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AN ADVANCED CHARGING MECHANISM FOR ELECTRIC BIKESUSINGNOVEL POWER ELECTRONIC TOPOLOGIES

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ABSTRACT

This paper presents a two-stage onboard charger (OBC) design that enhances efficiency, power quality, and reliability for electric bike applications. The front-end stage consists of a single-phase Vienna rectifier, which achieves effective power factor correction while minimizing total harmonic distortion (THD). A fuzzy logic controller (FLC) dynamically regulates the rectifier based on voltage feedback to maintain stable and adaptive control. The back-end stage is designed as an LLC resonant converter, providing galvanic isolation and efficient regulation of the DC output. The converter control is implemented through a current-based FLC to optimize the switching frequency, ensuring better voltage regulation with minimal losses. By incorporating fuzzy logic control in both stages, the system enhances overall efficiency, reduces THD, and maintains robust performance across different load conditions. The proposed design is validated through simulation and is capable of delivering 500 W of power at an output of 52 V and 10 A, meeting the charging requirements of 48 V e-bike batteries. Therefore, the proposed OBC architecture provides a high-performance and scalable solution for next-generation e-bike charging systems while adhering to industrial standards for efficiency, reliability, and power quality.

Keywords: E-bike charging, LLC resonant converter, Vienna rectifier, On-board charger (OBC), Fuzzy logic control

1. Introduction

Electric vehicles (EVs) have emerged as a popular option for mitigating the negative environmental impacts of traditional fuel-powered vehicles. Among them, e-bikes are particularly effective for urban mobility due to their cost-effectiveness and eco-friendly nature. A critical component in any EV is the onboard charger (OBC), responsible for converting AC from the grid into a regulated DC output suitable for charging the battery. The efficiency of an OBC directly affects charging time, battery life, power quality, and overall system performance.

However, traditional charging systems face several issues, including low power factor, high total harmonic distortion (THD), poor efficiency, and increased switching losses. To address these challenges, a Vienna rectifier and an LLC resonant converter controlled by a Fuzzy Logic Controller (FLC) are employed in this study. This paper proposes an onboard charging system optimized for e-bikes using the aforementioned technologies.

The proposed system consists of two power conversion stages:

1. **Front-end stage:** A Vienna rectifier with a Wye-connected three-switch power factor correction (PFC) stage. This stage ensures high efficiency, low harmonic distortion, and compliance with power quality standards.
2. **Back-end stage:** An LLC resonant converter that provides high efficiency under varying load conditions, soft-switching capability, and reduced electromagnetic interference (EMI).

The Fuzzy Logic Controller (FLC) dynamically adjusts the gate pulses of the Vienna rectifier and the LLC converter in response to real-time measurements of current, voltage, and the battery's state of charge (SoC). This intelligent control mechanism optimizes power flow, minimizes energy losses, and enhances charging efficiency. Compared to conventional PI controllers, fuzzy logic offers greater adaptability and robustness under variable load and grid conditions.

Furthermore, the inclusion of a galvanically isolated transformer improves both reliability and safety by ensuring electrical separation between the battery and the grid. The proposed system is suitable for lightweight electric mobility applications, delivering 500 W of output power for charging a 48 V e-bike battery. MATLAB/Simulink simulations validate the design, showing improvements in power factor, efficiency, and reduced THD compared to traditional rectifier-based chargers. Hardware implementation further demonstrates its potential for commercial deployment in next-generation e-bike charging systems, confirming its practical efficacy.

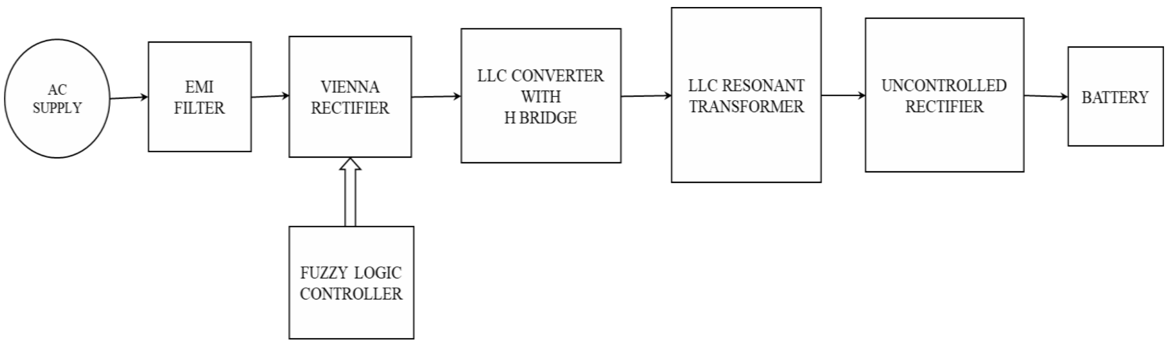

Figure 1: Block diagram of the proposed two-stage battery charger

The flow of the proposed two-stage battery charger, which is controlled by fuzzy logic, is shown in Figure 1. By integrating an LLC resonant converter with intelligent fuzzy logic control and a high-performance Vienna rectifier, this design advances the development of reliable, efficient, and optimized EV charging solutions. It contributes to improved e-bike performance while promoting sustainable energy usage.

2. Literature

Electric vehicle (EV) chargers play a crucial role in the adoption of sustainable transportation. Several studies have explored power electronic converters, specifically Vienna rectifiers and LLC resonant converters, for their efficiency and performance in onboard charging applications.

Abdel-Rahman and Infineon Technologies (2012) provided a detailed operation and design methodology for the resonant LLC converter, highlighting its advantages in achieving high efficiency and reduced switching losses [1]. Deng et al. (2013) further developed a design methodology for LLC resonant converters specifically for EV battery chargers, optimizing efficiency across varying loads [6]. Similarly, Wang et al. (2014) analyzed a full-bridge LLC-based charger optimized for wide battery voltage ranges, making it suitable for diverse EV applications [15].

Vienna rectifiers have also been extensively studied for their role in power factor correction (PFC) and high-efficiency conversion. Vahedi et al. (2015) proposed a single-phase, single-switch Vienna rectifier for EV battery charging, demonstrating its potential for simplified control and high power density [14]. Thangavelu et al. (2015) modeled and controlled a Vienna rectifier, focusing on single-phase applications and improved efficiency [13]. More recently, Ali et al. (2021) introduced a soft-switched Vienna rectifier topology for EV chargers, enhancing efficiency and reducing switching losses [2].

Several researchers have explored integrated charging solutions using Vienna rectifiers and LLC resonant converters. Chaurasiya and Singh (2020) developed a home charging system integrating a Vienna-based modified CUK converter with an LLC resonant converter, improving efficiency and power quality [4]. Similarly, Pandey and Singh (2020) proposed an EV charger utilizing a Vienna rectifier and LLC resonance, emphasizing its superior performance over conventional PFC circuits [8]. Band R (2022) demonstrated an onboard EV charging system incorporating these technologies, providing insights into practical implementation challenges and solutions [3].

Beyond circuit design, control strategies play a crucial role in optimizing charger performance. Prasad et al. (2015) introduced a unidirectional onboard automotive charger utilizing sine charging, showing its impact on lithium-ion battery longevity [11]. Shabarish et al. (2020) explored a fuzzy logic-based approach for wireless EV charging, highlighting its benefits in enhancing efficiency and adaptability [12].

Practical design considerations and real-world implementations have also been studied. Daniel and Chandrakala (2021) presented the design of an isolated onboard plug-in EV charger, focusing on reliability and safety aspects [5]. Praneet et al. (2019) proposed a universal onboard battery charger capable of supporting a wide output voltage range, making it a versatile solution for various EV types [9].

The reviewed literature highlights significant advancements in EV onboard charger development, focusing on high-efficiency power conversion, robust control strategies, and practical design implementations. The integration of Vienna rectifiers with LLC resonant converters has emerged as a promising solution, offering improved power factor correction, efficiency, and adaptability to varying battery conditions. These studies provide a strong foundation for further research in optimizing onboard charging systems for electric vehicles.

I. On-boardBatteryCharger

Modern power conversion technologies, such as two-level onboard chargers (OBCs), can efficiently and reliably charge electric vehicles (EVs). Voltage regulation and damping are incorporated during both the rectification phase and the back-end DC–DC conversion phase. This modular approach enables optimal performance in terms of power factor correction, voltage regulation, and load compatibility. The front-end Vienna-type single-stage rectifier and the LLC resonant inverter [5], based on the equivalent circuit of the proposed architecture shown in Figure 2, form the foundation of this research.

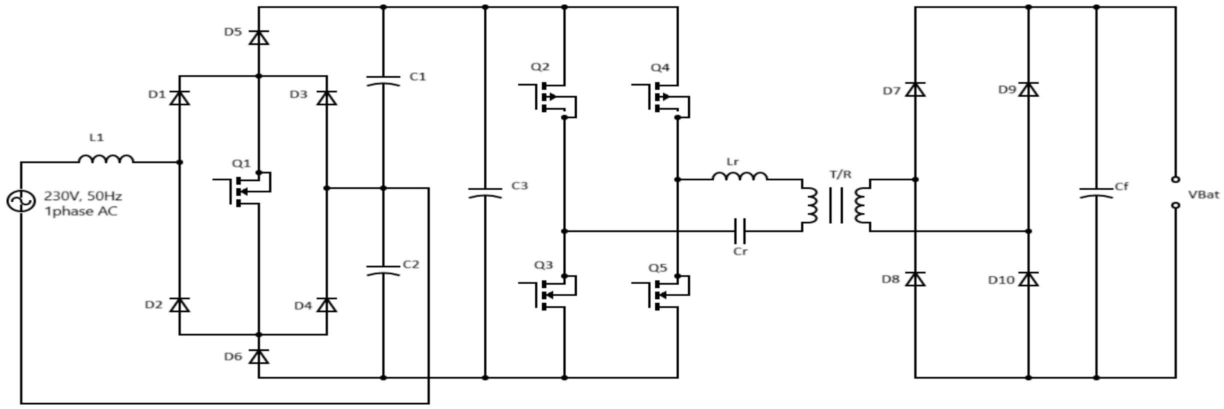

Figure2: Equivalent Circuit of Proposed methodology

A single-stage Vienna rectifier [14], which utilizes a single active electronic switch with six diodes, is designed to serve as an EV battery charger. Power factor correction (PFC) is recommended by the IEC 61000-3-2 standard [4], and the Vienna rectifier provides excellent PFC performance for EV charging applications. In the next stage, the rectifier's DC output is further processed by a DC–DC resonant converter to meet the voltage and current requirements of the battery [15]. The gentle switching characteristics of the LLC resonant converter enable high performance across a wide load range while providing galvanic isolation between input and output, making it the preferred choice for this stage. Full-bridge LLC stages can also be scaled to higher power levels due to their high power density and conversion efficiency [15].

To ensure a stable DC output and effective PFC under varying grid conditions, a fuzzy logic controller (FLC) utilizes the voltage feedback loop in the front-end Vienna rectifier. The FLC regulates the LLC resonant converter's output current and voltage based on current feedback, preventing overcharging and overheating while guaranteeing optimal battery charging.

Unlike conventional PID controllers, the FLC handles system uncertainties and nonlinearities through rule-based decision-making, enabling precise control and smooth performance adjustments. This design significantly improves system efficiency, reduces total harmonic distortion (THD), and ensures reliable and high-quality charging for electric bike applications.

Single-stage Vienna Rectifier

The single-stage, single-switch Vienna rectifier [14] is derived from the three-stage Vienna rectifier shown in Figure 3. To minimize input current harmonics, power factor correction (PFC) is employed [16], which also helps reduce interference with other devices operating from the same power source [14]. Due to its connection topology, this rectifier offers several advantages: each component provides half of the DC bus voltage at any given time [14]. It should be noted that during each half-cycle of the input AC waveform, the maximum DC voltage VdcV_{dc}Vdc is divided into two equal parts, each equal to Vdc/2V_{dc}/2Vdc/2.

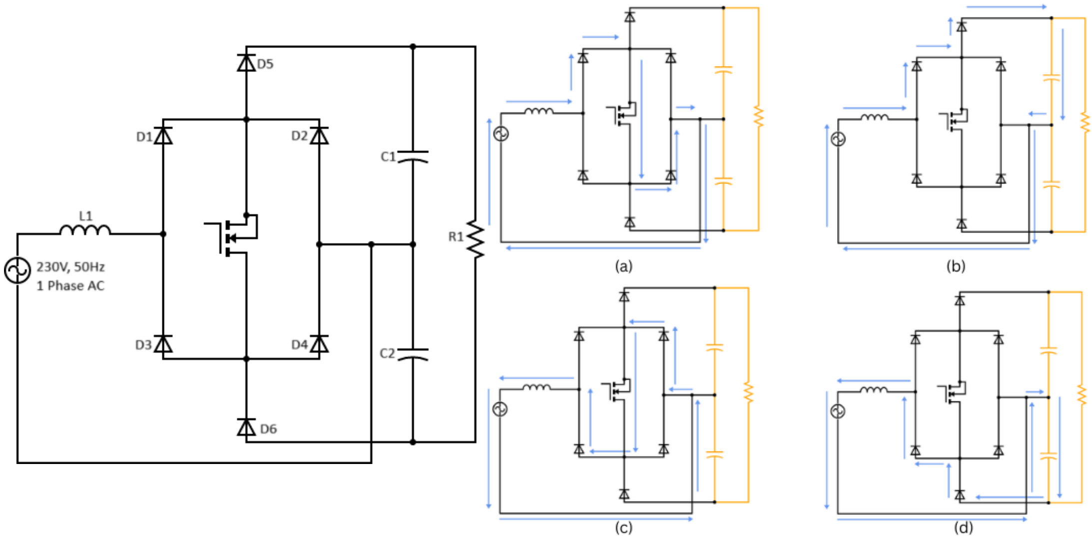

Figure 3: Single-phase Vienna rectifier with its mode of operation

Single-stage Vienna rectifiers have the intrinsic ability to balance the capacitor voltage without additional control and sensing circuitry [4], across a single AC voltage waveform cycle. There are four components to the power transfer. As shown in Figure 3 [13], when Q1 is turned on during the input power supply's positive half-cycle (a), current builds up in the inductor L1 and passes via D1, Q1, and D4 to charge the inductor. Concurrently, due to their sufficient size, the output capacitors C1 and C2 provide the load. Thus, it can be said that there won't be any change in the output voltage [13].

In the opposite direction of the input power supply's positive half-cycle (b), the energy stored in the inductor is transferred to the output capacitor C1 when Q1 is closed. Until it reaches neutral, the inductor's current passes through Q1, D1, D5, and C1 [13]. Additionally, current R1 flows within the load, finds the way to neutral through C2, and releases C2 a little.

When Q1 is turned on during the input power supply's (c) negative half-cycle, current L1 builds up in the inductor in the opposite direction of Mode I and moves from neutral to phase via D2, Q1, and D3 [13]. The load is supplied by output capacitors C1 and C2. During the same negative half-cycle of the input power supply (d), when Q1 is closed, the energy stored in the inductor at the output capacitor C2 is transferred, causing the inductor current to diverge from Q1 and flow through C2, D6, and D3 from neutral to phase. Furthermore, a portion of the current passes via load R1, causing C1 to partially discharge [13].

Resonant Converter – LLC

The proposed H-bridge LLC resonant converter topology offers several desirable characteristics, including high power density, low electromagnetic interference (EMI), and high efficiency [1]. However, the design process for resonant converters is more labor-intensive and requires more complex optimization compared to conventional converters such as PWM-based designs [1].

The LLC resonant converter also enables soft-switching operation. Current flows through the main switching devices only when the voltage is zero, achieving ideal zero-voltage switching (ZVS) [1]. The converter operates under resonant conditions, where the resonance frequency of the tank circuit matches the resonant switching frequency [1]. The resonant frequency of the tank circuit is determined by the resonant capacitance and resonant inductance. The LLC converter reaches resonance at only one operating point, at which the gain of the converter is unity [1].

Although certain disadvantages exist, the LLC resonant converter continues to operate effectively and consistently under practical conditions.

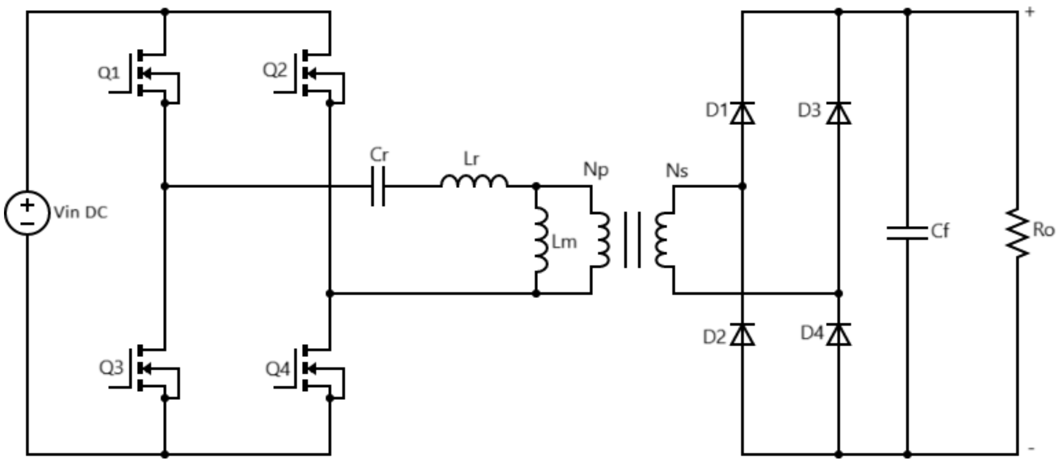

Figure 4: LLC resonant converter

As shown in Figure 4 [15], the operation of a H-bridge LLC resonant converter has four parts: (a) a DC voltage source with a fully regulated H-bridge converter that acts as a pulse generator like a square wave; (b) Resonance tank; (c) Transformer with turns ratio: 1; (d) Full bridge without rectifier control and filter capacitor. To put it simply, a [1] transformer and rectifier in the output section scales and rectifies the sinusoidal current that is supplied by the LLC resonant tank, which is excited by a square wave produced by the switching bridge. The output capacitor rectifies the AC current and sends it as a DC voltage that the battery needs to charge. It also serves as a filter. The battery pack is regarded as a resistive load, which is determined by dividing the charging current by the battery voltage [15]. According to [15], the LLC resonant converter also serves as a filter. This removes the input square wave's higher odd harmonics. The peak resonance current has been calculated, as shown in

$$I_{RP} = \frac{2\pi P}{2V_b}$$

With the selected switching frequency of 100KHz, Resonant capacitors are implemented using

$$C_r = \frac{I_{RP}}{2\pi F_s}$$

To obtain the converter voltage [5], the ratio of Lm and Lr is used as a default of 0.3, so the resonant
inductance and magnetic inductance can be calculated as;

$$L_r = \frac{1}{(2\pi F_s)^2 C_r}$$

$$L_m = 0.3L_r$$

Fuzzy Logic Control Implementation

Fuzzy logic controllers help maintain accuracy and reduce poor performance [12]. The input part involves transforming the fuzzy input into a corresponding membership function, such as a trapezoid or Gaussian. The next step calculates the input according to the rules, such as centroids, weighted averages, etc., and then, in the third and final step, the data is de-fuzzified [12].

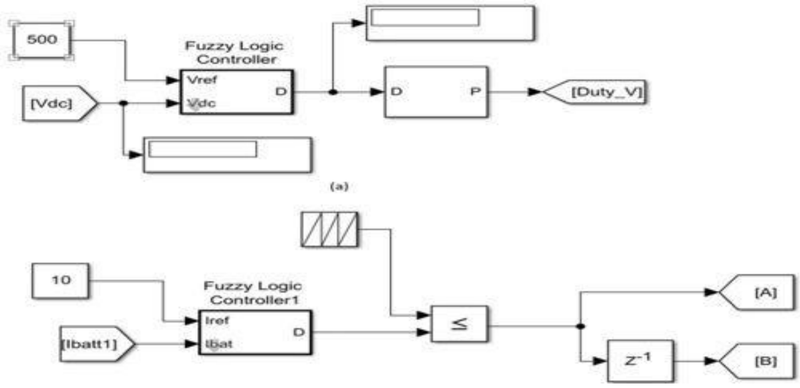

Figure5: Fuzzy Logic Control Implementation

The fuzzy logic controller used in the OBC charger controls two functions. The switching control of the Vienna rectifier using a voltage provides an optimized PWM output, as shown in Figure 5. Another operation is controlling the H-bridge LLC by sensing the current value to the battery to achieve fast charging and better battery life. Thus, the controller can manage system uncertainties and nonlinearities, allowing for accurate control and seamless performance changes.

3. Simulation Results

The proposed onboard charger simulation, shown in Figure 6 with specifications in Table 1, was developed in MATLAB/Simulink and tested on a 48 V lithium-ion battery. The simulation was run for a period of 10 seconds. A maximum current of 10 A is reached at the output, with an output voltage of 52 V at the battery, as shown in Figures 7 and 8. The Vienna rectifier increases the input voltage to 500 V with a PFC of 94.77%, and it works reliably under the current operating conditions.

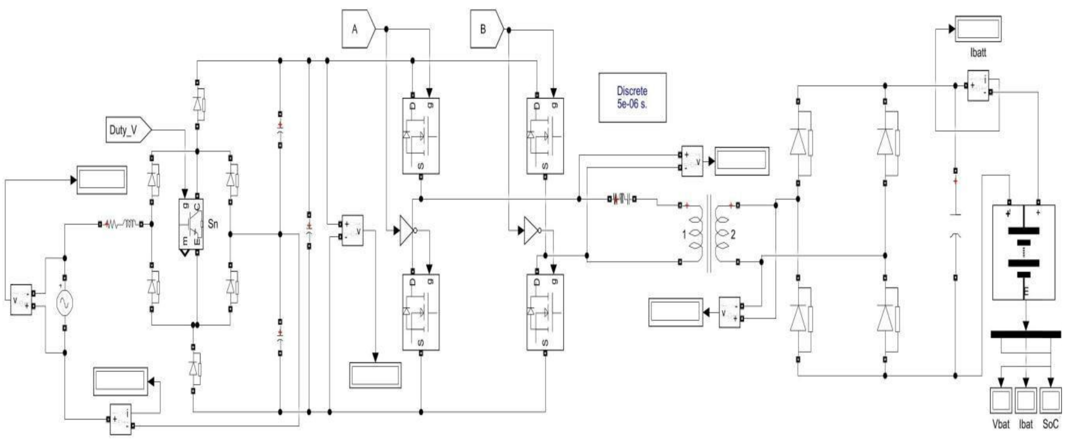

Figure6: Simulation of Proposed Topology

Quantity	Parameters
Vin	325V
Vo	50V
Io	10A
Efficiency	92
Resonant Capacitor	9.24nF
ResonantInductor	274.1μH
MagnetizingInductor	1644.6μH
FilterCapacitor	7000μF
SwitchingFrequency	20kHz
L1	1mH
DC-LinkCapacitor	1500μF

Table1: Specifications of Proposed Topology

A maximum current of 10 A is reached at the output, with an output voltage of 52 V at the battery, as shown in Figures 7 and 8. The Vienna rectifier increases the input voltage to 500 V with a PFC of 94.77%, and it works reliably under the current operating conditions.

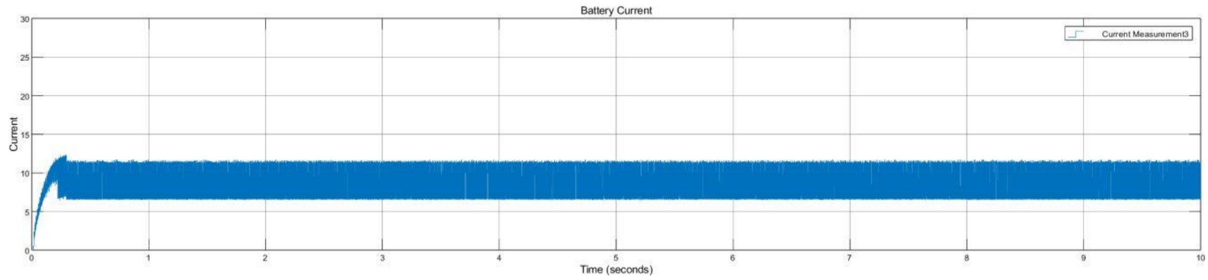

Figure7:OutputCurrent

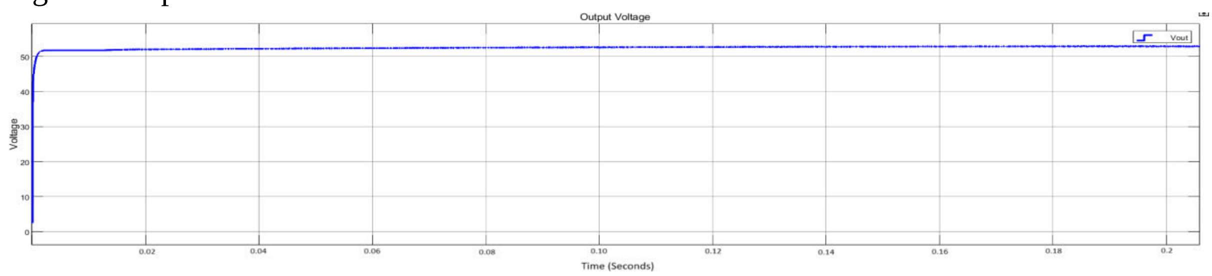

Figure8:OutputVoltage

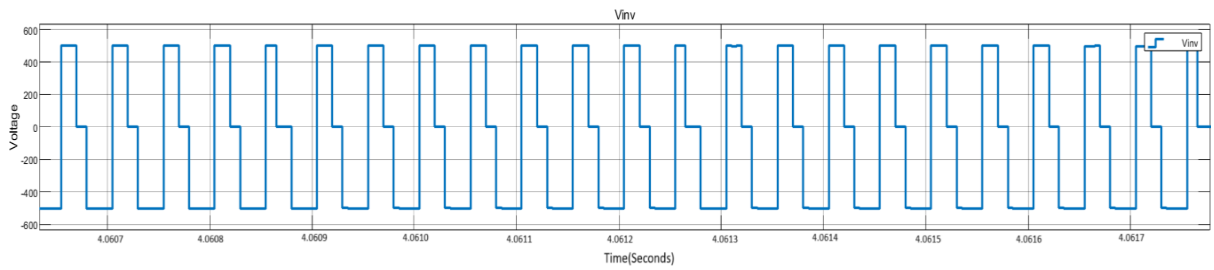

Figure 9: H-Bridge Inverter Output Voltage

Figures 9 and 10 show the voltage of the inverter and after the LLC transformer. The battery is rated at 48 V, and at an initial state of 50%, it is charged using the presented charger..

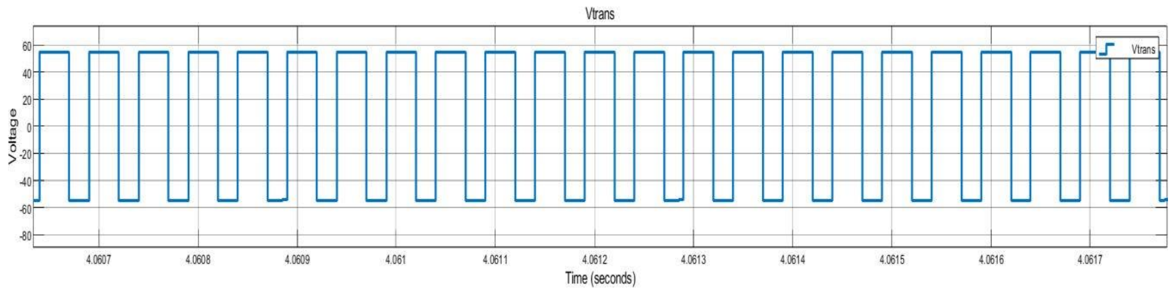

Figure 10: LLC transformer output voltage

A full-bridge LLC resonant converter is connected to the battery, which charges according to the requirements using fuzzy logic control. Different parameters of the battery are taken as the state of charge (SOC) over time, as shown in Figure 11.

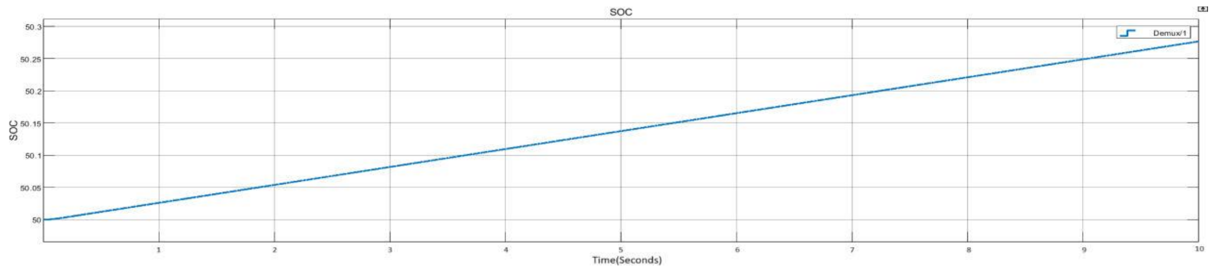

Figure 11: State of charge (SOC) of the battery

The proposed onboard battery charger, using a front-end Vienna rectifier and a back-end LLC resonant converter, charges the battery in an optimized and reliable manner using fuzzy logic control, as shown in the above figure. With this charging topology, low-voltage batteries can be efficiently used in the electric vehicle sector.

4. Conclusion

In this paper, an optimized charging system for e-bikes using a Vienna rectifier and an LLC resonant converter controlled by a fuzzy logic controller was proposed and analyzed. The system was designed to enhance power factor correction, improve efficiency, and ensure stable charging performance. A simulation model was developed in MATLAB/Simulink to validate the proposed topology.

The simulation results demonstrated that the system achieved an output voltage of 50 V and a current of 10 A, meeting the charging requirements for a 48 V e-bike battery. The Vienna rectifier effectively improved the power factor while minimizing harmonics, and the LLC resonant converter enabled soft switching, reducing losses and enhancing overall efficiency. The fuzzy logic controller dynamically adjusted to variations in battery conditions, ensuring optimal power flow and improving battery lifespan. Compared to conventional chargers, the proposed system provided better voltage regulation and current stability.

Future work can focus on hardware implementation and experimental validation of the proposed system. Additionally, integrating advanced machine learning techniques could enhance the controller's adaptability, further optimizing charging efficiency. Expanding the system for higher power applications and bidirectional energy transfer for vehicle-to-grid (V2G) applications can also be explored.

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