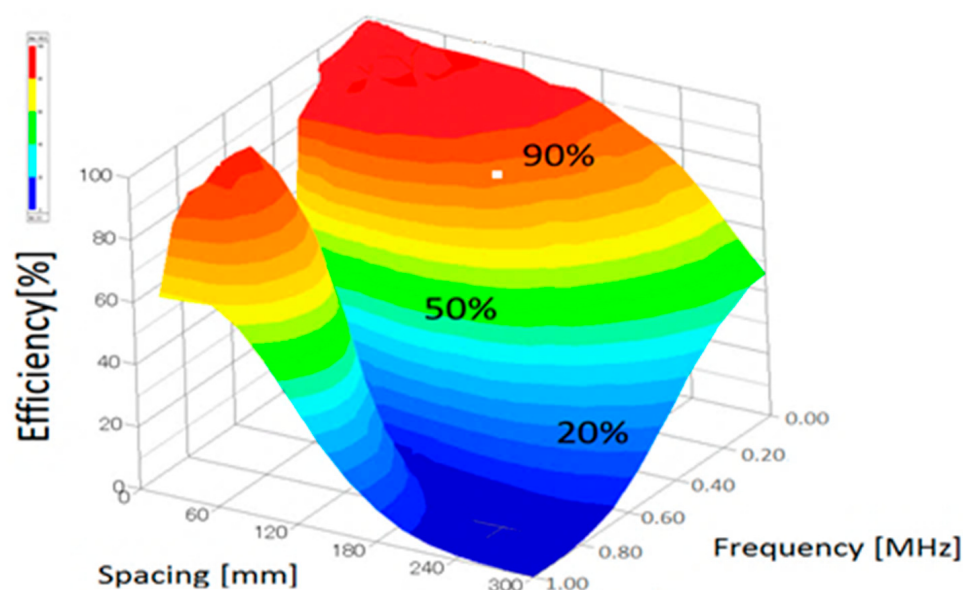


Figure 8. Three-dimensional quadrilateral graph of efficiency, spacing and frequency.

The 3D quadrilateral plot shown in Figure 8 and the plot in Figure 7 aid in proving the efficiency of the system with regard to the layout between the coils and their functioning frequency, the efficiency being around 92.1% with space equaling 100 mm and the frequency around 0.35 MHz. To facilitate the frequency analysis of the system, a transient analysis was undertaken with an end time of 0.5 ms, minimum time step of 0.01 μ s and maximum time step of 100 μ s. Several Bode plots showing the spacing along with the input power, output power, input/output voltage and input/output current, respectively, were also obtained. The ANSYS analysis indicated that the input/output voltage and current were in the form of sinusoidal waves. Table 3 shows further numerical results obtained from the ANSYS simulation. In order to avoid incorrect conclusions and to further validate the obtained efficiency with respect to the input and output voltages and current, Figure 9 from ANSYS Simplorer depicts almost the same efficiency along with the system steady-state waveforms.

Table 3. Numerical results for mutual inductances between the transmitting coil and receiving coil with the coupling coefficient.

Z_Space (mm)	L (Receiver_in, Receiver_in) (μ H) Setup 1: Last Adaptive	L (Receiver_in, Transmitter_in) (μ H) Setup 1: Last Adaptive	CpCoef (Receiver_in, Transmitter_in) Setup 1: Last Adaptive	L (Transmitter_in, Transmitter_in) (μ H) Setup 1: Last Adaptive
90	6.342	0.359	0.906	1.342
100	6.344	0.287	0.896	1.332
120	6.360	0.188	0.849	1.365
150	6.364	0.106	0.817	1.387
180	6.379	0.0636	0.749	1.350
191	6.364	0.053	0.718	1.341
200	6.349	0.0464	0.707	1.359
210	6.369	0.0399	0.679	1.362
240	6.369	0.026	0.634	1.369
250	6.342	0.023	0.604	1.352
270	6.373	0.017	0.569	1.384
300	6.356	0.012	0.510	1.355

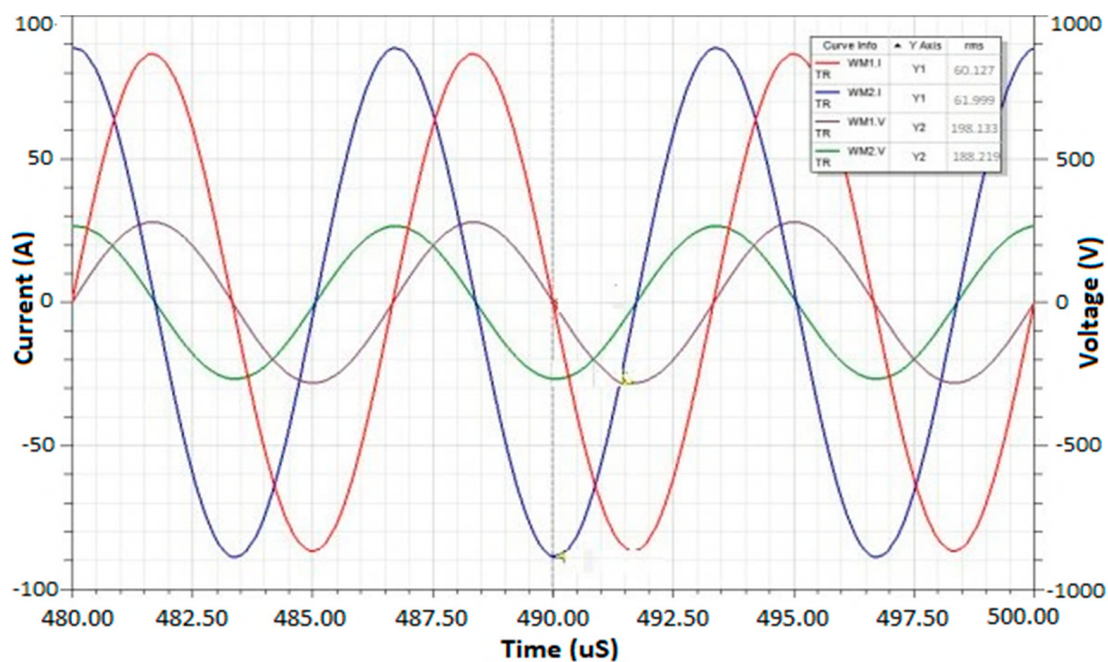


Figure 9. Input current (in blue), output current (in red), input voltage (in purple) and output voltage (in green).

It can be observed from Figure 9 that the input/output voltage and current show steady-state waveforms. The output current was 60.127 (rms) A, the input current was 61.999 (rms) A, the input voltage was 198.133 (rms) V and the output voltage was 188.219 (rms) V. Based on the ratio of the input and output powers, the efficiency was approximately 92.128%, which was almost the same as the value obtained previously but with a small difference due to approximation and/or accumulation iteration errors in ANSYS after running many simulations. The overall system efficiency was estimated to be a little bit less than the wireless power transfer efficiency based on the measurement from the Simulink simulation model of 91.4735. If the component's losses are ignored, the efficiency would be almost the same because it includes the losses of electronic power converters and controllers. The main goal was to focus on the wireless transfer and the unstable output under dynamic charging. The losses were minimal in the simulation. It would be more realistic and practical to undertake this analysis based on an experimental system, which is what we are working on right now. We included this under the proposed future work for experimental and efficiency analysis of the overall system based on real data and under different scenarios.

3. EV Dynamic WPT via a Three-Level Cascaded PI Controller with MPPT

The main goal of this part of the study was to construct the whole system based on the ANSYS results in Simulink and to validate it utilizing a real-time simulator. A further goal was to use solar power to charge the station and MPPT and different control techniques to enhance the dynamic response when the vehicle is charging while in motion. Figure 10 presents a schematic diagram for the overall system including its controller.

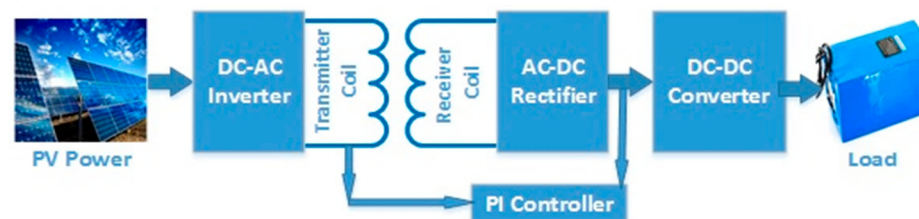


Figure 10. Schematic diagram for the overall system.

The complete wireless power structure was designed with a battery-load source. The transmitting and receiving coils were employed at a resonant frequency of 60 Hz. The induced voltage at the receiving coil of the system is contingent on the mutual link between the transmitting coil and the receiver end and their subjection to the parting between the coils and the coil inductance. As the distance between the two coils becomes greater, the voltage at the receiving-coil end of the transmission decreases. To compensate for the discrepancy in the voltage, a three-level PI controller was devised together with the closed loop of the scheme. At this point, three loops were employed inside each other. The most external loop controlled the DC voltage, the middle control loop managed the voltage to the wireless circuit and the inmost control loop controlled the current to the wireless circuit. The output of the scheme was realized in such a way as to sustain a constant voltage of 12 V and 5 A, whereas the input voltage ranged from 80 V to 160 V. Additionally, an MPPT controller was combined with the system. The projected system contained a photovoltaic array, a boost DC–DC converter, a transmitting coil, an inverter, a receiving coil, a buck converter, a rectifier and batteries as loads. The MPPT controller was implemented to track the highest required voltage and current from the photovoltaic (PV) array and charge a battery with the maximum power-point voltage, which was calculated as 61 V. Correspondingly, the stability of the closed-loop system with the three-level PI controller was examined, and the system was found to be asymptotically stable. A wireless transfer system utilizing a three-level cascaded MPPT control was proposed and designed. Employment of MPPT involves a procedure that typically samples voltages and currents and fluctuates the duty ratio in sequence as needed. The implemented MPPT controller utilized the “perturb and observe” technique, in which the voltage differs by a small amount from the PV array and power is restrained. This discrepancy lasts until the power stops increasing.

3.1. Transmitter and Receiver Coils Design

The voltage output of the solar panels is transformed to the needed AC frequency by the inverter circuit switch at an adequate frequency in order to make the transmitter and the receiver coils resonate correspondingly. The high AC frequency is transported to the transmitter coil, which then induces a magnetic field that is received by the receiver coil through electromagnetic induction. Subsequently, the coil creates an EMF. This, in turn, requires a rectifier and a DC–DC buck converter, as the battery necessitates a DC voltage to function. A three-level cascaded PI controller aids in controlling the discrepancy of the voltage induced at the receiving coil in order to facilitate a steady voltage output to the load battery. The output of the inverter energizes the transmitting coil, the functioning frequency of which is 60 Hz. The coil’s inductance was calculated using the Wheeler’s long-coil formula [49], as shown in Equation (23).

$$L = \frac{r^2 N^2}{9r + 10l} \quad (23)$$

where l is the air-core length and r is the radius of the coil in inches. A length of 9.5 cm, width of 4 mm and diameter of 8.5 cm were presumed in this study. From the previous parameters specified, an inductance of $L = 19.1 \mu\text{H}$ and a capacitance of $C = 0.3 \mu\text{F}$ were supposed.

The receiving coil was designed to operate at a similar resonance frequency as the transmitting coil. A flat-spiral spring with an inner diameter r (D_i) of 1.15 cm, a thickness (w) of 1 mm, a space between the coils (s) of 0.54 mm and 45 turns ($N = 45$) was assumed for the receiving coil. The calculation of the coil’s inductance was undertaken by means of Equations (24) and (25) [50]:

$$\frac{N^2 \times A^2}{30 \times A - 11 \times D} \quad (24)$$

$$\frac{D_i + N(w + s)}{2} \quad (25)$$

The coil's inductance was around 94.5 μH and its capacitance was 0.02 μF . The mutual inductance between the primary and the secondary coil was specified as $\sqrt{kL_1L_2}$. The coupling coefficient k ranged between 0.2 and 0.5. The value of k utilized in the design of the mutual inductance between the two coils was 0.2, and a mutual inductance of 12 μH was calculated from the previous expression.

3.2. Buck Converter Design

The key components of the buck converter circuit are the diode, inductor, capacitor, pulsing generation circuit and the MOSFET switches. The output of the buck converter is given as $V_{\text{out}} = D \cdot V_{\text{in}}$, where D = duty cycle assuming a 16% duty cycle with $V_{\text{in}} = 76 \text{ V}$ and $V_{\text{out}} = 12 \text{ V}$. The output current $I_{\text{out}} = V_{\text{out}}/R$. The inductance of the buck converter is presented in Equation (26).

$$L = \frac{V \cdot D}{F_{\text{sw}} \cdot D I_L} \quad (26)$$

where $V = 76 \text{ V}$; F_{sw} is the switching frequency, which equals 60 Hz; $D I_L = 4\%$ of the output current; and $L = 4.8 \text{ mH}$.

$$C = \frac{D I_L}{8 F_{\text{sw}} \cdot D V_{\text{out}}} \quad (27)$$

Assuming 4% voltage ripple = 0.8 V, $C = 2 \mu\text{F}$.

3.3. Proportional-Integral Controller Design

In this section we present the self-tuning technique for the design of the proportional-integral (PI) controller, for which we utilized Equations (28) and (29). The controller helps to achieve a constant voltage under several varieties of input voltage.

$$Dc(s) = K_p + \frac{K_I}{s} + K_D s \quad (28)$$

$$U(t) = K_p e(t) + K_I \int_{t_0}^t e(t) dt + K_D e(t) \quad (29)$$

where K_p is the system's gain, K_I is the integral feedback to limit the steady state error and K_D is the derivative feedback to limit overshoot.

The technique utilized to tune the PI controller was trial and error. K_i was set to zero while K_p was amplified until the system oscillated. The value at which K_p oscillated was 100. At this oscillating point, K_i became diverse until the system stopped oscillating and reached a steady state.

3.4. Open-Loop WPT System

The block diagram for the open-loop system in the WPT system is shown in Figure 11 and the open-loop simulation results are shown in Figure 12. The simulation of the system was undertaken in MATLAB Simulink. The buck converter's output was found to be 12 V and an output current of 5 A was obtained with a lot of undulations and non-robustness. The effects of the change at the input side of the buck converter were then transported in order to recognize the effects for the controller at the receiving coil. When altering the input voltage from 120 V to 80 V, this resulted in output voltage changes of 6 V to 17 V and an output current change of around 5 A. The input into the buck converter was supposed to fluctuate as the space between the two coils changed. Figure 12 shows the simulation results for a variable input.

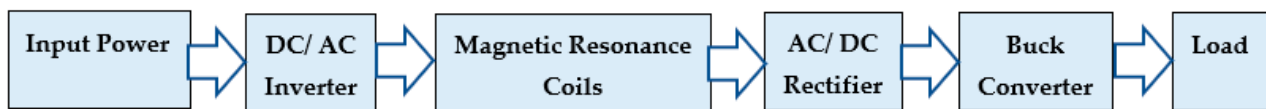


Figure 11. Open-loop WPT block diagram.

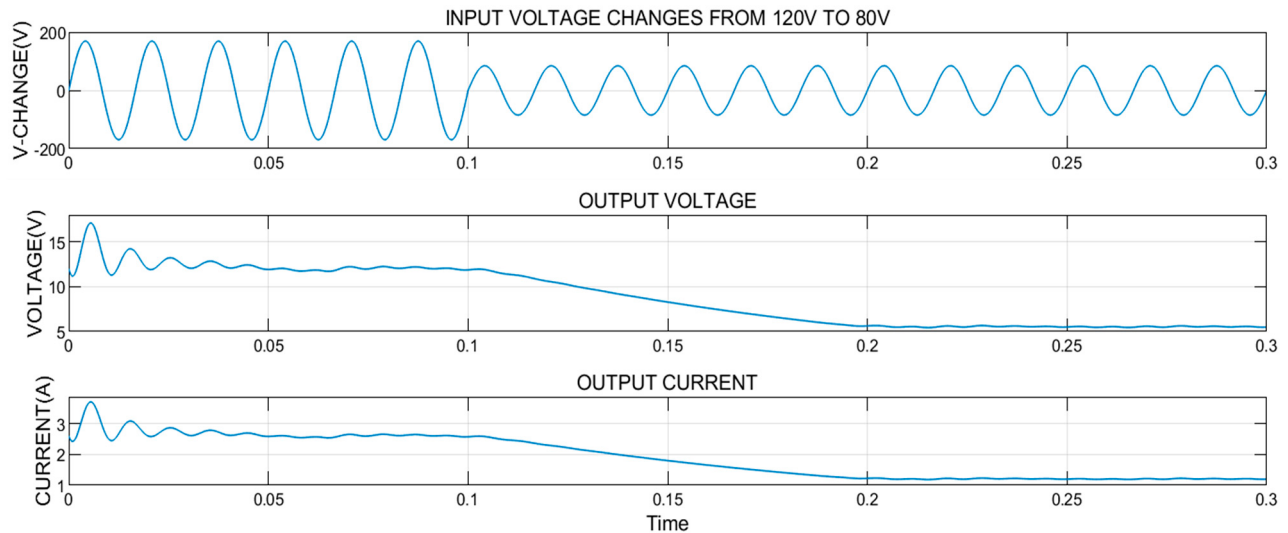


Figure 12. Open-loop simulation results for change in input.

3.5. Closed-Loop Three-Level Cascaded Control WPT System

Figures 10 and 11 show the closed-loop circuit for the three-level cascaded controllers. The outermost loop controls the DC voltage. The middle loop controls the input voltage to the transmitting coil and the inmost loop controls the receiving circuit's current. It can be seen from Figure 13 that the proportional-integral controller creates a fixed voltage of 12 V and a fixed current of 5 A when the input voltages change from 120 V to 80 V to 160 V to 80 V in order to recognize the stability.

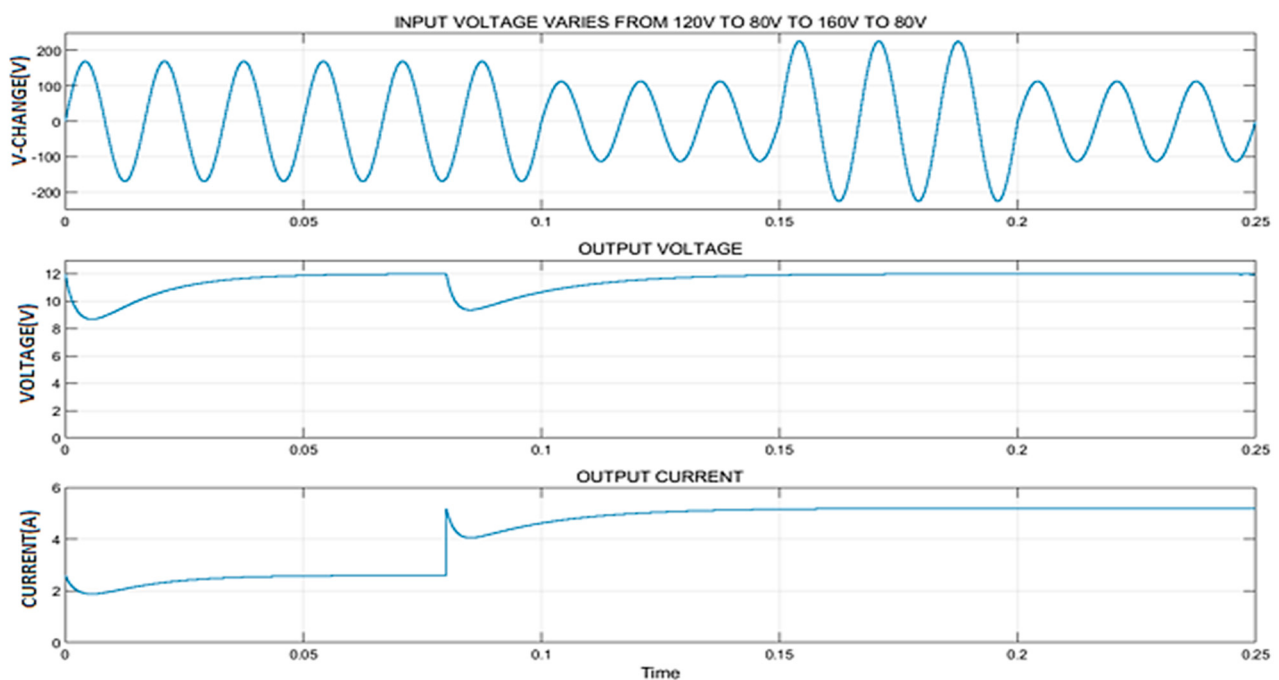


Figure 13. Closed-loop three-level cascaded controller simulation result.

3.6. Closed-Loop Single-Level Cascaded Control WPT System

Figures 10 and 11 were revisited again to replace the three-level cascaded control with a single-level PI controller and compare their outcomes. A single-level PI controller was considered, in which the PI controls the input voltage to the receiving coil. Figure 14 illustrates the simulation outcomes, where the changes in input voltage from 120 V to 80 V to 160 V to 80 V to 160 V result in an unstable voltage value of 15 V and an unstable current value of 3 A. Therefore, the three-level cascaded PI controller was judged to be able to produce the desired voltage and current values with better accuracy.

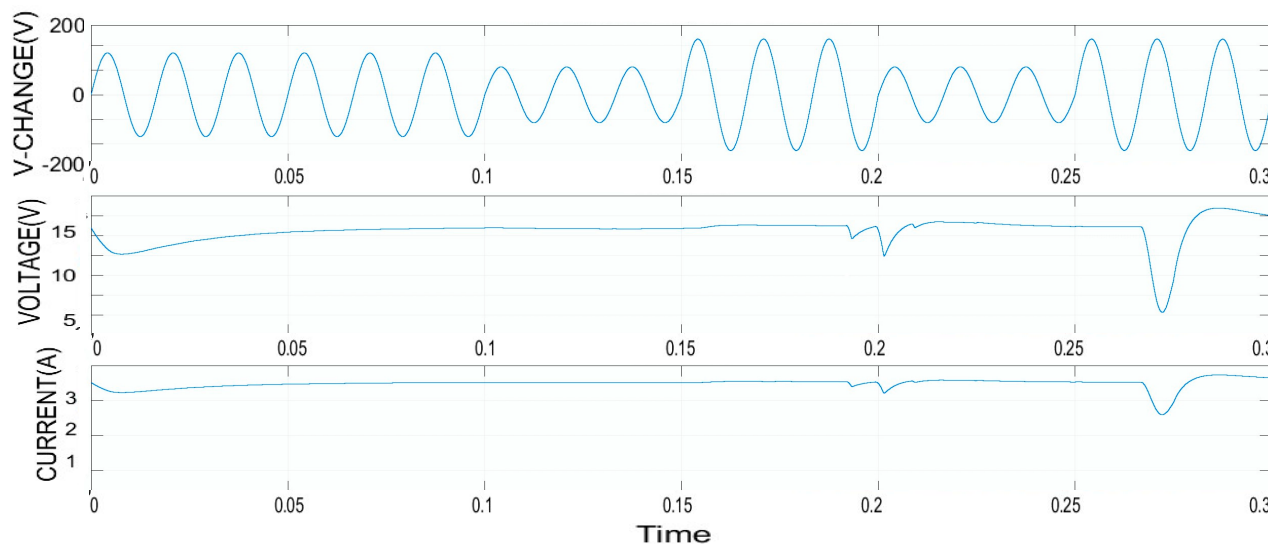


Figure 14. Closed-loop single-level simulation results.

3.7. Complete Design of the MPPT-Controlled WPT

The WPT system design with the MPPT-controlled PV panels was completed after adding the MPPT control scheme to Figures 10 and 11. It was implemented using MATLAB Simulink. MPPT assists in tracking the highest voltage and current from the solar PV array. As the solar PV panels were DC devices, the voltage from them can be transferred through the boost converter (DC–DC converter) to increase the voltage of the solar PV panel to 240 V. This is because, for MPPT to function appropriately, the source impedance must be matched with the load impedance and this results in dropping half of the source voltage crossways to the source impedance, and the load will have half of the voltage. Consequently, to address this issue and still have 120 V transported to the rectifier, the source voltage must be increased to 240 V; hence, the necessity for the boost converter. The inverter assists in changing the DC voltage back to AC voltage, which is necessary to supply the transmitting and receiving coils. The AC voltage from the receiver coil is transferred to the rectifier and then through the buck converter in order to reduce the voltage to the level required to charge the load (battery).

The characteristics of the PV module used in the simulation are shown in Table 4.

Table 4. Requirements for the PV module used.

Maximum power (P_{MPP})	30.5 (W)
Voltage at P_{MPP} (V_{MPP})	61 (V)
Current at P_{MPP} (I_{MPP})	0.5 (A)
Short-circuit current (I_{SC})	0.6 (A)
Open-circuit voltage (V_{OC})	71 (V)

Simulations were undertaken at an irradiance of 1000 W/m^2 and temperatures of 25°C and 40°C . The results indicated that the output power of the PV array was 30.5 W, the voltage was 61 V and the current was 0.5 A. The voltage and current were controlled

by the second-level voltage-current controller. The receiver-rectified side was regulated by the second-level voltage-current controller. The initial state of the battery's charge was 40%, the battery current was negative for charging and the battery voltage was ~12 V. Figures 15 and 16 show that the V-I and P-V characteristics of the PV module were reached at constant temperatures of 25 °C and 40 °C and at 1000 W/m² irradiance.

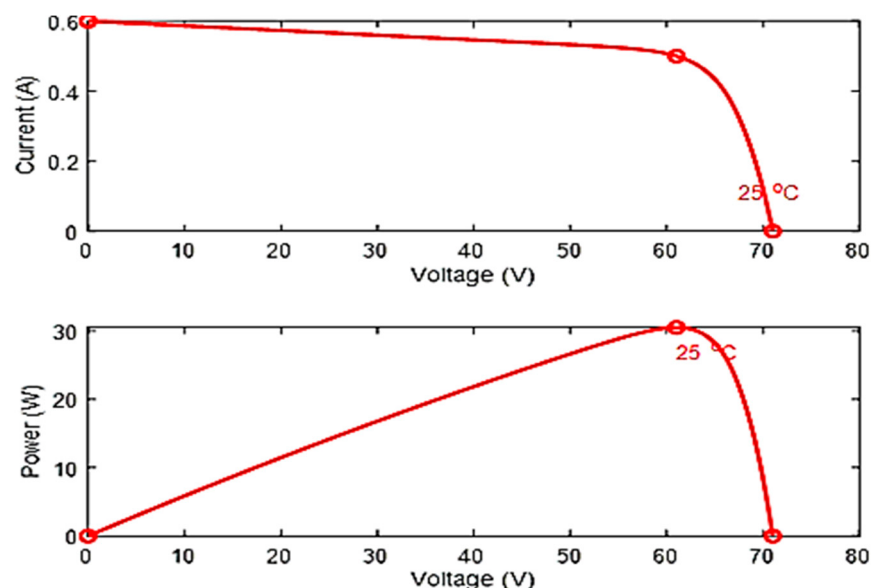


Figure 15. V-I and P-I characteristics at 25 °C.

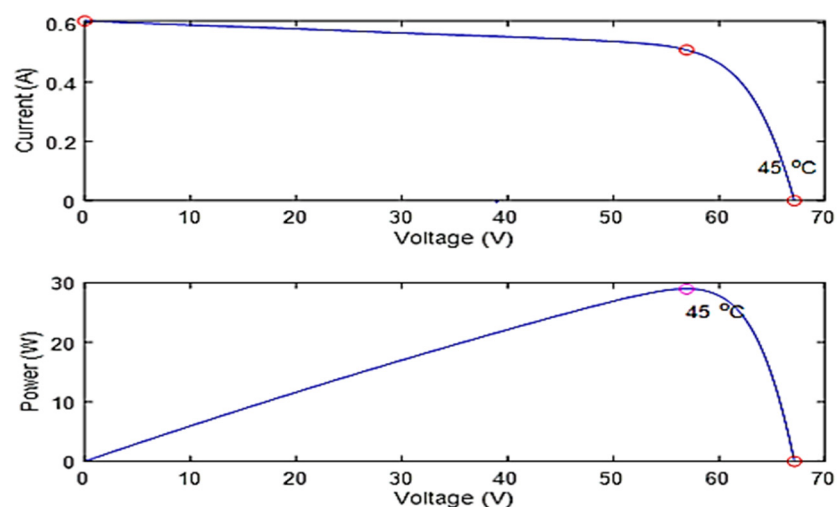


Figure 16. V-I and P-I characteristics at 40 °C.

Further simulations were undertaken in MATLAB Simulink at an irradiance of 1000 W/m² and temperatures of 25 °C and 40 °C. The results in Figures 17 and 18 show that the voltage was 61.5 V, the current was 0.496 A and output power of the PV array was 30.5 W. The voltage and current were regulated by the second-level voltage-current controller. By dividing the amount of power required to charge this system by the maximum power for the PV modules, the number of required PV panels could be estimated, taking into consideration the use of other PV modules with higher power ratings in the future.

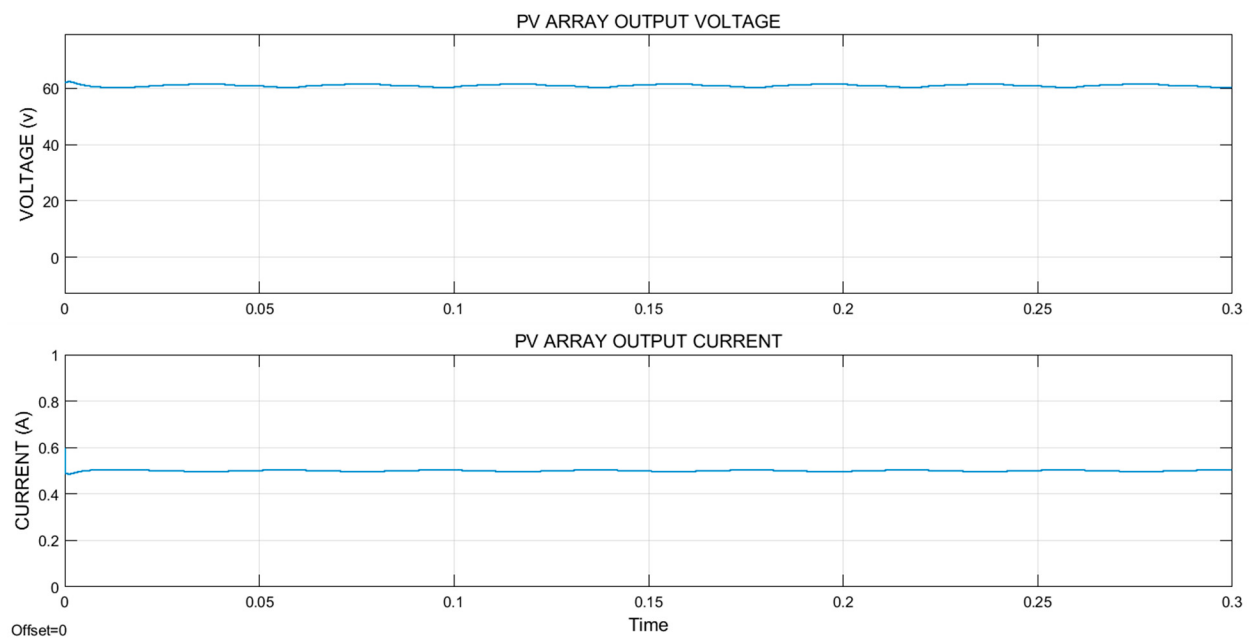


Figure 17. PV array output voltage and current.

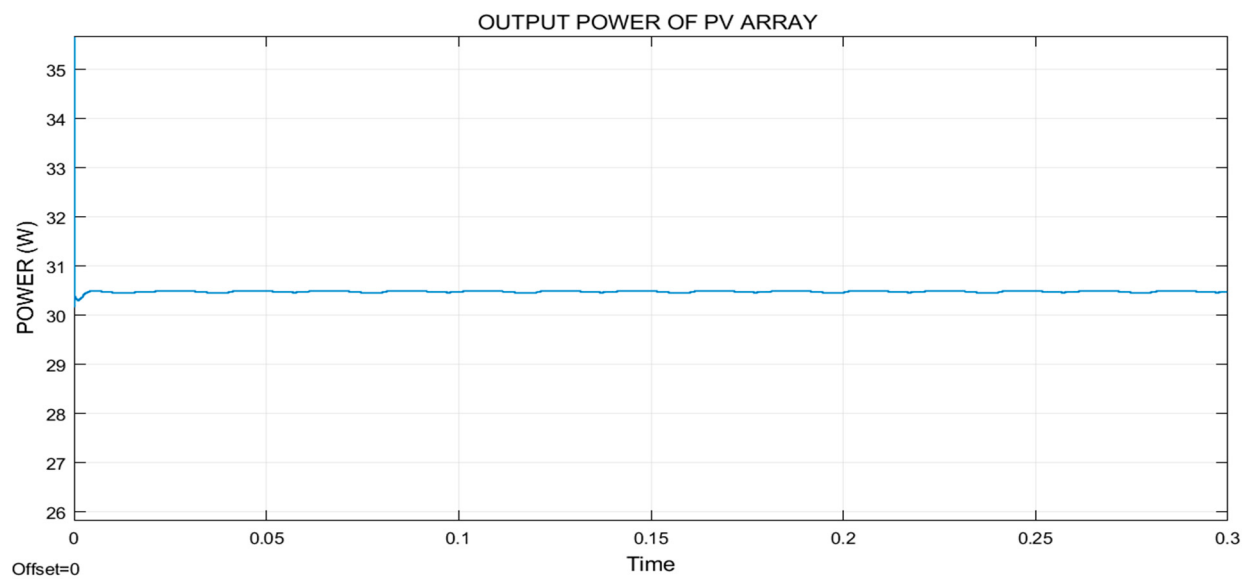


Figure 18. PV array output power.

However, the maximum power-point voltage was 61 V from the “perturb and observe”-based MPPT algorithm, as shown in Figure 19.

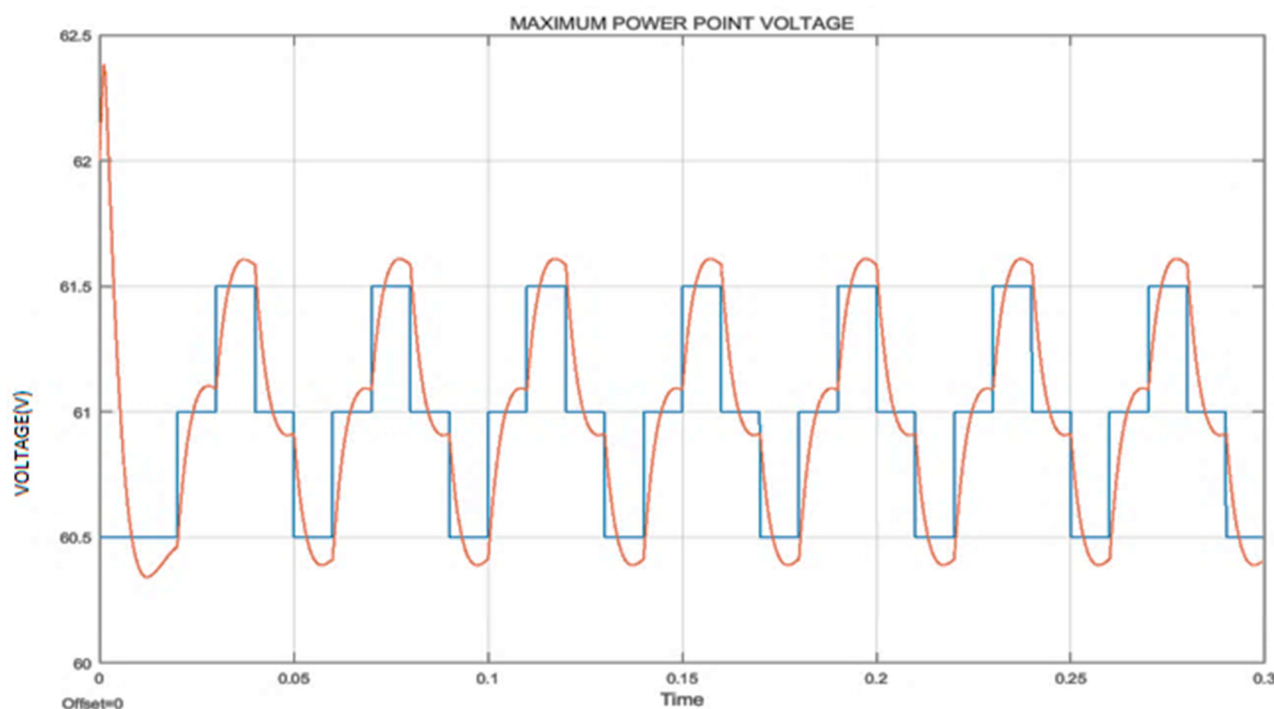


Figure 19. Maximum power-point voltage.

4. EV Dynamic WPT via Fuzzy and Neuro-Fuzzy Controllers with MPPT

4.1. WPT via Fuzzy Logic Controller

Fuzzy logic and neuro-fuzzy controllers were proposed and employed in order for the wireless electric vehicle transfer system to gain more robustness than with the PI controllers. There is one input, one output and seven membership functions for both the input and output in the planned wireless power transfer system. The input is the error in the voltage and the output is the current's reference. If the error is low, the output is reserved as low; if the error is high, the output is high. Fuzzification, fuzzy inference and defuzzification processes were carried out. The centroid method was utilized for the defuzzification. However, the fuzzy logic control rules and fuzzy surface viewer were adjusted. Figure 20 shows that the output current is low when the error in voltage is low and vice-versa. The employment of fuzzy logic enabled the features required to avoid the low disturbance.

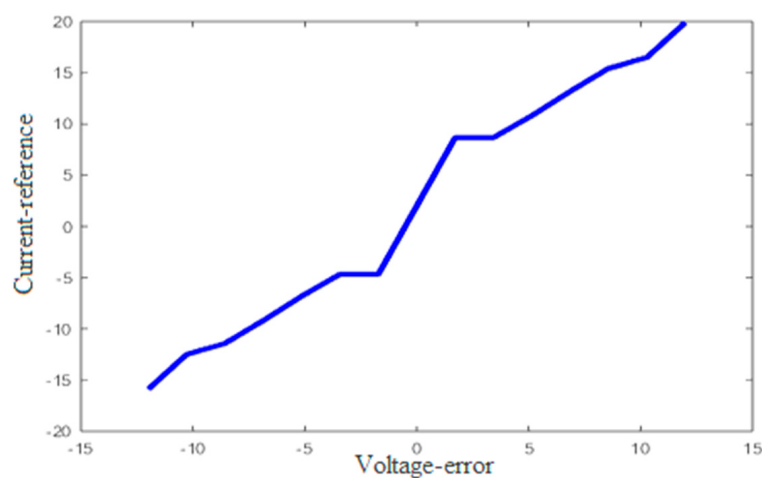


Figure 20. Fuzzy surface viewer.

The modified version of the complete EV wireless charging system including a fuzzy logic controller is described here. Figure 21 presents the simulation results associated with

the fuzzy logic controller. At $T = 0.08$ s, a 2.6 ohm resistor providing extra load resistance was coupled in parallel crosswise to the output in order to mimic the unexpected load variations in real-life applications. It was observed that the fuzzy controller achieved better characteristics when the load current increased and it was incomparable with a conventional (PI) control. It reached a specific level before achieving the rated value of 12 V. Such a voltage dip is completely unwanted in real applications, as the load's performance will be depreciated and, in some cases, failure may occur. In contrast, the fuzzy logic controller could avoid this. With the FLC, a fixed output voltage of 12 V was sustained as the load current increased. The fuzzy logic controller helped to reduce the output impedance of the buck converter and hence the voltage dip because the load addition was insignificant. Consequently, it displayed greater system robustness.

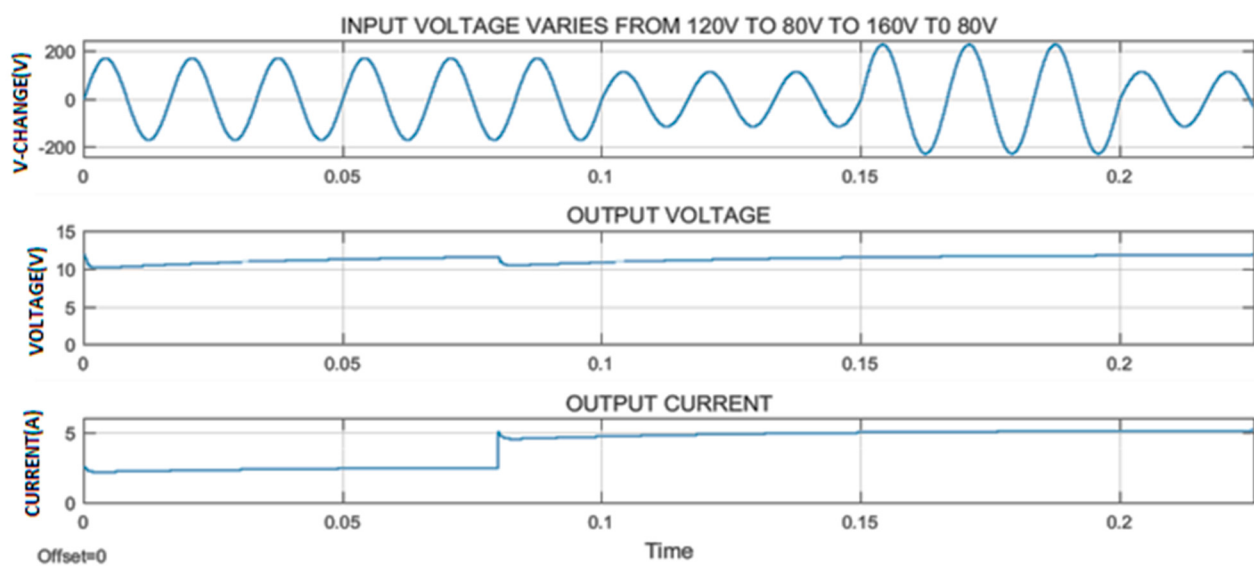


Figure 21. Fuzzy logic controller simulation results.

4.2. WPT via Neuro-Fuzzy Logic Controller

Neuro-fuzzy schemes utilize an algorithm to control the parameters by mixing neural networks and fuzzy logic. The system used included a three-layer feed-forward neural network: the first layer was the input, the hidden layer included the fuzzy rules and the third layer was the output. The neuro-fuzzy scheme was planned by mapping an input and an output with their respective membership functions to the rules. The proposed system had one input with seven MFs, one output with seven MFs and seven rules. Then, input/output data were overloaded for training. Later, the FIS model was trained by an adaptive neural fuzzy inference system (ANFIS) to contest the data used for training by fine-tuning the MF with respect to the error state. This adjustment permitted the fuzzy system to learn from the data that had been demonstrated. The tuning was achieved with the assistance of a hybrid optimization technique with ten epochs. The input/output data for training totally represented the structures of the trained FIS data for better system operation. Neuro-fuzzy logic is more precise because it utilizes a neural network to train the fuzzy logic system, thus enabling greater adaptability. In this study we used the Sugeno model with the wtaver method for defuzzification. The complete EV wireless charging system includes a neuro-fuzzy controller as a modified version of the complete system. Figure 22 presents the neuro-fuzzy controller simulation results. At 0.08 s, an ohm resistor with a load of 2.6 ohms was coupled in parallel across the output to represent the unexpected load variations in real-life situations. It demonstrated a negligible undershoot and greater system robustness. The neuro-fuzzy controller could achieve better characteristics when the load current increased and it was incomparable with the conventional (PI) control and

the fuzzy logic control. The output voltage was 12 V and the output current was 5 A, which was what was required.

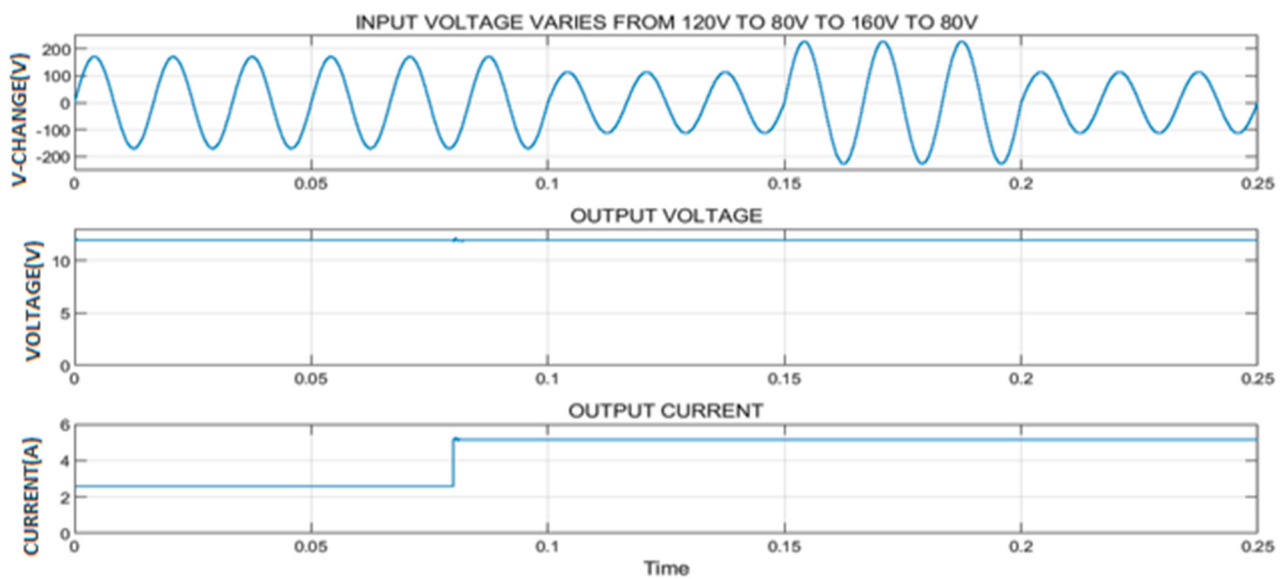


Figure 22. Neuro-fuzzy simulation design.

5. Validation of Simulation Models

The OPAL-RT simulator was used to verify the simulation models implemented in this paper. OP4510 RT-LAB-RCP/HIL equipment was used [51]. This was to take advantage of the benefits of its real-time modeling simulation capability, whereby it can act as a physical system at a rate similar to real time. The WPT Simulink models were compressed out of the apex and SM, SS and SC were used in RT-LAB to ensure the functions of various portions. The OPAL-RT-SC subsystem allows for real-time observation, data communication between the main parameters and construction of a curve within the simulation system. The fundamental module gathers and displays data. The OPAL-RT-SM subsystem is responsible for real-time observation and network synchronization. The OPAL-RT-SS subsystem appertains to the system simulation models. Each model encompasses these subsystems SM, SC and SS, along with an oscilloscope, switch and logic selection. The opcomm synchronous communication module signal reaches the previous subsystems and acts as a substantial part of the simulation [52]. Figure 23 illustrates the RT testing program with a simulation step of 10 μ s. The modules exposed to the events were swapped for RT-EVENTS modules. The output module of RT-LAB was the OP5110-5120 Digital Out module, which has the capacity to process the output signals. The analog input module was the Analog In module, which has the capacity to process the input signals. FPGA was intermingled with the OP5110-5120 Opsync synchronous drive module. The SC subsystem processes the system information, the current and the voltage with the same sampling rate. Figure 24 shows the OPAL-RT simulator testing results for the open-loop simulation (a), the closed-loop three-level cascaded simulation (b), the fuzzy logic controller simulation (c) and the neuro-fuzzy simulation (d). A comparison between the data from the OPAL-RT simulator testing and the Simulink models indicated great matching with minimal error.

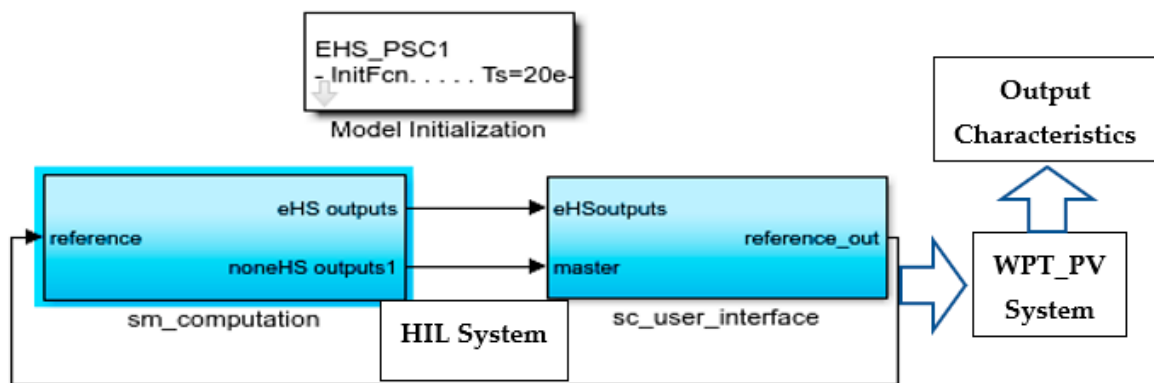
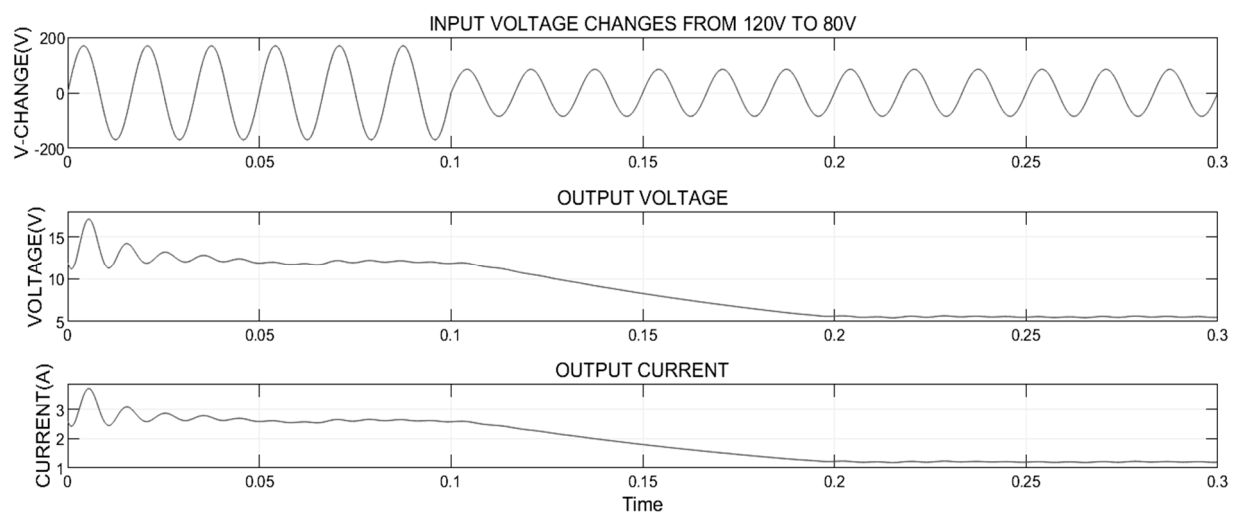
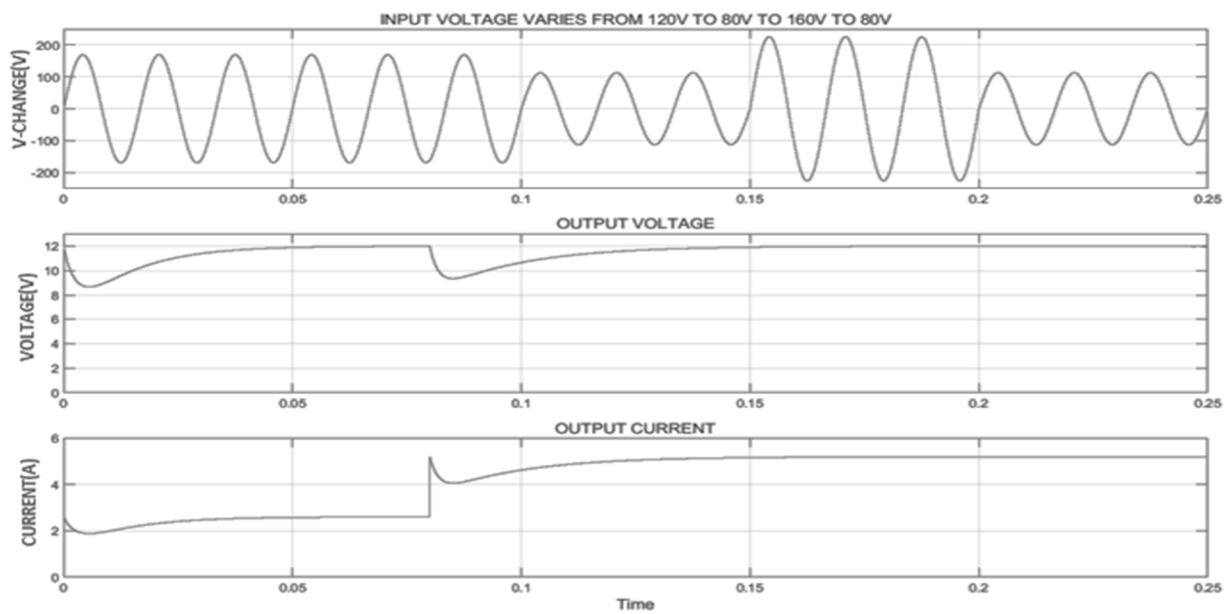


Figure 23. OPAL-RT testing experiment.

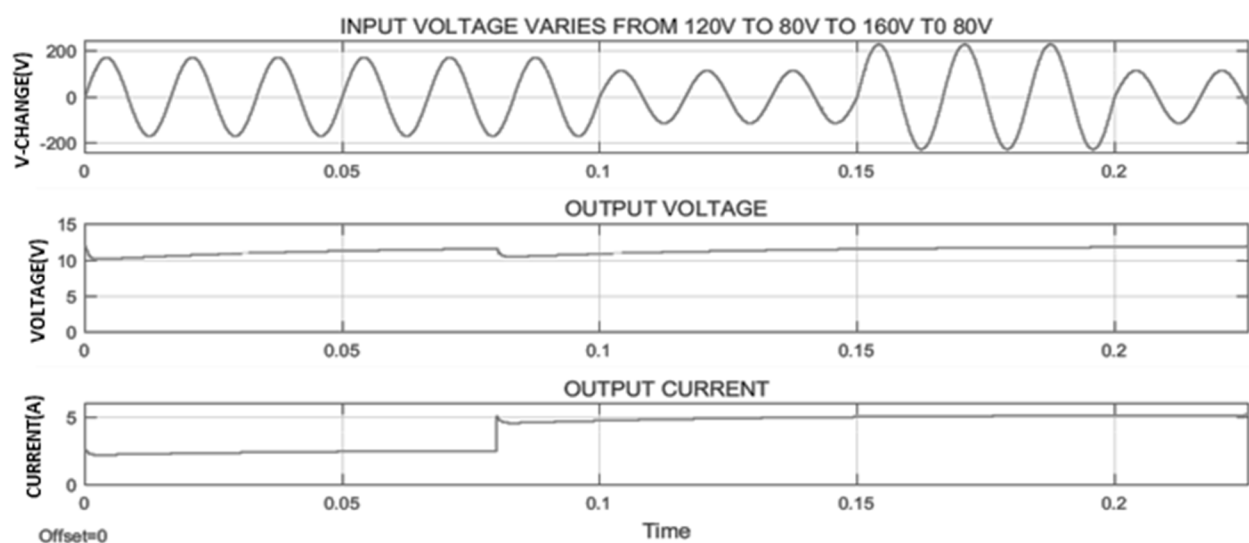


(a)

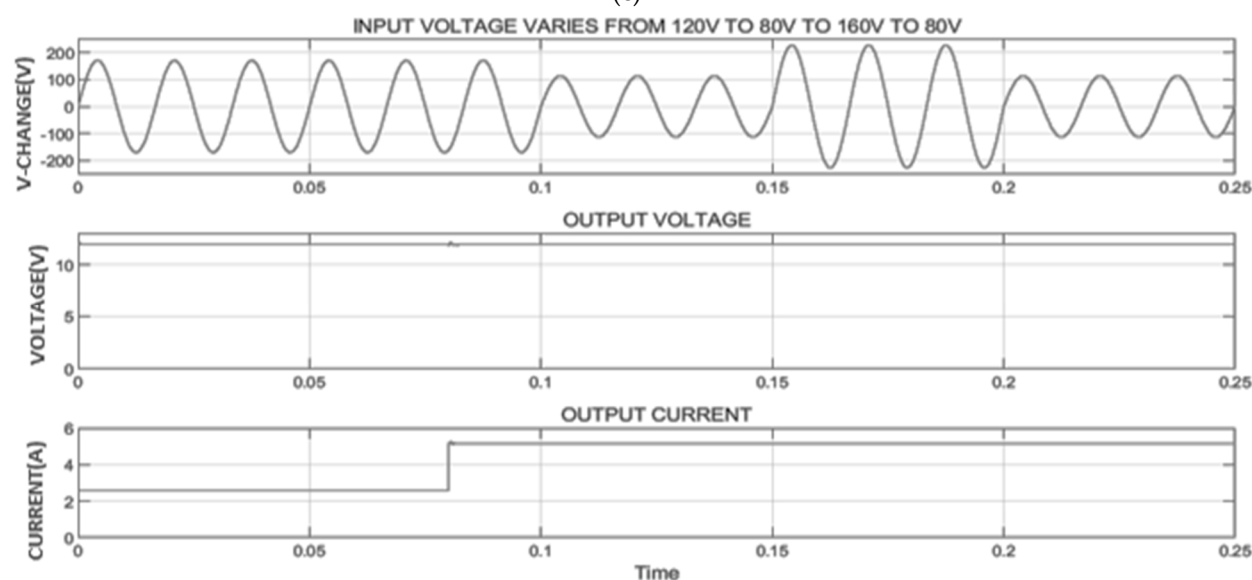


(b)

Figure 24. Cont.



(c)



(d)

Figure 24. OPAL-RT simulator data validation. (a) OPAL-RT open-loop simulation validation; (b) OPAL-RT closed-loop three-level cascaded validation; (c) OPAL-RT fuzzy logic controller simulation validation; (d) OPAL-RT neuro-fuzzy simulation validation.

Additionally, we used the battery model from Simulink after doing our best to adapt it as much as possible to one of our old lab batteries. Its specifications and ratings were as follows: 12 V 10 Ah Lithium LiFePO₄ deep-cycle battery, 2000+ cycles rechargeable battery, maintenance-free battery for solar/wind power, lighting, power wheels, fish finder and more; built-in BMS. Battery type: Lithium ion; cycle life: >2000 cycle; rated capacity: 10 Ah (0.2 °C, 25 °C); voltage: 12.8 volts; wattage: 128 watts; weight: 2.64 LB; terminal type: F2; charging voltage: 14.4 ± 0.2 V; dimensions: $5.94 \times 2.56 \times 3.7$ inches (L $\times$ W $\times$ H); continue discharge current: 10 A; continue charge current: 6 A; operating temperature—discharging: -4 °F to 140 °F; charging: 32 °F to 113 °F. It was observed that the initial state of charge was 40%, the battery current is negative for charging and the battery voltage was 12 V.

6. DC–DC Converter Stability Analysis

In this part of the study we undertook a stability investigation based on the polynomial Lyapunov function and sum-of-squares optimization for the DC–DC converter embedded

in the system. The Lyapunov function $V(x)$ was intended to meet the Lyapunov settings in a province Ω about the equilibrium solution, given as follows in Equations (30)–(33):

$$\begin{cases} V(x) > 0 \text{ for } \forall x \neq 0 \\ V(0) = 0 \end{cases} \quad (30)$$

$$\dot{V}(x) = \nabla V(x) \cdot F(x) \leq 0 \text{ for } \forall x \quad (31)$$

$$\dot{x} = F(x) \quad (32)$$

where (x) indicates the functions of the system differential equations

$$V(x) < \gamma, \forall x \in ROA \quad (33)$$

The software SOSTOOLS 2.05, SeDuMi 1.3 and Multipoly 2.00 were used to carry out this analysis. The stability analysis applied in this part of the study indicated good validation for microgrid applications [53,54].

For the stability analysis of the closed-loop system depicted in Figure 25, a DC–DC converter modeled in Simulink was considered.

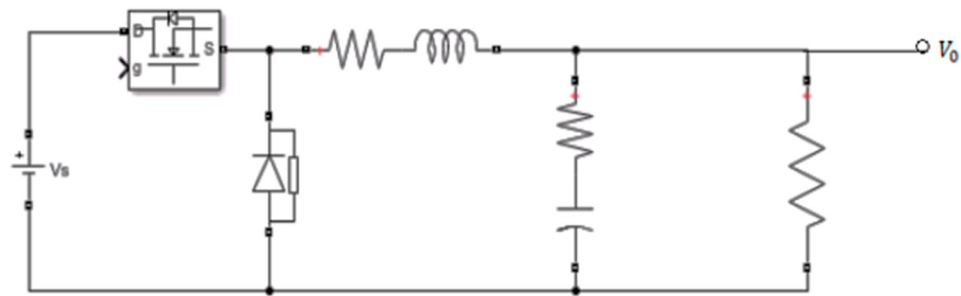


Figure 25. DC–DC converter model.

With respect to the buck converter model shown above, the switch in the MOSFET (S) closes during the ON state; hence, energy flows from the source voltage (v_s) to the inductor (L). Here, the current that passes through the inductor increases at a steady state, which charges the inductor.

Figure 26 shows the linearized form of the buck converter so that the control theory can be applied. The control signals are the duty cycle and the load current in the output voltage.

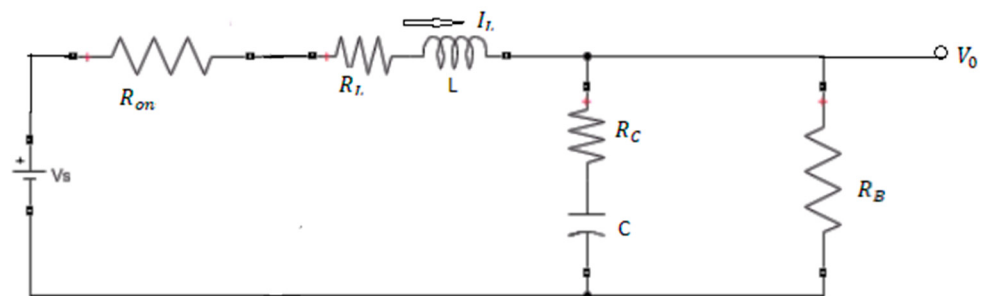


Figure 26. Linearized DC–DC buck converter model.

Applying Kirchhoff's law to the above figure in its ON state, i.e., when S is closed [55], gives the following:

$$-V_s + R_{on} \cdot L \frac{di_L}{dt} + R_L \cdot I_L + V_0 = 0 \quad (34)$$

$$L \frac{di_L}{dt} = V_s - L \frac{di_L}{dt} - R_L \cdot I_L - V_0 \quad (35)$$

$$L \frac{di_L}{dt} = I_L - I_R \quad (36)$$

$$L \frac{di_L}{dt} = I_L - \frac{V_0}{R_B} \quad (37)$$

where

$$V_0 = V_C + I_C \cdot R_C \quad (38)$$

$$\frac{V_0 - V_C}{R_C} = I_C \quad (39)$$

Combining Equations (38) and (39) gives:

$$\frac{V_0 - V_C}{R_C} = I_L - \frac{V_0}{R_B} \quad (40)$$

$$V_0(R_B + R_C) = R_B(V_C + I_L \cdot R_C) \quad (41)$$

$$V_0 = \frac{R_B(V_C + I_L \cdot R_C)}{R_B + R_C} \quad (42)$$

Putting Equation (42) into (39) gives:

$$I_C = \frac{\frac{R_B(V_C + I_L \cdot R_C)}{R_B + R_C} - V_C}{R_C} \quad (43)$$

$$I_C = I_L \frac{R_B}{R_B + R_C} - \frac{V_C}{R_B + R_C} \quad (44)$$

Then,

$$C \frac{dv}{dt} = I_L \frac{R_B}{R_B + R_C} - \frac{V_C}{R_B + R_C} \quad (45)$$

Hence,

$$L \frac{di_L}{dt} = V_s - \left(R_{on} + \frac{R_B \cdot R_C}{R_B + R_C} + R_L \right) \cdot I_L - V_C \frac{R_B}{R_B + R_C} \quad (46)$$

Then, the state-space equation matrices are as follows:

$$[L \ 0 \ 0 \ C] \left[\frac{di_L}{dt} \ \frac{dv_C}{dt} \right] = \left[- \left(R_{on} + \frac{R_B \cdot R_C}{R_B + R_C} + R_L \right) - \frac{R_B}{R_B + R_C} \ \frac{R_B}{R_B + R_C} - \frac{1}{R_B + R_C} \right] [i_L \ V_C] + [1 \ 0] \cdot V_s \quad (47)$$

$$[V_0 \ I_R] = \left[\frac{R_B \cdot R_C}{R_B + R_C} \ \frac{R_B}{R_B + R_C} \ \frac{R_C}{R_B + R_C} \ \frac{1}{R_B + R_C} \right] [i_L \ V_C] + [0 \ 0] \cdot V_s \quad (48)$$

We know that the general state-space equation is $\dot{x} = AX + Bu$

$$\dot{y} = CX + D$$

$$\text{Therefore } A = \left[-\frac{1}{L} \left(R_{on} + \frac{R_B \cdot R_C}{R_B + R_C} + R_L \right) - \frac{1}{L} \cdot \frac{R_B}{R_B + R_C} \ \frac{1}{C} \cdot \frac{R_B}{R_B + R_C} - \frac{1}{C} \cdot \frac{1}{R_B + R_C} \right]$$

$$B = [1 \ 0]C = \left[\frac{R_B \cdot R_C}{R_B + R_C} \ \frac{R_B}{R_B + R_C} \ \frac{R_C}{R_B + R_C} \ \frac{1}{R_B + R_C} \right] D = [0 \ 0]$$

$$\dot{x}_1 = \frac{di_L}{dt}; \ \dot{x}_2 = \frac{dv_C}{dt} \quad (49)$$

and $R_L = 0.025$, $L = 2e^{-3}H$, $C = 1.5e^{-3}F$, $R_C = 0.001$, $R_B = 4.6$, $R_{on} = 1e^{-3}$

Substituting the values in A , $\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = [-13.499 - 499.89 \ 666.52 - 144.89] \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + [1 \ 0] \cdot V_s$

Figure Equation (49).

$$x_1 = i_L x_2 = v_C$$

Substituting the values in C , $y = [0.00099 \ 0.999 \ 0.00083 \ 0.083][x_1 \ x_2]$
 Therefore, the system matrices can be given as $[\dot{x}_1 \ \dot{x}_2] = [-13.499 \ -499.89 \ 666.52 \ -144.89][x_1 \ x_2] + [1 \ 0] \cdot V_s$
 From

$$y = [0.0099 \ 0.999 \ 0.00022 \ 0.217][x_1 \ x_2] \quad (50)$$

the Lyapunov of the system matrix can be found in Equation

$$f|V(x_1, x_2) - V(x_1, x_2)| \quad (51)$$

Assuming a value for $V_x = x_1^2 + x_2^2$ and substituting Equation (51) gives:

$$\begin{aligned} &= f|-13.499x_1^2 - 499.89x_2^2 + 666.52x_1^2 - 144.89x_2^2 - x_1^2 + x_2^2| \\ &182.22x_1^2 + 13496x_1x_2 + 249890.012x_2^2 + 444248.9x_1^2 + 193144.16x_1x_2 + 20993.1121x_2^2 - x_1^2 + x_2^2 \\ &444431.12x_1^2 + 270883.124x_2^2 + 13496x_1x_2 - x_1^2 + x_2^2 \end{aligned}$$

If $x \leq 0$, then $f|V(x_1, x_2) - V(x_1, x_2)| \leq 0$. Therefore, the system is asymptotically stable.

7. Conclusions

In this study, magnetic resonance wireless electric vehicle charging was investigated. The designs of the complete circuit prototype and of the physical model were implemented using ANSYS Simplorer and Maxwell. The simulation results demonstrated the usefulness of the magnetic resonance wireless electric vehicle charging. The efficiency was estimated to be around 92.1%. We then introduced how the wireless power system was able to deploy a short-range dynamic distance utilizing proportional-integral, fuzzy logic and neuro-fuzzy controllers. The design and simulation of the three-level cascaded PI controller for the dynamic wireless charging system resulted in the ability to power a battery load of 12 V and 5 A. Then, the system was compared with a single-level PI controller system to demonstrate its greater effectiveness as a form of validation. The voltage conducted in wireless power transfer depends on the distance between the two coils. The closed-loop circuit utilizing the proportional-integral controller at the receiver end of the wireless power transfer could disregard the disparity in the voltage because of variable space between the two coils. The values of K_p and K_i were determined by means of a trial and error process until a fixed-load voltage and current were sustained for the variable spacing between the transmitter and the receiver coils. The disparity in distance was accomplished by changing the coupling coefficient between the coils, which in turn varied the mutual inductance of the coils. The implemented system contained a solar photovoltaic array, a transmitting coil, a boost DC–DC converter, an inverter, a receiving coil, a rectifier, a buck converter and load batteries. The MPPT controller was designed to track the maximum voltage and current required from the solar array to charge a load battery with maximum power-point voltage. Additionally, fuzzy logic and neuro-fuzzy controllers were utilized and were found to have greater robustness than the PI controller due to the fact that there was no undershoot in the output voltage. The MPPT controller supplied the battery with the highest power by tracking the highest voltage and current from the solar array.

The OPAL-RT simulator was used for validation purposes and to test the data from the open-loop, closed-loop, fuzzy logic and neuro-fuzzy simulations. The comparison indicated excellent matching with minimal error between the simulation and the real-time data. The stability of the DC–DC converter embedded in the closed-loop system for dynamic wireless power transfer in electric vehicles was inspected, and the system was found to be asymptotically stable. Overall, the study shows that dynamic wireless EV charging with the proposed enhancements is important and effective from various perspectives, such as design, modeling, analysis and advanced control.

8. Planned Future Work to Enhance the System Performance and Overcome Limitations

8.1. Future Considerations and Research Limitations

Some limitations of the work and future research directions are listed below. The designed magnetic resonance wireless power transfer system could be enhanced by undertaking further magneto-static and experimental analyses. An adaptive neuro-fuzzy inference (ANFIS) model was used to train the system's data, and it was discovered that the number and type of membership functions affect the ANFIS model. In light of this, the root-mean-square error and the number of epochs were used to choose a suitable model. Hence, future work should review the types and numbers of MFs and the epochs, inputs, rules and training data used for the improvement of the ANFIS model in order to implement a more efficient dynamic wireless power transfer system. For future work, the neuro-fuzzy controller should be designed in such a way that the input and output data for training completely represent the features of the trained FIS data. In addition, the design of a wireless electric vehicle charging system with constraints on human electromagnetic field exposure should be investigated. Furthermore, we intend to build a large, complete system including actual coil sizes and outdoor PV panels. Additionally, we plan to investigate the use of various artificial intelligence techniques to maximize the output and enhance the efficiency. Finally, more investigations into the utilization of PV as a power source, including the variability and uncertainty of PV generation and output based on the day, month and other environmental factors, are needed. These uncertainties in the PV output can affect the circuit's response and various components in the circuit might change, which needs to be highlighted.

8.2. Sample of Techniques and Procedures to Overcome the Research Limitations

This section proposes some solutions, techniques and procedures to overcome the system limitations.

8.2.1. New Proposed Smart Charging System to Handle the PV Generation Variations and Other Uncertainties

The proposed system has various uncertainties that must be addressed, such as the hourly PV generation, the EV arrival/departure time, the variable customer load demands, the required charging power, etc. These uncertainties significantly impact the parameters of the system when using the current/traditional algorithms. There is thus a need for an efficient solution that can incorporate these uncertainties into the system and guarantee stable and precise functioning of the EV charging system's operations and load behavior. Additionally, the system may function differently in physical applications because various pragmatic considerations were shortened in the algorithms used here. This is why it is necessary to validate the algorithm in a physical environment. Moreover, PV integration into the power grid is constrained by the load performance (linear and nonlinear) and EV chargers.

8.2.2. Particle Swarm Optimization for MPPT to Enhance PV Generation

A PSO-based MPPT algorithm could be utilized to enhance the PV dynamics and address uncertainties, which would lead to a better dynamic response and maximization of power. This technique will be applied in the future with other experimental techniques to enhance the overall quality of the system. This technique has been shown to demonstrate great validity and excellent performance by one of the authors in previous work [51,56,57].

8.2.3. Investigation of WEV System Effect in Human Exposure

Lengthy exposure to EMI can cause extensive health issues in humans and pets relating to indirect coupling from exposure to medical devices, both worn and implanted, and lack of standardized exposure assessment due to varying factors. Due to the lack of standardized exposure assessments, it is necessary to point out that the results obtained in the safety study were based on the specific coil prototypes used in this project.

8.2.4. Proposed Future Efficiency Analysis Based on Complete Experimental System

The main goal in this study was to focus on the wireless system and unstable output under dynamic charging. The research team is currently performing a complete performance efficiency analysis for a mismatched Tx and Rx. It is more realistic and practical to undertake this analysis based on our real experimental system, which we are working on right now based on real data and under different scenarios. Our real-size system is under construction right now, but we have also published some related work concerning a small lab-scale prototype [58]. Additionally, the research team has run a simulation for another wireless charging technique, inductive coupling, to show the fidelity of the magnetic resonance technique. Using the same coil design and parameters and keeping the same distance between the coils as in the magnetic resonance method, the results show that the efficiency of the inductive coupling method reached a peak at 60.145%. This confirms that wireless power efficiency is low when the inductive coupling method is used over large distances, as shown in Figure 27.

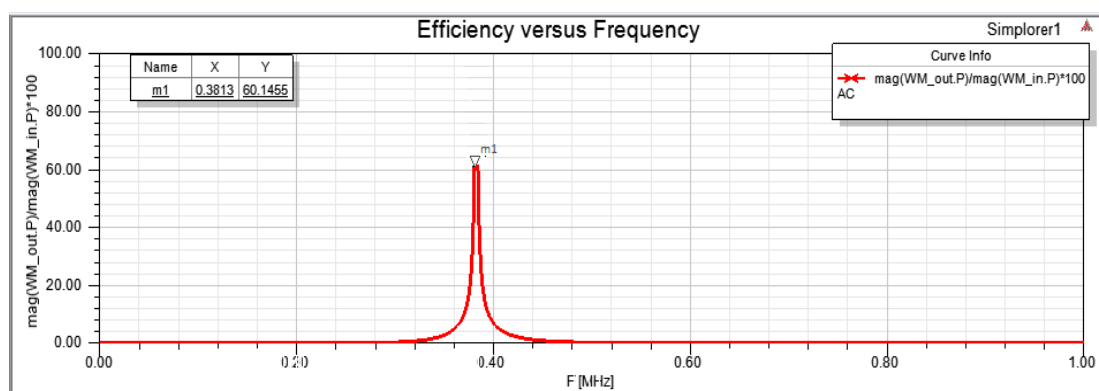


Figure 27. Efficiency and frequency for the inductive coupling technique.

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Abbreviations

The following Symbols/ Abbreviations are used in this manuscript:

I	Current
R	Resistance
C	Capacitance
L	Inductor
V	Voltage
Z	Impedance
Q	Quality factor
M	Mutual inductance
N	Number of turns
L	Length of air core
R	Radius
d	Diameter

w	Thickness of coil
D	Duty cycle
D_i	Inner diameter
F_{sw}	Switching frequency

References

1. Tesla, N.; Marincic, A.S. Nikola Tesla and the wireless transmission of energy. *IEEE Trans. Power App. Syst.* **1982**, PAS-101, 4064–4068.
2. Hui, S.Y.R. Planar Wireless Charging Technology for Portable Electronic Products and Qi. *Proc. IEEE* **2013**, 101, 1290–1301. [\[CrossRef\]](#)
3. Ahn, D.; Hong, S. Wireless Power Transmission with Self-Regulated Output Voltage for Biomedical Implant. *IEEE Trans. Ind. Electron.* **2013**, 61, 2225–2235. [\[CrossRef\]](#)
4. Beh, T.C.; Imura, T.; Kato, M.; Hori, Y. Basic study of improving efficiency of wireless power transfer via magnetic resonance coupling based on impedance matching. In Proceedings of the 2010 IEEE International Symposium on Industrial Electronics, Bari, Italy, 4–7 July 2010; pp. 2011–2016. [\[CrossRef\]](#)
5. Vilathgamuwa, D.M.; Sampath, J.P.K. *Power Systems*; Springer Science and Business Media: Singapore, 2015.
6. Swain, K.; Neath, M.J.; Madawala, U.K.; Thrima, D.J. A dynamic multivariable state-space model for bidirectional inductive power transfer systems. *IEEE Trans. Power Electron.* **2012**, 27, 4772–4780. [\[CrossRef\]](#)
7. Ravikiran, V.; Keshiri, R.K. Comparative Evaluation of S-S and P-S Topologies for Wireless Charging of Electrical Vehicles. In Proceedings of the IEEE Industrial Electronics Society Annual Conference, Beijing, China, 29 October–1 November 2017; pp. 5324–5329.
8. Liao, C.; Li, J.; Li, S. Design of LCC Impedance Matching Circuit for Wireless Power Transfer System under Rectifier Load. *CPSS Trans. Power Electron. Appl.* **2017**, 2, 237–245. [\[CrossRef\]](#)
9. Tran, D.H.; Vu, V.B.; Choi, W. Design of a High-Efficiency Wireless Power Transfer System with Intermediate Coils for the On-Board Chargers of Electric Vehicles. *IEEE Trans. Power Electron.* **2017**, 33, 175–187. [\[CrossRef\]](#)
10. Zhang, Y.; Zhao, Z.; Jiang, Y. Modeling and analysis of wireless power transfer system with constant-voltage source and constant-current load. In Proceedings of the 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, USA, 1–5 October 2017; pp. 975–979. [\[CrossRef\]](#)
11. Yeo, T.-D.; Kwon, D.; Khang, S.-T.; Yu, J.-W. Design of Maximum Efficiency Tracking Control Scheme for Closed-Loop Wireless Power Charging System Employing Series Resonant Tank. *IEEE Trans. Power Electron.* **2016**, 32, 471–478. [\[CrossRef\]](#)
12. Zhang, X.; Yuan, Z.; Yang, Q.; Li, Y.; Zhu, J.; Li, Y. Coil Design and Efficiency Analysis for Dynamic Wireless Charging System for Electric Vehicles. *IEEE Trans. Magn.* **2016**, 52, 1–4. [\[CrossRef\]](#)
13. Campi, T.; Cruciani, S.; Maradei, F.; Feliziani, M. Conducted Emission of Wireless Power Transfer Charging System in Electric Vehicle. In Proceedings of the IEEE International Symposium on Electromagnetic Compatibility & Signal/Power Integrity, Washington, DC, USA, 7–11 August 2017.
14. Cui, H.; Zhong, W.; Li, H.; He, F.; Chen, M.; Xu, D. A study on the shielding for wireless charging systems of electric vehicles. In Proceedings of the 2018 IEEE Applied Power Electronics Conference and Exposition (APEC), San Antonio, TX, USA, 4–8 March 2018; pp. 1336–1343. [\[CrossRef\]](#)
15. Campi, T.; Cruciani, S.; Feliziani, M.; Maradei, F. Magnetic field generated by a 22 kW–85 kHz wireless power transfer system for an EV. In Proceedings of the 2017 AEIT International Annual Conference, Cagliari, Italy, 20–22 September 2017. [\[CrossRef\]](#)
16. Wang, Q.; Li, W.; Kang, J.; Wang, Y. Electromagnetic safety of magnetic resonant wireless charging system in electric vehicles. In Proceedings of the 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), Chongqing, China, 20–22 May 2017. [\[CrossRef\]](#)
17. Wang, Q.; Li, W.; Kang, J.; Wang, Y. Magnetic Field Distribution in a WPT System for Electric Vehicle Charging. In Proceedings of the Progress in Electromagnetic Research Symposium (PIERS), Shanghai, China, 8 August–11 September 2016; p. 5165.
18. Sibakoti, M.J.; Hambleton, J. *Wireless Power Transmission Using Magnetic Resonance*; Cornell College PHY312: Mount Vernon, IA, USA, 2011.
19. Hui, W.X.; He, Z.; Shun, L.Y. Analysis on the Efficiency of Magnetic Resonance Coupling Wireless Charging for Electric Vehicles. In Proceedings of the IEEE International Conference on Cyber Technology in Automation Control and Intelligent Systems, Nanjing, China, 26–29 May 2013.
20. Salim, G.; Habib, B.; Zouheir, R. New approach for the evaluation of magnetic fields in dynamic wireless. In Proceedings of the IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles and International Transportation Electrification Conference (ESARS-ITEC), Toulouse, France, 2–4 November 2018; pp. 1–5.
21. Liu, S.; Ye, Z.; Lu, W. Electric vehicle dynamic wireless charging technology based on multi-parallel primary coils. In Proceedings of the IEEE International Conference on Electronics and Communications Engineering (ICECE), Xi'an, China, 10–12 December 2018; pp. 120–124.

22. Shumei, C.; Xin, G.B.G.; Shuai, D. A narrow-width three phase magnetic coupling mechanism with constant output power for electric vehicles dynamic wireless charging. In Proceedings of the IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer, Montreal, QC, Canada, 3–7 June 2018; pp. 1–6.
23. Rong, L.; Liyan, Z.; Qihong, C. Soft switching strategy of dynamic wireless charging systems for electric vehicles. In Proceedings of the 3rd Youth Academic Annual Conference of Chinese Association of Automation (YAC), Nanjing, China, 18–20 May 2018; pp. 738–742.
24. Yeran, L.; Ruikun, M.; Pengfei, Y.; Zhengyou, H. Efficiency optimization for wireless dynamic charging system with overlapped DD coil arrays. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC), Tampa, FL, USA, 26–30 May 2017; pp. 1439–1442.
25. Dimitrios, K.; Leandros, A.M.; Michalis, M.; Sotiris, M.; Antonios, A.; Anthanasios, M.; Helge, J. Route optimization of electric vehicles based on dynamic wireless charging. *IEEE Access* **2018**, *6*, 42551–42565.
26. Bahuti, M.; Abreu, L.H.P.; Junior, T.Y.; De Lima, R.R.; Campos, A.T. Performance of Fuzzy Inference Systems to Predict The Surface Temperature Of Broiler Chickens. *Sci. Flo.* **2018**, *38*, 813–823. [\[CrossRef\]](#)
27. Zhen, Z.; Hongliang, P.; Christopher, H.T.L.; Xiangkui, X.; Xile, W.; Jiang, W. Comparative analysis and optimization of dynamic charging of coils for roadway-powered electric vehicles. *IEEE Trans. Magn.* **2017**, *53*, 9402106. [\[CrossRef\]](#)
28. Illhoe, H.; Young, J.J.; Young, D.K.; Min, S.L. System optimization for a dynamic wireless charging electric vehicles operating in a multiple-road environment. *IEEE Trans. Intell. Transp. Syst.* **2018**, *19*, 6.
29. Ayisire, E. Modeling of Magnetic Resonance Electric Vehicles Wireless Charging. Master's Thesis, Georgia Southern University, Statesboro, GA, USA, 2019.
30. Ayisire, E.; El-Shahat, A.; Sharaf, A. Magnetic Resonance Coupling Modelling for Electric Vehicles Wireless Charging. In Proceedings of the 2018 IEEE Global Humanitarian Technology Conference (GHTC), San Jose, CA, USA, 18–21 October 2018; pp. 1–2. [\[CrossRef\]](#)
31. Ayisire, E.; El-Shahat, A.; Ramadan, H.S. Dynamic Wireless Power Transfer Model for Electric Vehicle with Fuzzy-Logic Controller. In Proceedings of the IEEE SoutheastCon 2019, Huntsville, AL, USA, 11–14 April 2019.
32. El-Shahat, A.; Ayisire, E.; Wu, Y.; Rahman, M.; Nelms, D. Electric Vehicles Wireless Power Transfer State-of-The-Art. *Energy Procedia J.* **2019**, *162*, 24–37. [\[CrossRef\]](#)
33. Yousuf, A.; Das, T.K.; Khallil, E.; Aziz, N.A.A.; Rana, J.; Hossain, S. Comparison Study of Inductive Coupling and Magnetic Resonant Coupling Method for Wireless Power Transmission of Electric Vehicles. In Proceedings of the 2021 2nd International Conference on Robotics, Electrical and Signal Processing Techniques (ICREST), Dhaka, Bangladesh, 5–7 January 2021; pp. 737–741. [\[CrossRef\]](#)
34. Akhil, A.G.; Harisankar, S.; Jishnu, K.; Sreenand, S.; Vijay, V.; Asha, C.A.; Preetha, P.K. Coupled Wireless Charging system for Electric Vehicles. In Proceedings of the 2021 Third International Conference on Intelligent Communication Technologies and Virtual Mobile Networks (ICICV), Tirunelveli, India, 4–6 February 2021; pp. 475–479. [\[CrossRef\]](#)
35. Zhan, B.; Xia, W.; Xiong, C.; Liu, S. Simulation Analysis of Coupling Coil of 13.56 MHz Magnetic Coupling Resonant Wireless Energy Transmission System. In Proceedings of the 2021 22nd International Conference on Electronic Packaging Technology (ICEPT), Xiamen, China, 14–17 September 2021; pp. 1–6. [\[CrossRef\]](#)
36. Bagchi, A.C.; Kamineni, A.; Zane, R.A.; Carlson, R.B. Review and Comparative Analysis of Topologies and Control Methods in Dynamic Wireless Charging of Electric Vehicles. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *9*, 4947–4962. [\[CrossRef\]](#)
37. Kadem, K.; Bensetti, M.; Le Bihan, Y.; Labouré, E.; Debbou, M. Optimal Coupler Topology for Dynamic Wireless Power Transfer for Electric Vehicle. *Energies* **2021**, *14*, 3983. [\[CrossRef\]](#)
38. Kelin, L. South Korean Road Wirelessly Recharges OLEV Buses. Available online: <https://www.bbc.com/news/technology-23603751> (accessed on 30 October 2021).
39. Israel Tests Wireless Charging Roads for Electric Vehicles. Available online: <https://www.scientificamerican.com/article/israel-tests-wireless-charging-roads-for-electric-vehicles/> (accessed on 1 November 2021).
40. Liu, Q.; Hu, S.; Angeloudis, P.; Wang, Y.; Zhang, L.; Yang, Q.; Li, Y. Dynamic wireless power transfer system for electric-powered connected and autonomous vehicle on urban road network. *IET Intell. Transp. Syst.* **2021**, *15*, 1153–1166. [\[CrossRef\]](#)
41. Jang, Y.J. Survey of the operation and system study on wireless charging electric vehicle systems. *Transp. Res. Part C: Emerg. Technol.* **2018**, *95*, 844–866. [\[CrossRef\]](#)
42. Yin, A.; Wu, S.; Li, W.; Hu, J. Analysis of Battery Reduction for an Improved Opportunistic Wireless-Charged Electric Bus. *Energies* **2019**, *12*, 2866. [\[CrossRef\]](#)
43. Behzadnezhad, B.; Collick, B.D.; Behdad, N.; McMillan, A.B. Dielectric properties of 3D-printed materials for anatomy specific 3D-printed MRI coils. *J. Magn. Reson.* **2018**, *289*, 113–121. [\[CrossRef\]](#)
44. Hsieh, Y.-C.; Lin, Z.-R.; Chen, M.-C.; Hsieh, H.-C.; Liu, Y.-C.; Chiu, H.-J. High-Efficiency Wireless Power Transfer System for Electric Vehicle Applications. *IEEE Trans. Circuits Syst. II Express Briefs* **2016**, *64*, 942–946. [\[CrossRef\]](#)
45. Zhang, W.; Mi, C. Compensation Topologies of High-Power Wireless Power Transfer Systems. *IEEE Trans. Veh. Technol.* **2015**, *65*, 4768–4778. [\[CrossRef\]](#)
46. Gao, Y.; Ginart, A.; Farley, K.B.; Tse, Z.T.H. Misalignment effect on efficiency of wireless power transfer for electric vehicles. In Proceedings of the 2016 IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 20–24 March 2016; pp. 3526–3528. [\[CrossRef\]](#)

47. Etacheri, V.; Marom, R.; Elazari, R.; Salitra, G.; Aurbach, D. Challenges in the development of advanced Li-ion batteries: A review. *Energy Environ. Sci.* **2011**, *4*, 3243–3262. [[CrossRef](#)]
48. Madawala, U.; Schweizer, P.; Haerri, V. Living and mobility—A novel multipurpose in-house grid interface with plug in hybrid blue angle. In Proceedings of the IEEE International Conference on Sustainable Energy Technologies, Singapore, 24–27 November 2008.
49. Hashempour, M.M.; Yang, M.-Y.; Lee, T.-L. An Adaptive Control of DPWM for Clamped-Three-Level Photovoltaic Inverters with Unbalanced Neutral-Point Voltage. *IEEE Trans. Ind. Appl.* **2018**, *54*, 6133–6148. [[CrossRef](#)]
50. Patil, D.; McDonough, M.K.; Miller, J.M.; Fahimi, B.; Balsara, P.T. Wireless Power Transfer for Vehicular Applications: Overview and Challenges. *IEEE Trans. Transp. Electrification* **2017**, *4*, 3–37. [[CrossRef](#)]
51. Koad, R.B.A.; Zobaa, A.; El-Shahat, A. A Novel MPPT Algorithm Based on Particle Swarm Optimization for Photovoltaic Systems. *IEEE Trans. Sustain. Energy* **2016**, *8*, 468–476. [[CrossRef](#)]
52. Benigni, A.; Monti, A. A Parallel Approach to Real-Time Simulation of Power Electronics Systems. *IEEE Trans. Power Electron.* **2014**, *30*, 5192–5206. [[CrossRef](#)]
53. Mazumder, S.K.; de la Fuente, E.P. Dynamic stability analysis of power network. In Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, Canada, 20–24 September 2015; pp. 5808–5815.
54. Mazumder, S.K.; de la Fuente, E.P. Stability Analysis of Micropower Network. *IEEE J. Emerg. Sel. Top. Power Electron.* **2016**, *4*, 1299–1309. [[CrossRef](#)]
55. Sumsurooah, S.; Odiavic, M.; Bozhko, S.; Boroyevich, D.D. Robust stability analysis of a dc-dc buck converter under multiple parameter uncertainties. *IEEE Trans. Power Electron.* **2018**, *33*, 5426–5441. [[CrossRef](#)]
56. El-Shahat, A.; Sumaiya, S. DC-Microgrid System Design, Control, and Analysis. *Electronics* **2019**, *8*, 124. [[CrossRef](#)]
57. Sumaiya, S.; El-Shahat, A.; Haddad, R.; Ramadan, H.; Becherif, M. A Standalone PV-Micro-grid Efficiency Enhancement. In Proceedings of the 2019 SoutheastCon, Huntsville, AL, USA, 11–14 April 2019; pp. 1–5. [[CrossRef](#)]
58. El-Shahat, A.; Thomas, S.; Lawson, A.; Moore, M. Magnetic Induction Wireless Power Transfer in Solar Roads for Electric Vehicles (Experimental Case Project). In Proceedings of the 9th International Renewable and Sustainable Energy Conference (IRSEC), Tetouan, Morocco, 23–27 November 2021.