Fuzzy-Based Efficient Wireless Charging System with Solar PV Interface for Sustainable Transportation

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ABSTRACT

With the growing demand for sustainable transportation, the integration of renewable energy sources into wireless charging systems has gained significant attention. This paper presents the design and implementation of a fuzzy logic-based efficient wireless charging system with a solar photovoltaic (PV) interface, aimed at enhancing the reliability and sustainability of electric vehicle (EV) charging. The proposed system employs a fuzzy compensation scheme to optimize power transfer efficiency by dynamically adjusting charging parameters based on real-time variations in load and environmental conditions. The solar PV interface ensures a renewable energy supply, reducing dependency on the conventional grid and lowering carbon emissions. The wireless power transfer (WPT) system utilizes resonant inductive coupling to achieve high efficiency while mitigating misalignment issues. The paper proposes the utilization of FLC compensated constant current (CC) and constant voltage (CV) system for PV-integrated static WPT systems. Simulation results validate the effectiveness of the proposed approach, demonstrating improved power transfer efficiency, stability, and adaptability under varying operational conditions.

Keywords: Wireless power transfer, Fuzzy logic controller, Solar photovoltaic, Electric vehicle charging, Sustainable transportation, Constant current/constant voltage control, Resonant inductive coupling.

INTRODUCTION

The increasing global demand for sustainable and clean energy solutions has accelerated the development of fuel cell technology. Fuel cells provide an efficient, reliable, and environmentally friendly alternative to conventional fossil-fuel-based power generation. However, the inherent low voltage output of fuel cells necessitates the use of power conversion techniques, such as boost converters, to enhance voltage levels and facilitate integration into electrical systems. The performance of these converters significantly impacts the overall efficiency and stability of fuel cell systems, making advanced control strategies imperative.

Traditional control techniques, such as Proportional-Integral-Derivative (PID) and fuzzy logic controllers, have been extensively used in power electronics applications. While PID controllers offer simple implementation and robust performance in linear systems, their effectiveness diminishes in the presence of nonlinearities and system uncertainties. Fuzzy logic controllers provide better adaptability to nonlinear conditions but may struggle with optimal parameter tuning. The Adaptive Neuro-Fuzzy Inference System (ANFIS) overcomes these limitations by combining the learning capabilities of artificial neural networks (ANN) with the rule-based decision-making process of fuzzy logic systems.

ANFIS-based controllers leverage machine learning algorithms to fine-tune control parameters dynamically, leading to improved voltage regulation, faster transient response, and higher efficiency. This study presents an in-depth analysis of an ANFIS controller applied to a fuel cell-integrated boost converter, comparing its performance with conventional PID and fuzzy logic controllers. The effectiveness of the ANFIS-based control strategy is validated through simulation results, showcasing its potential for enhancing power conversion efficiency in renewable energy applications.

The global shift towards sustainable transportation has intensified the focus on electric vehicles (EVs) as a viable solution to reducing carbon emissions and dependence on fossil fuels. Despite advancements in battery technology and charging infrastructure, efficient and reliable charging remains a key challenge. Conventional plug-in charging stations face issues such as connector wear, user inconvenience, and electrical safety concerns. Wireless power transfer (WPT) has emerged as an innovative alternative, offering contactless charging with improved convenience and safety. However, optimizing power transfer efficiency in WPT systems remains a significant challenge, especially in dynamic environments where misalignment, load variations, and environmental factors impact charging performance.

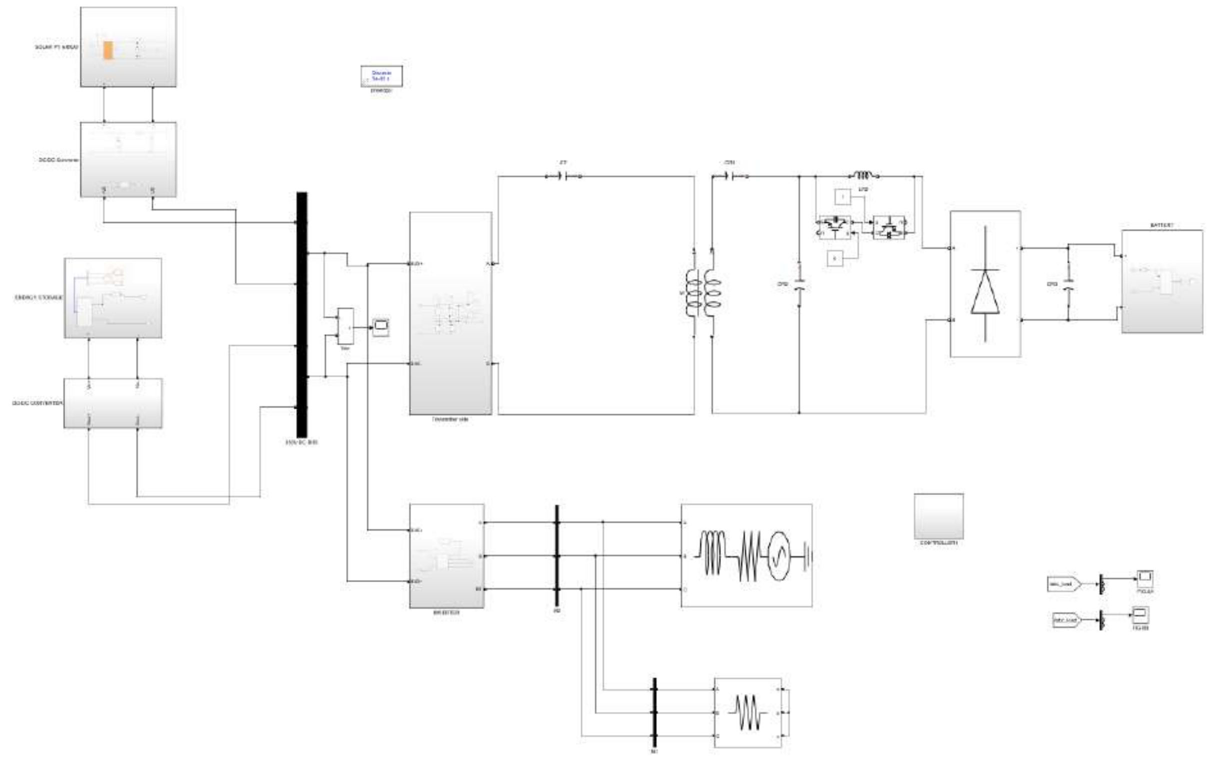


FIGURE 1. Simulink diagram of PV integrated wireless charging system.

To enhance the efficiency and sustainability of wireless EV charging, integrating renewable energy sources such as solar photovoltaic (PV) systems has gained traction. Solar PV-based charging reduces reliance on the conventional power grid and mitigates the carbon footprint associated with EV charging. However, variations in solar irradiance and temperature affect power generation, necessitating an intelligent control strategy for stable and efficient power transfer. A fuzzy logic controller (FLC) presents a robust solution by dynamically adjusting system parameters in response to real-time variations in environmental and load conditions.

This paper proposes a fuzzy-based efficient wireless charging system with a solar PV interface to improve the adaptability and performance of static WPT systems. The proposed system employs a fuzzy compensation scheme to optimize power transfer efficiency through intelligent control of charging parameters. The FLC compensates for variations in solar energy input and receiver positioning, ensuring consistent charging performance. Additionally, a constant current (CC) and constant voltage (CV) control mechanism is implemented to maintain optimal battery charging conditions and prevent overcharging or undercharging scenarios.

Wireless power transfer in EV applications predominantly relies on resonant inductive coupling, which enables efficient energy transfer over a certain distance. However, one of the primary limitations of WPT systems is sensitivity to misalignment between the transmitting and receiving coils. Small misalignments can lead to significant reductions in efficiency, thereby impacting overall charging performance. The proposed system addresses this challenge by incorporating an FLC-based dynamic compensation mechanism that continuously monitors and adjusts the charging parameters to maintain high efficiency under varying alignment conditions.

The integration of a solar PV interface introduces additional complexities, as fluctuations in solar power generation can lead to unstable charging behavior. Conventional control methods, such as proportional-integral-derivative (PID) controllers, are often inadequate in handling such nonlinearities. Fuzzy logic control offers a better alternative due to its ability to handle uncertainties and adaptively regulate power flow without requiring an explicit mathematical model. By intelligently adjusting the duty cycle of the power converters based on real-time measurements, the FLC ensures stable power delivery to the EV battery.

Another critical aspect of the proposed system is the use of a dual-stage power conversion architecture. The first stage consists of a maximum power point tracking (MPPT) system that optimally extracts energy from the solar PV source. The second stage involves a DC-DC converter that regulates the power flow to the WPT system, ensuring compatibility between the PV output and the WPT system requirements. This two-stage approach enhances the overall efficiency and reliability of the wireless charging infrastructure.

The effectiveness of the proposed fuzzy-based wireless charging system is validated through MATLAB/Simulink-based simulations. The results demonstrate that the system achieves higher power transfer efficiency, improved voltage and current stability, and enhanced adaptability compared to conventional PID-controlled WPT systems. Furthermore, the fuzzy logic-based control system reduces power losses and mitigates the impact of environmental fluctuations, making it a robust solution for real-world applications.

LITERATURE SURVEY

The integration of fuel cells into modern power systems has gained significant attention in recent years. Various control techniques have been developed to enhance the performance of fuel cell-integrated boost converters. This section reviews relevant literature on traditional and intelligent control approaches, highlighting their advantages and limitations. Traditional control methods, including PID controllers, have been widely applied in power electronics due to their simplicity and ease of implementation. Several studies have explored the application of PID controllers for fuel cell-integrated boost converters. According to [1], a conventional PID controller provides adequate voltage regulation in steady-state conditions but suffers from slow transient response and poor adaptability to dynamic load variations. Researchers in [2] proposed an optimized PID controller using particle swarm optimization (PSO) to enhance performance; however, the approach required extensive computational effort for tuning parameters.

Fuzzy logic controllers have emerged as an alternative to PID controllers due to their ability to handle system nonlinearities. In [3], a fuzzy logic-based boost converter controller demonstrated improved adaptability compared to PID controllers but required extensive expert knowledge for rule formulation. A comparative study in [4] revealed that while fuzzy controllers outperform PID controllers in handling nonlinearities, they lack the self-learning capability required for real-time optimization. The growing complexity of power electronic systems has necessitated the adoption of artificial intelligence (AI)-based control strategies. ANNs have been widely studied for their ability to learn system behavior and adapt to variations. Research in [5] explored an ANN-based boost converter controller that exhibited superior transient response compared to conventional methods; however, it required large training datasets and computational resources.

Hybrid AI techniques, such as ANFIS, have gained prominence for combining the advantages of fuzzy logic and neural networks. A study in [6] demonstrated that an ANFIS-based controller for a fuel cell-integrated boost converter achieved improved efficiency and reduced voltage ripple compared to conventional methods. Similarly, [7] reported that an ANFIS controller outperformed fuzzy and PID controllers in terms of transient response and steady-state error reduction.

ANFIS has been successfully applied in various power electronics applications, including renewable energy systems and smart grids. Research in [8] highlighted the use of ANFIS for maximum power point tracking (MPPT) in photovoltaic systems, resulting in enhanced energy harvesting efficiency. In [9], an ANFIS-based control strategy for a hybrid renewable energy system demonstrated superior adaptability to changing environmental conditions. In the context of fuel cell applications, ANFIS has shown promise in optimizing power conversion. The study in [10] implemented an ANFIS controller for a fuel cell-powered electric vehicle, achieving improved voltage regulation and system stability. A similar approach in [11] demonstrated enhanced power quality in a fuel cell-integrated microgrid system.

Several studies have conducted performance comparisons between ANFIS and other control techniques. According to [12], ANFIS exhibited faster response times and lower overshoot than PID and fuzzy controllers. In [13], an ANFIS-based boost converter controller demonstrated higher efficiency and lower total harmonic distortion (THD) compared to conventional methods. While ANFIS offers significant advantages, challenges remain in terms of computational complexity and training data requirements. Research in [14] suggested that hybrid optimization techniques, such as genetic algorithms (GA) and PSO, can be integrated with ANFIS to enhance learning efficiency. The study in [15] proposed a real-time adaptive ANFIS controller that dynamically adjusts parameters based on operating conditions, further improving performance.

PROPOSED SYSTEM CONFIGURATION

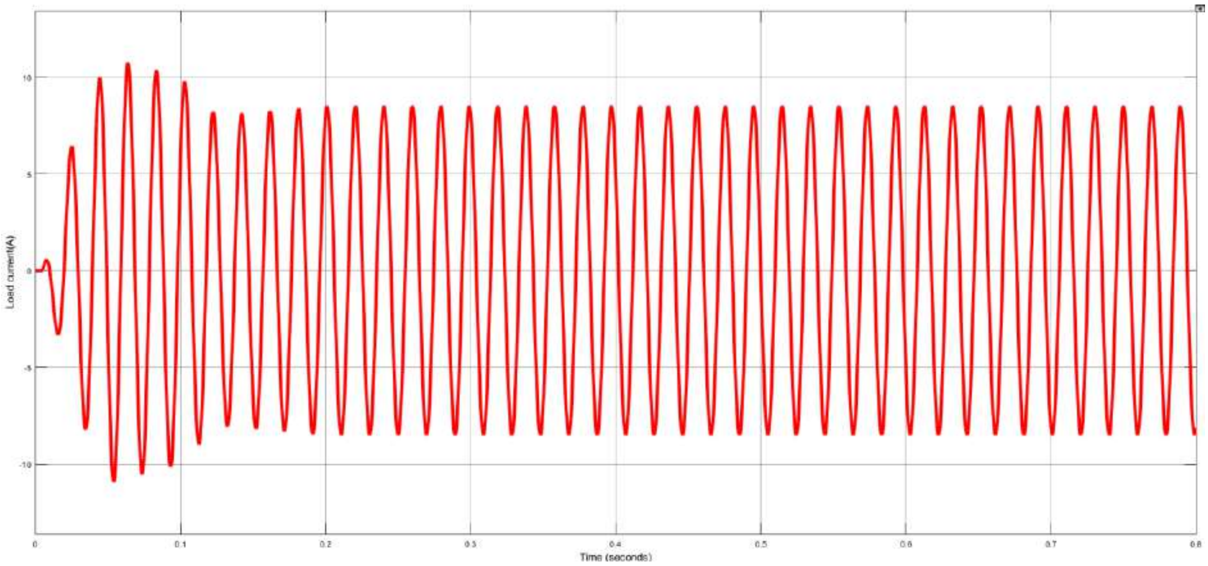
The proposed fuzzy-based efficient wireless charging system with a solar photovoltaic (PV) interface for sustainable transportation integrates multiple components to ensure optimal power transfer and system stability. The key elements of the system include the solar PV array, a maximum power point tracking (MPPT) algorithm, a fuzzy logic controller (FLC), a resonant inductive wireless power transfer (WPT) system, and a battery management system (BMS) for electric vehicle (EV) charging. The system is designed to enhance charging efficiency, minimize energy losses, and support sustainable transportation by reducing reliance on grid-based electricity. The solar PV interface serves as the primary energy source, converting sunlight into electrical energy. To maximize the efficiency of power extraction from the PV array, an MPPT algorithm is implemented. The commonly used perturb and observe (P&O) MPPT technique is employed to track the maximum power point (MPP) dynamically under varying solar irradiation and temperature conditions. The MPPT controller adjusts the duty cycle of the DC-DC converter connected to the PV system, ensuring optimal energy harvesting.

A boost DC-DC converter is used to step up the output voltage of the solar PV system to match the required charging voltage level for the EV battery. The converter is controlled using a fuzzy logic-based compensation system, which dynamically adjusts the operating parameters to maintain a stable and efficient power flow. The use of a fuzzy controller enhances adaptability to environmental variations and load changes, ensuring consistent power delivery. The FLC plays a crucial role in optimizing the efficiency of the wireless charging system. Unlike conventional PID controllers, which require precise mathematical models, the fuzzy controller operates based on a set of linguistic rules and membership functions. The FLC continuously monitors the system parameters, including the input voltage, output power, and charging current, and adjusts the duty cycle of the power electronics converters accordingly. This approach improves the robustness of the system, allowing it to handle nonlinearity and uncertainties associated with real-world operational conditions.

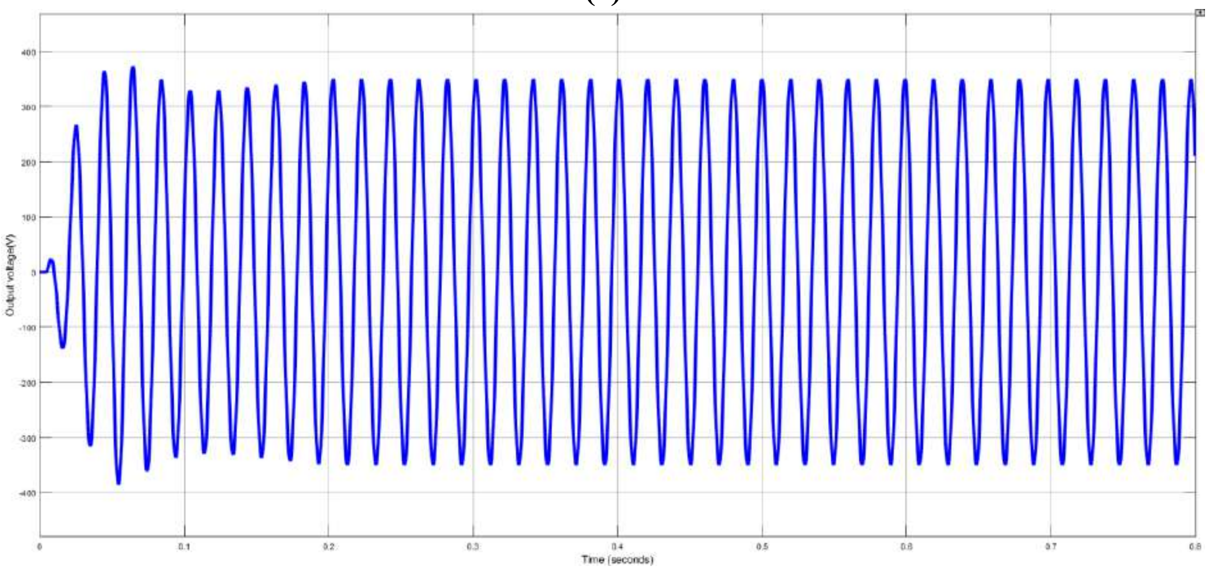
The wireless charging system employs resonant inductive coupling for efficient power transfer. The WPT system consists of a transmitter coil, a receiver coil, and compensation networks. The transmitter coil, connected to the power electronics circuit, generates an alternating magnetic field that induces a voltage in the receiver coil installed in the EV. To improve power transfer efficiency, the system uses series-series compensation topology, which minimizes power losses and mitigates the effects of coil misalignment. To ensure safe and reliable charging, the system employs an FLC-based CC-CV charging strategy. During the initial charging phase, the system operates in CC mode, supplying a stable current to the EV battery while gradually increasing the voltage. Once the battery reaches the predefined voltage threshold, the system switches to CV mode, maintaining a steady voltage while gradually reducing the charging current to prevent overcharging. The fuzzy logic controller dynamically adjusts the charging parameters in response to variations in battery state-of-charge (SOC) and environmental conditions.

A BMS is integrated into the charging system to monitor and control the battery charging process. The BMS ensures proper voltage and current levels, prevents overcharging and deep discharge, and balances individual battery cells to enhance the overall lifespan and safety of the battery pack. The BMS also communicates with the fuzzy controller to optimize charging performance based on real-time battery status. To enhance the reliability of the wireless charging system, a communication interface is established between the charging station and the EV. The system employs a wireless communication protocol to exchange data regarding charging status, battery SOC, and system efficiency. The fuzzy controller processes this data and makes real-time adjustments to optimize charging performance.

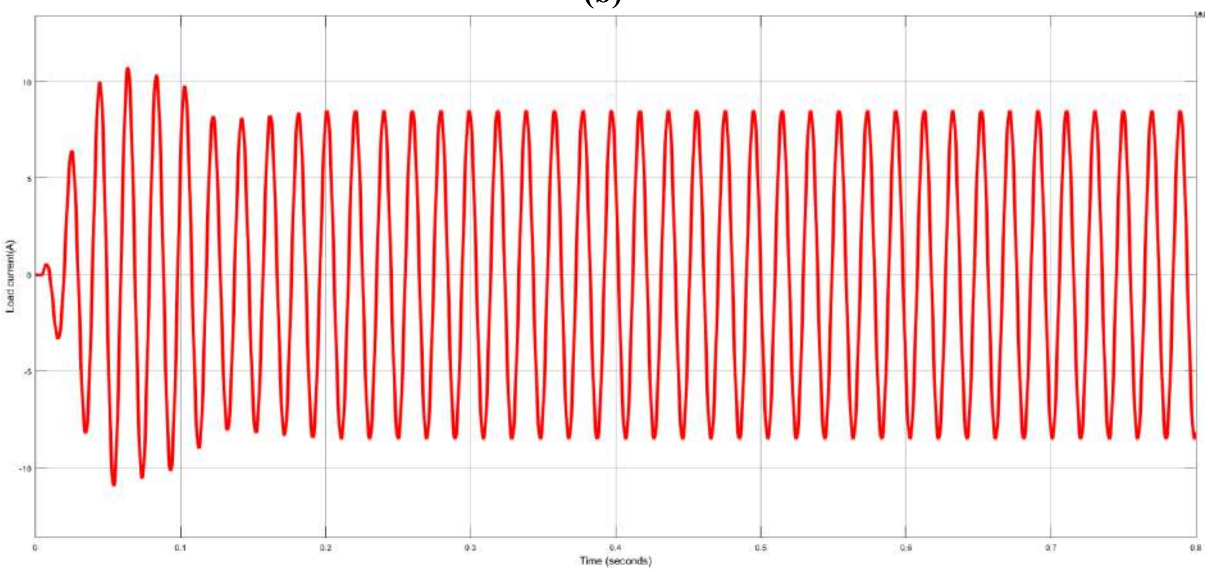
The proposed system is validated through MATLAB/Simulink simulations, where various operational scenarios are tested to assess system performance. Key performance metrics include power transfer efficiency, voltage and current stability, system response to environmental variations, and overall energy utilization. The simulation results confirm the effectiveness of the fuzzy-based compensation scheme, demonstrating improved charging efficiency, reduced power losses, and enhanced adaptability to varying conditions. The proposed circuit is modelled for the mentioned power rating of 3.3 kW and 85 kHz operating frequency. The load voltage and load current at different load resistance conditions are measured namely 25%, 50%, 75%, 100% of load resistance to validate the CC mode of operation. Similarly, to validate the CV mode the measured resistance are 125%, 150%, 175% and 200%. From the following analysis results it is observed that the load voltage is rising during the CC mode of operation maintaining the load current as constant value of 8.85 A. On the other side, the CV mode of operation maintains the load voltage as constant at 350 V with decrease in the load current value. Figure 6 and Figure 8 illustrate the measured load voltage and current waveform at different load resistance values. During the CC mode of operation, the voltage across the load side increasing as the equivalent resistance value is increased towards the rated resistance value. Figure 6 (b), (d) and (f) indicate that the corresponding changes in the load voltage by maintaining the load current as constant. On the other side, during the CV mode of operation, the load current rises when the load resistance value is reduced from the rated value. Moreover, the load voltage is kept constant irrespective of the changes in the equivalent resistance value. Figure 7 and 9 shows the THD% Load voltage and current of RL 100%.


Load current(A)
Time (seconds)

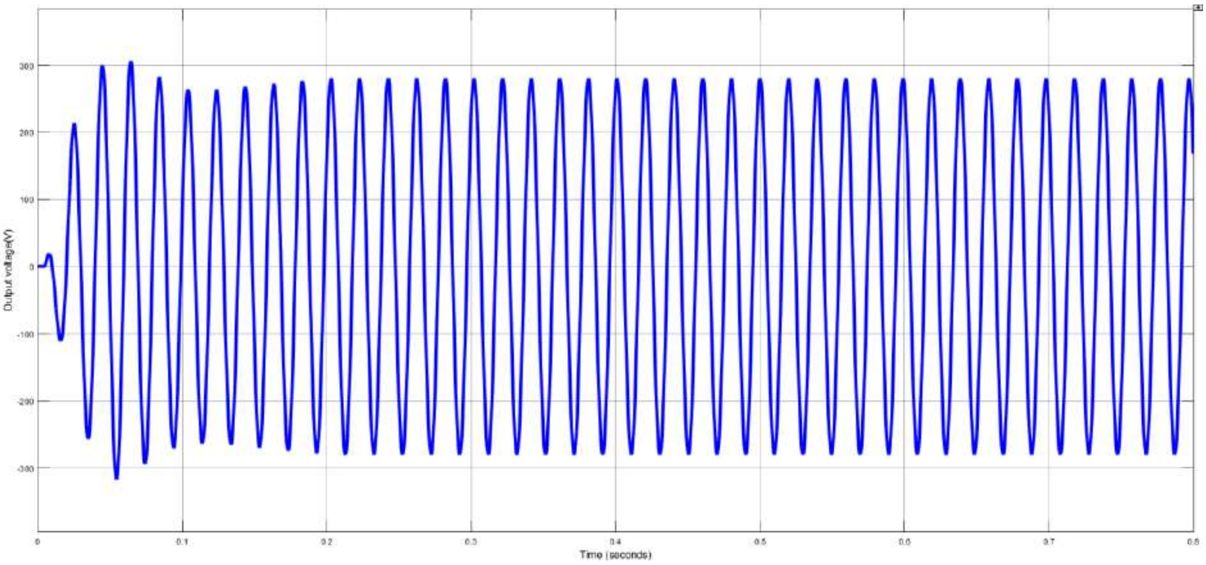
(a)


Output voltage(V)
Time (seconds)

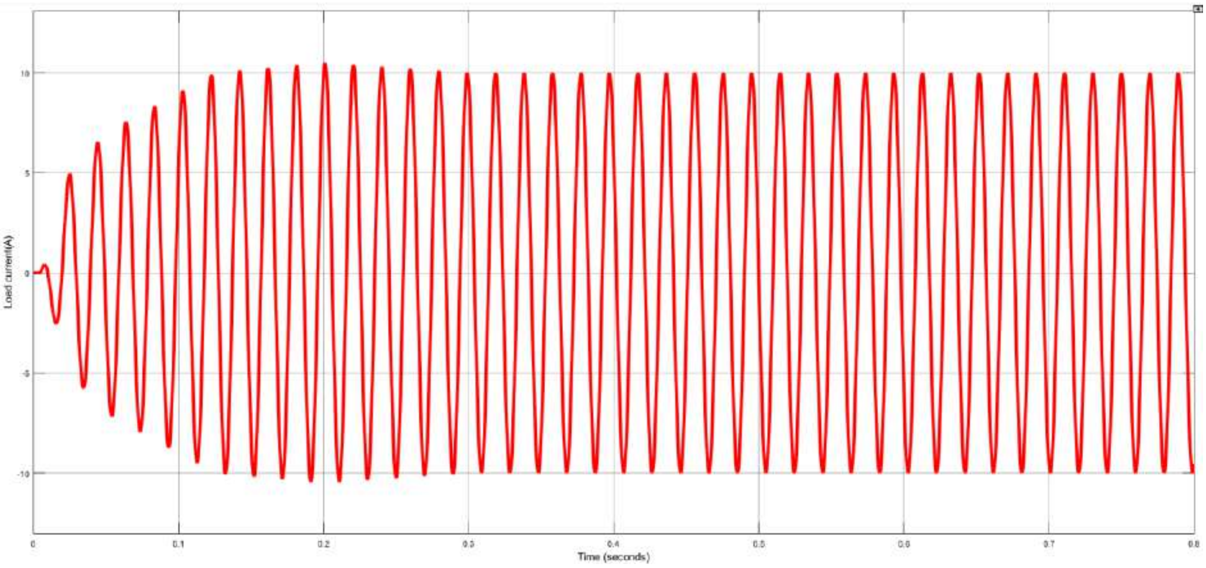
(b)


Load current(A)
Time (seconds)

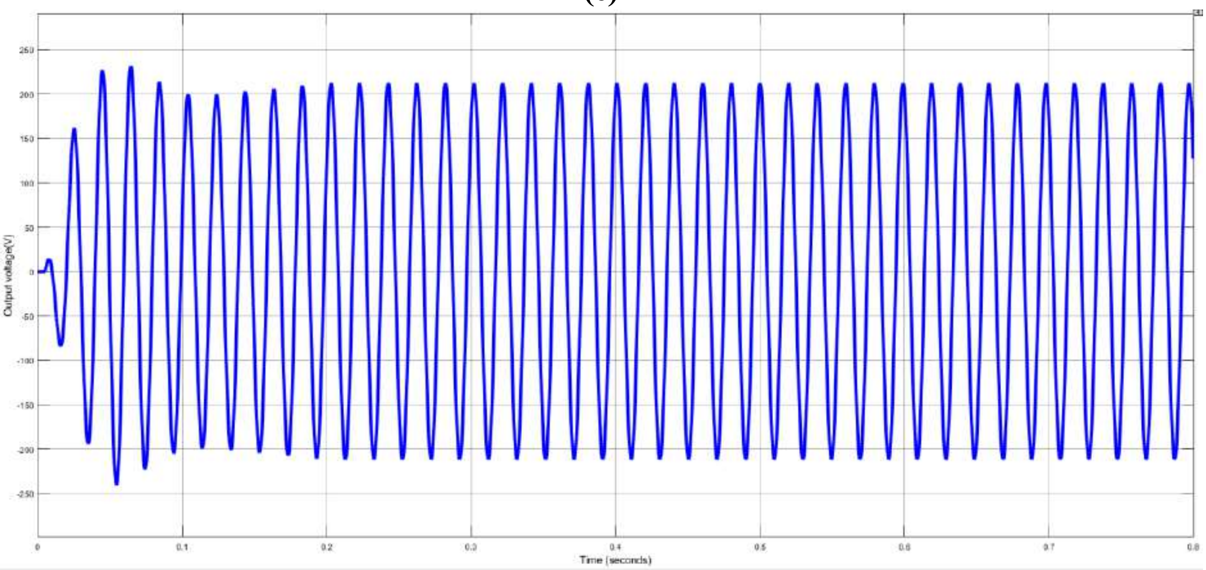
(c)


Output voltage(V)
300
200
100
0
-100
-200
-300
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Time (seconds)

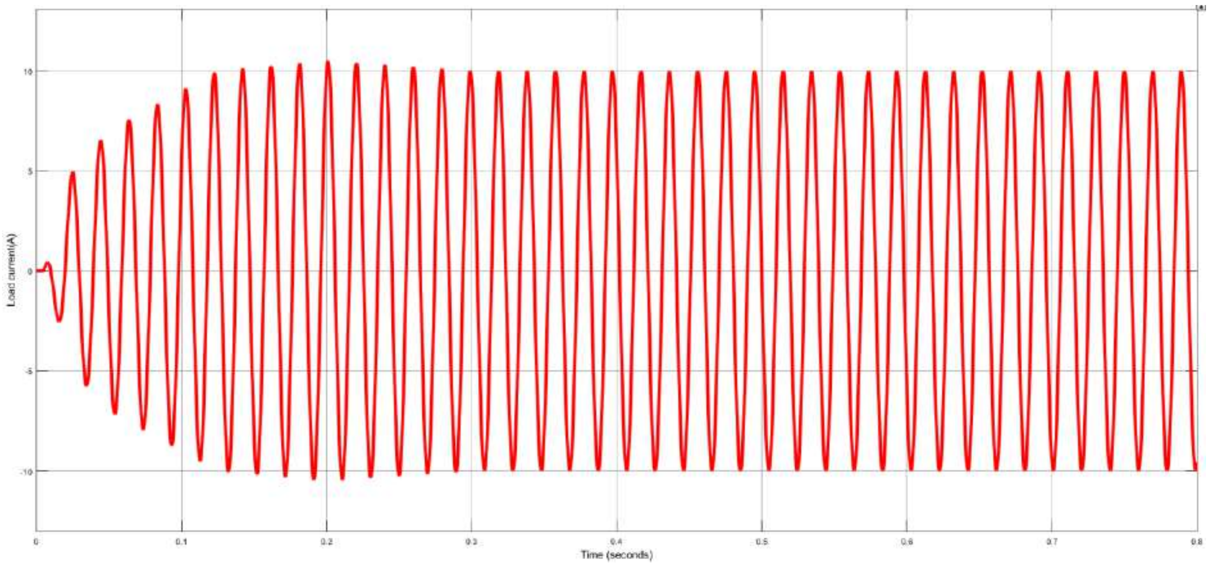
(d)


Load current(A)
10
5
0
-5
-10
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Time (seconds)

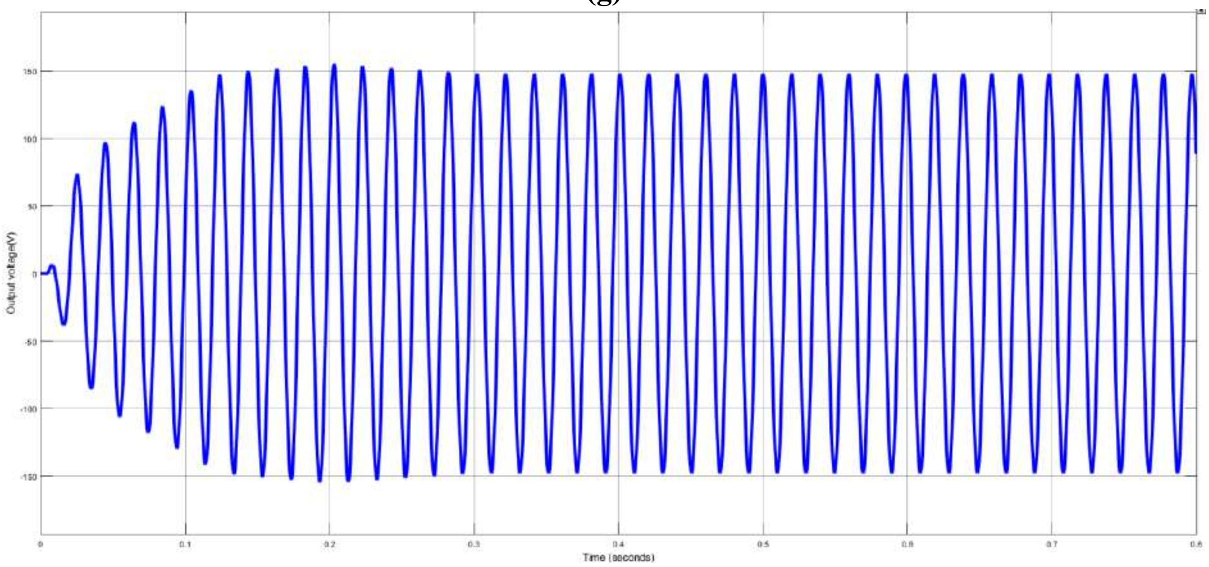
(e)


Output voltage(V)
250
200
150
100
50
0
-50
-100
-150
-200
-250
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Time (seconds)

(f)



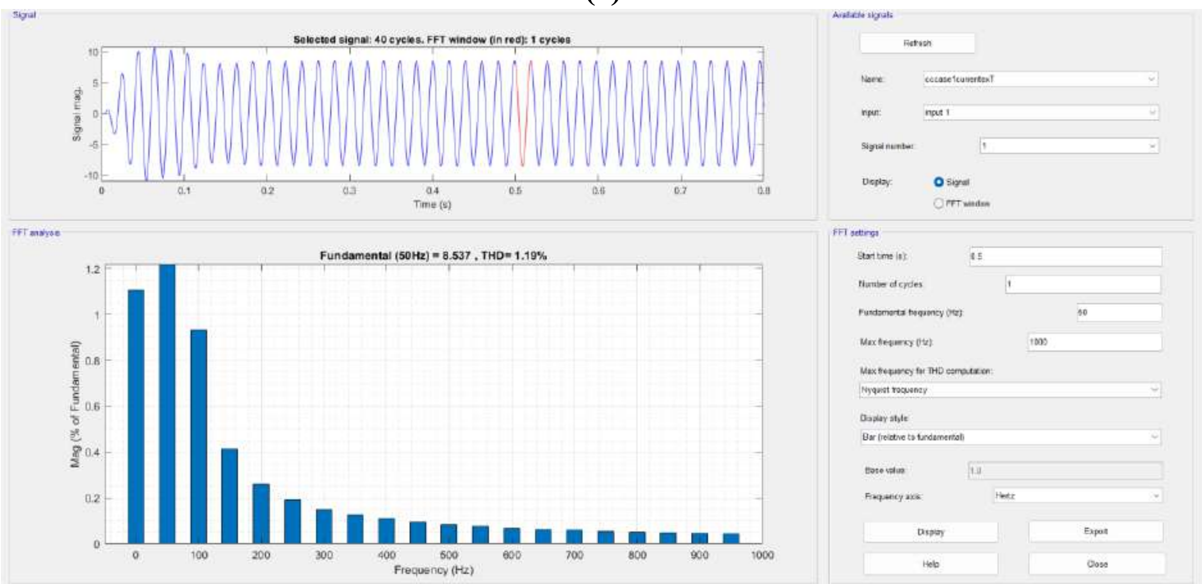
(g)



(h)

FIGURE 6 CC mode of operation measured load voltage and current (a) IL at 100% RL (b) VL at 100% RL (c) IL at 75% RL (d) VL at 75% RL (e) IL at 50% RL (f) VL at 50% RL (g) IL at 25% RL (h) VL at 25% RL .

(a)



(b)

FIG 7 THD% of Load voltage and current

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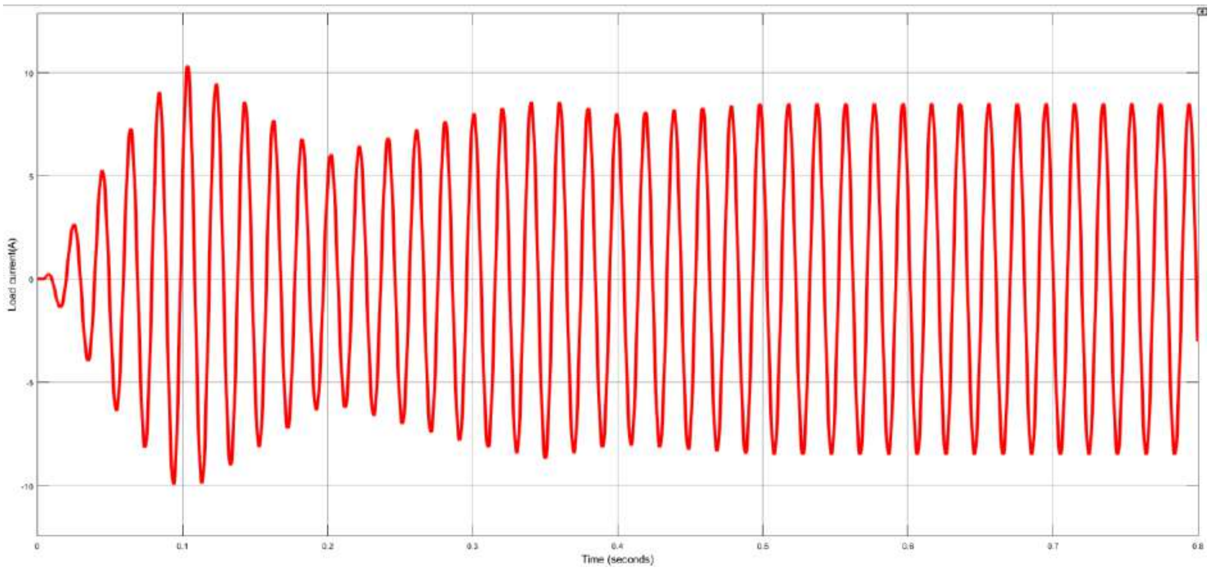
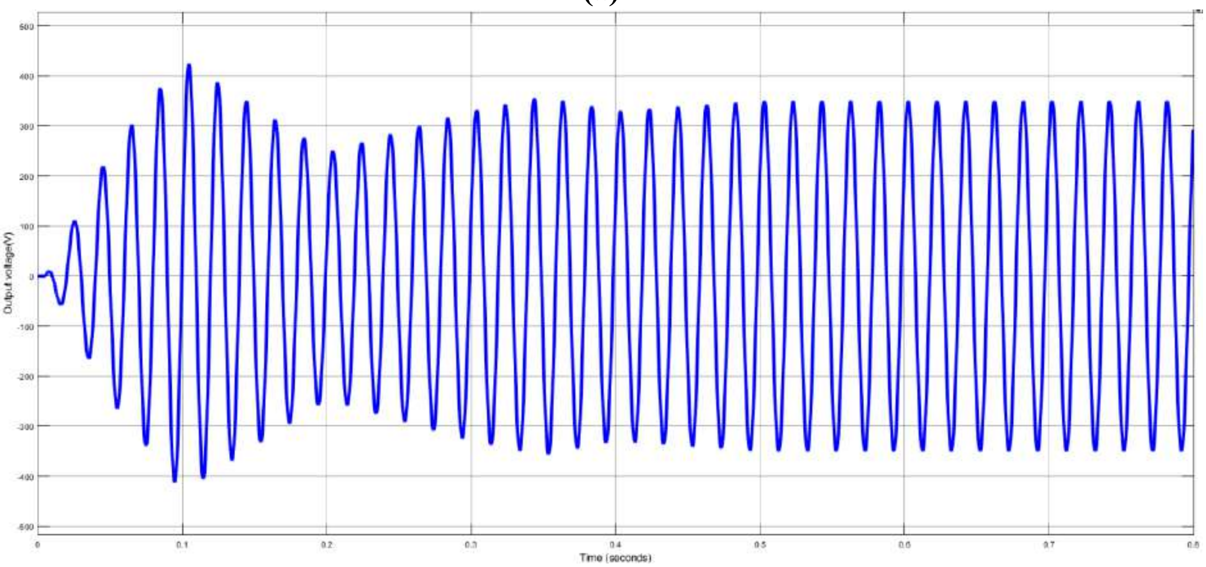
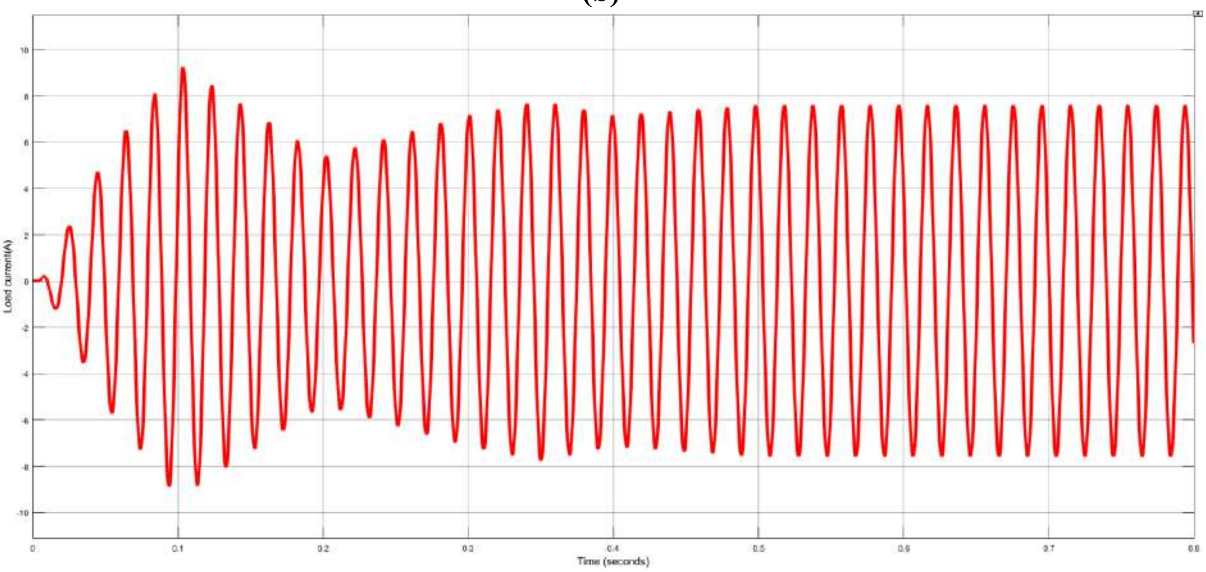


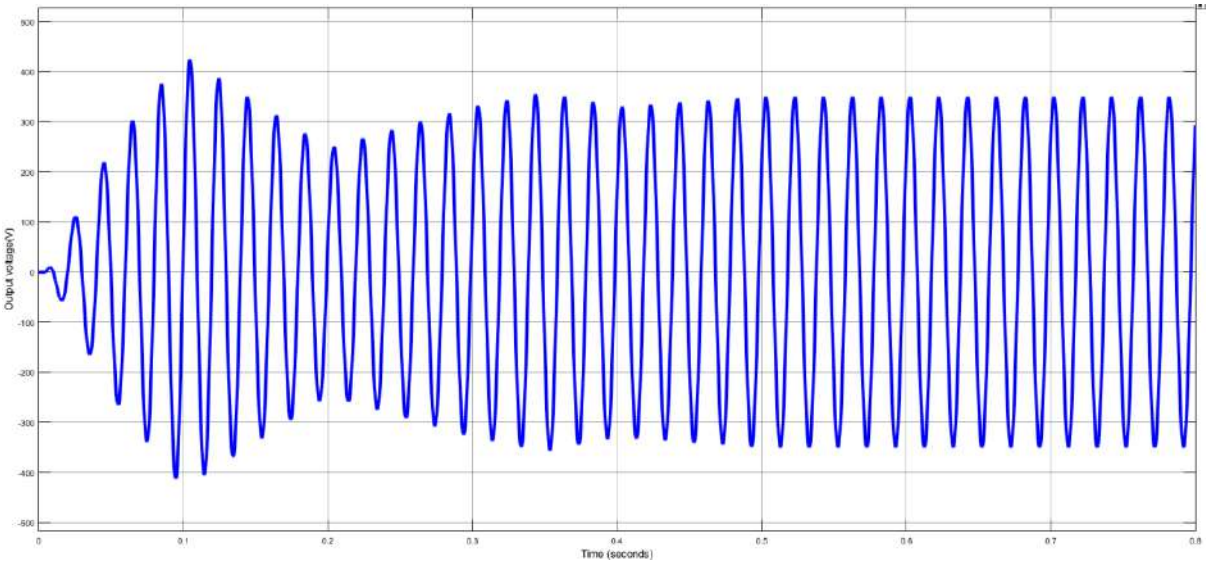
(a)



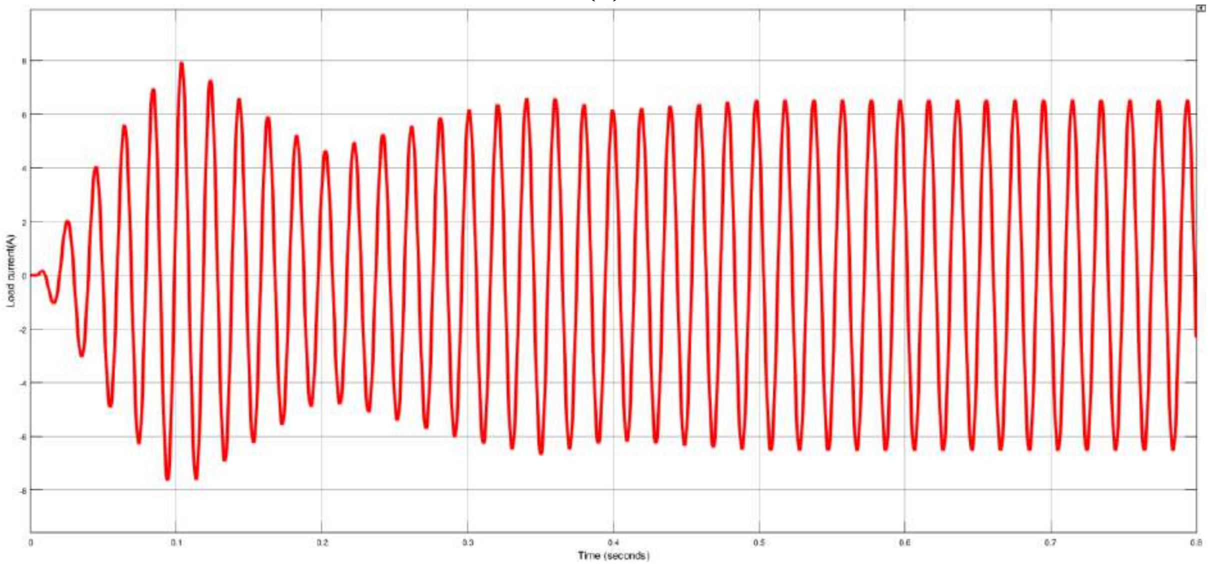
(b)



(c)


500
400
300
200
100
0
-100
-200
-300
-400
-500
Output voltage(V)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Time (seconds)

(d)


8
6
4
2
0
-2
-4
-6
-8
Load current(A)
0
0.1
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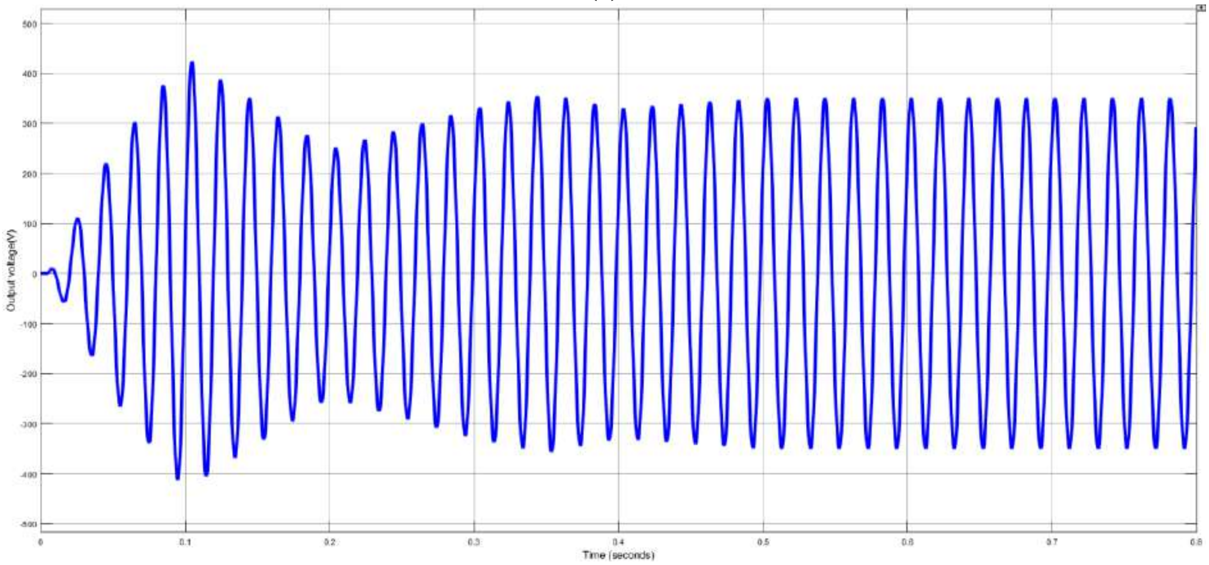
0.3
0.4
0.5
0.6
0.7
0.8
Time (seconds)

(e)


500
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-300
-400
-500
Output voltage(V)
0
0.1
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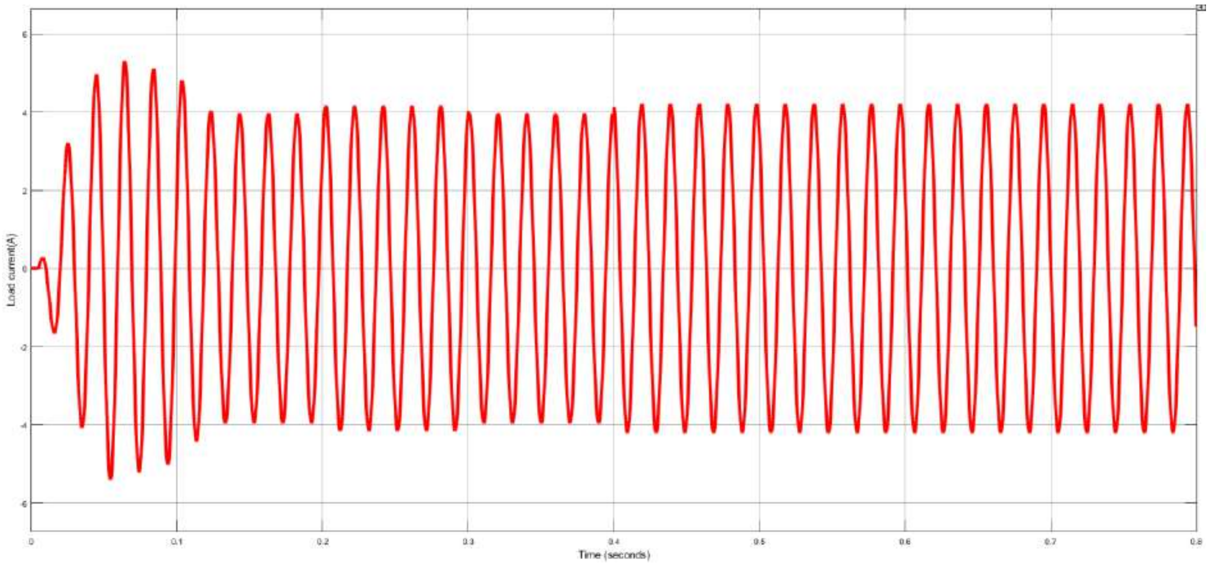
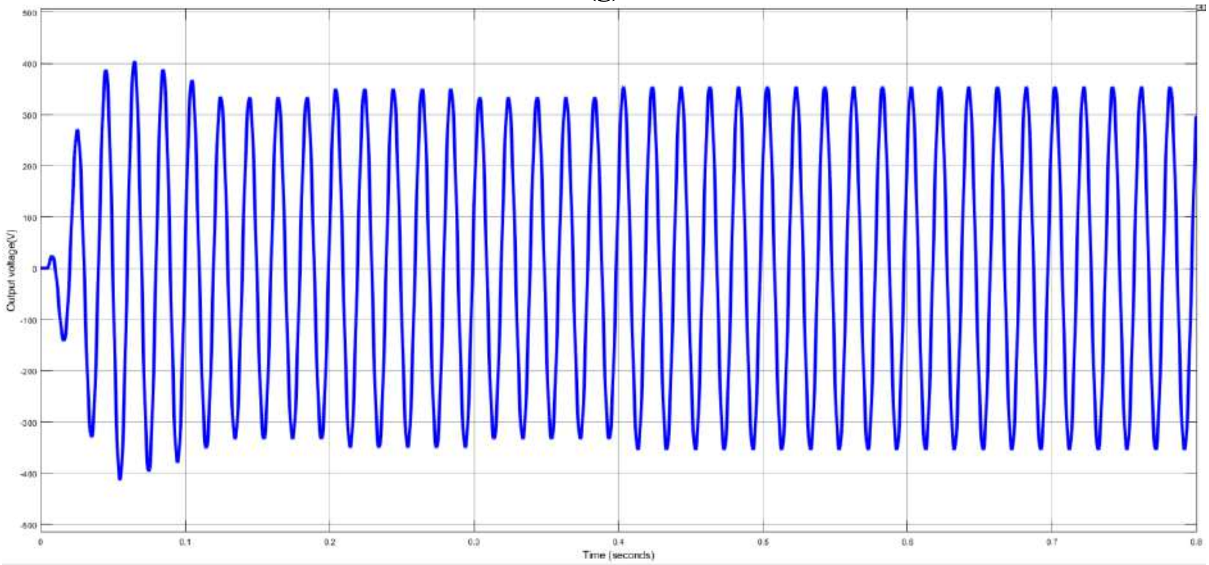
0.8
Time (seconds)

(f)

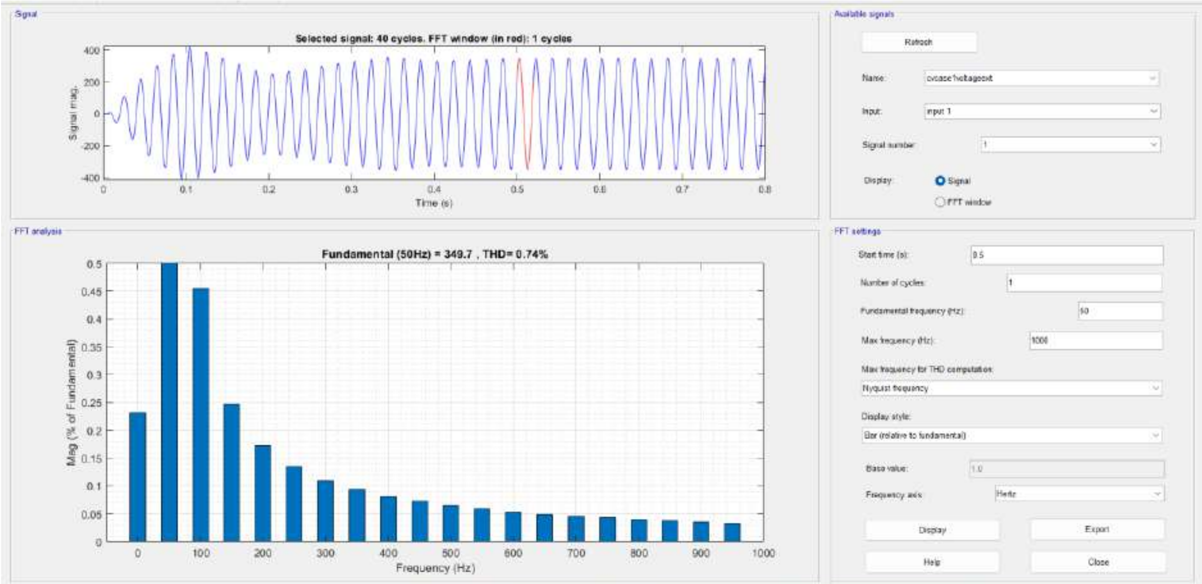


(g)

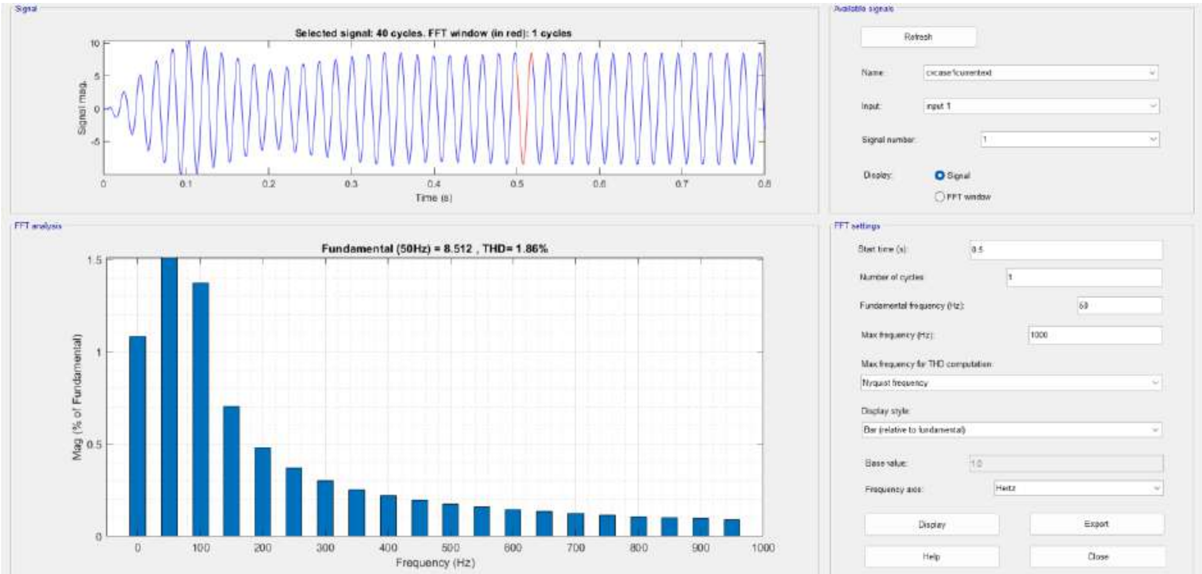


(h)

FIGURE 8 CV mode of operation measured load voltage and current (a) IL at 125% RL (b) VL at 125% RL (c) IL at 150% RL (d) VL at 150% RL (e) IL at 175% RL (f) VL at 175% RL (g) IL at 200% RL (h) VL at 200% RL



(a)



(b)

FIG 9 THD% of Load voltage and current

CONCLUSION

This paper introduces a PV integrated hybrid compensated WPT system that drives a receiver-side tuned resonant network-equipped constant wireless charging system. In addition to series compensation on the transmitter side, the control mechanism on the receiver side guarantees a consistent charging experience with constant current and voltage. The auxiliary switch facilitates mode changes, which are directed by driving pulses from the receiver-side controller in response to changes in battery voltage. Notably, this control method does away with the requirement for groundto-vehicle communication. The MPPT dc-dc converter keeps the voltage at the dc bus constant while the charging system is powered by the PV source and an energy storage device. Importantly, the proposed charging system runs independently of the utility grid, preventing it from adding to the network's growing power consumption. Due to its constant D.C. bus fed design, the stand-alone PV system consumes less power than a grid-connected system when charging the EV battery during periods of high irradiation. Even though the standalone PV integrated charging system primarily uses solar electricity, future utility grid interconnection is anticipated. The capacity to feed extra energy back into the grid during the generation of surplus electricity in high irradiation circumstances increases the system's adaptability and promotes grid sustainability. The limitation associated with the proposed system is that the absence of PV will make the system depend on the Grid or energy storage unit. However, the proposed system will cumulatively increase the usage of PV. Another limitation is that the pre calculation and design need to be done for the hybrid compensators considering the load and coupling variation to avoid the frequency bifurcation.

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