Design and Performance of a Fuzzy Logic Controlled High Current Density DC–DC Converter for Electric Vehicle Charging

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***Abstract*—** Electric vehicles (EVs) are becoming increasingly popular in the automotive industry due to their environmental benefits. Given that EVs rely on rechargeable batteries for power, it is crucial to have a reliable, efficient, and economical battery charger capable of delivering a stable and appropriate output for the specific EV battery. This proposed system presents a DC-DC converter with a fuzzy logic controller designed to achieve the required output voltage and high current density with minimal overshoot for a specified lithium-ion battery system, thereby reducing charging time.

In addition to minimizing power loss in active switches, the proposed system also reduces junction temperature, thereby extending the converter's lifespan. The converter's performance is analyzed under both ideal and non-ideal conditions, focusing on power loss and junction temperature of active MOSFET switches. Effective and economical dc and ac side inductors are designed and their impact on total power loss and temperature rise is evaluated. The results demonstrate that the proposed converter can maintain a power factor of around 92% and a total harmonic distortion of approximately 23%, making it ideal for high-density load currents. The reliability of the DC-DC converter is also assessed. Furthermore, a hardware prototype has been developed to validate its practicality for EV battery charging systems.

***Keywords*—** Buck converter, lithium-ion battery charger, dc-dc converter, isolated ac-dc converter, power factor correction, MOSFET power loss estimation, MOSFET thermal analysis, Fuzzy logic controller.

1. INTRODUCTION

In electric vehicles (EVs), the rechargeable battery is a crucial and sophisticated system that powers the vehicle. Therefore, it is essential to have an efficient, reliable, and economical battery charger for EVs. Typically, an AC-DC converter is required to meet these needs. AC-DC converters can be either isolated or non-isolated. In non-isolated systems, the diode and active switch experience more stress, resulting in higher power loss and increased temperatures. Additionally, the lack of isolation raises safety concerns. Conversely, isolated systems can lower voltage to meet requirements, reducing power loss and temperature at the junctions of these devices, and providing enhanced safety, which improves the system's overall reliability.

Conventional diode rectifiers used in AC-DC conversion led to significant power loss, degrading power factor and increasing total harmonic distortion (THD). While power factor correction (PFC) topologies can address these issues, they tend to be complex and costly. To overcome this, a low-frequency coupled inductor-based AC-DC converter has been proposed, incorporating an LCL filter and two diodes to improve efficiency. Following AC-DC conversion, the voltage must be regulated according to the lithium-ion battery's condition. A fuzzy logic controller integrated into a DC-DC converter can achieve this regulation. Conventional closed-loop DC-DC converters, however, dissipate high power loss in active switches, reducing the overall system's lifecycle due to conduction, switching, and leakage power losses. Additionally, output voltage and current overshoot can adversely affect lithium-ion batteries.

To address these challenges, a “fuzzy logic controller” (FLC) was introduced from previous work, further optimized to reduce conduction, switching, and leakage power losses. This modification enhances current regulation, thereby minimizing total power loss without compromising switching frequency, which helps maintain the size of passive components. Thermal management of the active switch is also considered, using heatsinks to maintain junction temperature by increasing the surface area exposed to ambient air.

This Prepose system presents a reliable, efficient, and economical AC-DC converter for charging EV lithium-ion batteries. A comprehensive analysis of the converter, including power loss and junction temperature of MOSFETs under three different conditions, is provided. The effectiveness of the proposed system is further validated through hardware prototype implementation and testing.

Isolation ensures safety by electrically separating the input and output, reducing stress on components, and improving reliability, whereas non-isolation is simpler and potentially less expensive but increases stress on components and poses safety risks. Power factor correction (PFC) is essential for reducing power loss and improving efficiency. Conventional PFC methods are complex and expensive, but the proposed system offers a simplified solution with a low-frequency coupled inductor and LCL filter. Voltage regulation with a fuzzy logic controller provides adaptive control to maintain optimal charging conditions, reduces power loss in active switches, and minimizes overshoot in output voltage and current, protecting the battery. The modified proportional integral (MPI) controller further reduces power loss through optimized control, enhances current regulation, and maintains efficient operation without increasing component size. Thermal management using heatsinks improves thermal dissipation, maintaining lower junction temperatures and enhancing component lifespan. Hardware prototype validation confirms the practical viability of the proposed system and demonstrates real-world performance and reliability.

The proposed AC-DC converter with a fuzzy logic controller offers a robust solution for EV battery charging, ensuring efficiency, reliability, and economical operation. The detailed analysis and hardware validation underline its potential for widespread adoption in the EV industry.

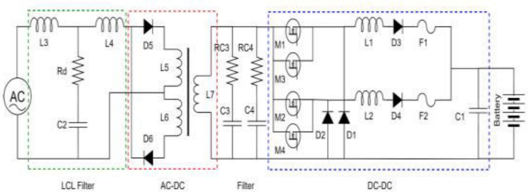

Figure 1. single-phase AC source to deliver power to the load

The proposed system, depicted in Figure 21, utilizes a single-phase AC source to deliver power to the load. An LCL network is positioned adjacent to the AC source for filtering purposes and to manipulate the power factor and total harmonic distortion (THD). Two diodes, D5 and D6, direct the AC flow to the primary side of a coupled inductor, where the rippled DC is obtained from the secondary side. To reduce these DC ripples, components RC3, RC4, C3, and C4 are employed. Following this, four MOSFETs, M1, M2, M3, and M4, adjust the DC output voltage based on load requirements, while diodes D1, D2, D3, and D4 ensure a consistent DC flow. Additional components, such as inductors L1 and L2, and capacitor C1, are used for storing and filtering purposes. Protection is provided by fuses F1 and F2. Finally, a 44V 110Ah Lithium-Ion battery serves as the load.

2. PROPOSED SYSTEM BLOCK DAIGRAM REPRESENDETION

The proposed system for charging a lithium-ion battery in an electric vehicle (EV) consists of several interconnected blocks, each playing a crucial role in ensuring efficient and reliable battery charging.

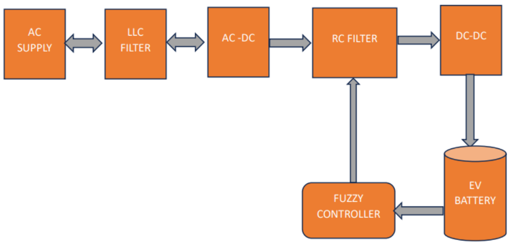

Figure 2. lock diagram for proposed system

The block diagram includes the following components AC Source Block, LLC Filter Block, AC-DC Converter Block, RC Filter Block, DC-DC Converter Block, EV Battery Block, and Fuzzy Logic Controller Block as shown Figure 2. The AC source block receives the input power, which is then processed through the LLC filter block to remove high-frequency noise and harmonics. The filtered AC power is converted to DC by the AC-DC converter block.

3. METHODOLOGY

3.1 AC-DC Converter Connected with LCL Filter.

The AC-DC converter connected with an LCL filter is designed to improve power quality by reducing harmonics and enhancing the power factor. The LCL filter consists of two inductors (L1 and L2) and a capacitor (C1) arranged in a specific configuration to achieve these goals.

The input as an AC source provide to AC to DC converter through LCL filter the AC source current calculate by the formula in equation 1.

$$I_{source} = \frac{\sqrt{2}\times P_{load}}{V_{ac}} A \quad (1)$$

The inductance from the LCL filter can be calculated as per our requirement that have standard formal given below equation 2.

$$L = \frac{X_L}{2\times\pi\times f_{ac}} H \quad (2)$$

Whare $X_{L=2\pi fL}$

By using above standard inductor formula we can be directly calculated from our proposed system and Maily we can calculate L_3 and L_4 in LCL filter.

The capacitor C_2 can be calculated in the LCL filter by using below given formula in equation 3.

$$C_2 = \frac{P_L}{2\pi f_{ac}\times V_{AC}} F \quad (3)$$

The resonant frequency can be calculated by using below formula equation 4.

$$F_r = \frac{1}{2\pi \times \sqrt{\frac{L_3 \times L4}{L_3 + L_4} \times C_2}} Hz \quad (4)$$

The damping resistance can be calculated aby using give formula in equation 5.

$$F_r = \frac{1}{6\pi\times F_r\times C_2} \quad (5)$$

Whare $f = AC\ source\ frequency, P_L = Load\ power$

The filter frequency response can be analysed based on the transfer function T(s) IN equation 6. and given herewith.

$$T(s) = \frac{R_d \times C_2 S + 1}{L_3 \times L_4 \times C_2 S^3 + (L_3 + L_4) \times R_d \times C_2 S^2 + (L_3 + L_4) S} \quad (6)$$

After adding the damping resistor, the overall response smooths and minimizes the spike that is associated with the system besides when the damping resistor was not concerned spikes do take place. Consequently, the designed filter exhibits more stability while the damping resistor is integrated.

3.2 DC-DC Converter Connected with RC Filter

The DC-DC converter, along with an RC filter, is essential for stabilizing the output voltage and minimizing fluctuations, providing a steady DC supply to the load. The RC filter includes resistors R1 and R2, and capacitors C1 and C2. R1 and C1 are connected in series, as are R2 and C2, and both pairs are then connected in parallel. This configuration effectively reduces high-frequency noise and ripple from the converter's output.

The transfer function H(s)of an RC filter in the Laplace domain can be expressed in equation 7.

$$Hs = \frac{1}{1 + RCs} \quad (7)$$

Where R is the resistance, C is the capacitance, s is the complex frequency variable.

Filtering High-Frequency Noise by The RC filter attenuates high-frequency components present in the DC output. The cutoff frequency f_c of the RC filter is given by formula in equation 8.

$$f_c = \frac{1}{2\pi RC} \quad (8)$$

Frequencies above f_c are significantly attenuated, reducing ripple and noise in the DC output.

The impedance Z(s) of the RC filter is frequency-dependent and can be expressed in equation 9.

$$Z(s) = R + \frac{1}{Cs} \quad (9)$$

At low frequencies DC component, the impedance is primarily resistive (R). At higher frequencies, the capacitive reactance $\frac{1}{Cs}$ decreases, allowing the capacitor to bypass high-frequency noise to ground, thus filtering it out from the output.

The RC filter smooths the DC output by charging and discharging the capacitor, reducing the ripple voltage. The ripple voltage V_r can be estimated in equation 10.

$$V_r \approx \frac{I_L}{fc} \quad (10)$$

Where I_L is the load current, f is the frequency of the ripple, and C is the capacitance.

The DC-DC converter connected with an RC filter enhances the quality of the DC output by reducing high-frequency noise and ripple. The RC filter's impedance characteristics and cutoff frequency play a critical role in attenuating unwanted components, ensuring a stable and smooth DC voltage suitable for sensitive electronic loads.

3.3 The Electric Vehicle concept

An electric vehicle (EV) is a type of vehicle that uses one or more electric motors for propulsion. Unlike conventional internal combustion engine vehicles that rely on gasoline or diesel, EVs are powered by electricity stored in batteries or other energy storage devices. This enables them to produce zero tailpipe emissions, making them environmentally friendly alternatives in the transportation sector. EVs can range from small electric cars to larger vehicles like trucks and buses, and they are gaining popularity globally as efforts to reduce carbon emissions and dependence on fossil fuels intensify.

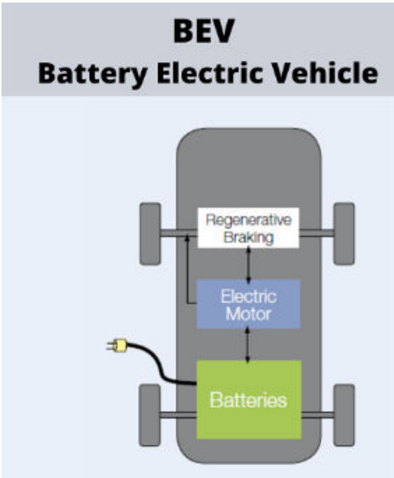

Figure 3 Battery Electric Vehicle (BEV)

A Battery Electric Vehicle (BEV) operates using high-capacity batteries and an electric motor for propulsion Figure 3. These vehicles rely solely on their battery packs for power, eliminating the need for internal combustion engines, fuel cells, or fuel tanks. Recharging is exclusively done through connection to a charging point. Prominent examples of AEVs/BEVs include the Chevy Spark and the Mercedes-Benz B-Class Electric, which are known for their emission-free driving and significant contributions to reducing environmental impact in urban settings.

3.4 Electric Vehicle Charging Station

An electric vehicle charging station is a specialized infrastructure designed to recharge electric vehicles (EVs). These stations provide electric power to charge the batteries of electric vehicles through various connection types, such as plug-in charging cables or wireless induction pads. Charging stations are classified into different levels based on the power output they provide, ranging from Level 1 is standard household outlet to Level 3 is DC fast charging, which can significantly reduce charging times. EV charging stations are crucial for extending the range and usability of electric vehicles, promoting their adoption by providing convenient and accessible charging solutions in public areas, workplaces, and homes. As the demand for electric vehicles grows, the development of an extensive charging infrastructure becomes increasingly important to support widespread EV use and reduce dependence on traditional fossil fuels.

We have developed a mathematical model to analyse the impact of EV chargers as non-linear loads. EV chargers operating at Level 2 AC charging, with a maximum current rating of 16 A and power rating of 3.3 kW, introduce harmonics, affect the voltage profile, and contribute to power losses in distribution transformers. Most electric vehicles operate within a power range of 0.5 kW to 1 kW, utilizing a single-phase 240 V, 50 Hz supply system. The model assesses how these factors combine to potentially overload transformers during EV charging operations.

The power demand from electric vehicle (EV) batteries affects the stability of the power distribution system due to their non-linear characteristics. Equation 11. expresses the power demand from an EV.

$$P_{EV} = \frac{C_{battey}}{T.D} \times SOC \qquad (11)$$

Where C_{battey} is the battery capacity, $T.D$ is the duration of charging, and SOC represents the state of charge of the battery, influencing whether the EV draws high or low power.

The total power demand from all EVs, Equation 12, is the sum of individual power demands.

$$P_{total} = \sum P_{EV} \qquad (12)$$

This equation signifies the cumulative impact of multiple EVs charging simultaneously on the power distribution system.

Harmonics are defined as the rise in high-frequency components of voltage and current compared to the fundamental frequency. These harmonics distort voltage and current waveforms, thereby affecting power quality. The impact of harmonics can be quantified using Total Harmonic Distortion (THD) for both current and voltage.

$$THD_i = \frac{\sqrt{\sum_{n-2}^{N} I_n^2}}{I_2} \times 100\% \quad (13)$$

$$THD_v = \frac{\sqrt{\sum_{n-2}^{N} v_n^2}}{v_2} \times 100\% \quad (14)$$

Equations (13) and (14) express the Total Harmonic Distortion (THD) for current and voltage, respectively. During slow charging, THD_I and THD_V are typically lower than during fast charging. Consequently, an EV with a low state of charge (SOC) is more likely to produce higher levels of harmonics.

The low voltage profile caused by EV charging poses a significant threat to the power network. Voltage stability refers to the power network's ability to remain stable following sudden increases or decreases in loads. EVs draw substantial amounts of power in a short duration, which can degrade the voltage profile and destabilize the grid.

He masses deployment of EVs adds significant stress to distribution transformers, affecting their life cycles. To mitigate this, the daily EV charging rate should be limited, and charging stations should be located far from transformers to reduce power loss. Harmonic currents cause load losses in transformers, while harmonic voltages result in no-load losses. These harmonic losses increase heating compared to a pure sinusoidal wave. The transformer's ability to withstand these harmonic effects is measured by a factor called the k-factor equation 15.

$$K - factor = \sum_{n-1}^{N} n^2 \left[\frac{I_n}{I_R}\right]^2 \quad (15)$$

The current related to the nth harmonic, I_n and the rated load current, I_R, determine the transformer's heating due to harmonics. Overheating from harmonics necessitates selecting transformers based on their capability to handle higher harmonic currents for non-linear loads.

4. FUZZY LOGIC CONTROL STRATEGY

A Fuzzy Logic Controller (FLC) is a control system that uses fuzzy logic to manage imprecise or uncertain information, making it ideal for complex and nonlinear systems. In the context of electric vehicle (EV) charging, an FLC offers significant advantages due to its adaptability and robustness. It can effectively handle the variable nature of power supply and demand in EV charging stations, adjusting the charging parameters dynamically to optimize efficiency and performance. By incorporating human-like reasoning, the FLC can make decisions based on a range of inputs and conditions, such as battery state, charging speed, and temperature. This results in a more efficient and reliable charging process, ensuring that EV batteries are charged quickly and safely while minimizing energy wastage and reducing the strain on the electrical grid.

A Fuzzy Logic Controller (FLC) is a control system that utilizes fuzzy logic, a mathematical framework designed for approximate reasoning rather than fixed, exact values. Unlike traditional binary logic, where variables must be either true or false, fuzzy logic allows variables to have truth values ranging from 0 to 1. This flexibility makes it particularly well-suited for control systems that need to manage uncertain or imprecise information.

The operation of an FLC involves several key components fuzzification, which converts crisp input values into fuzzy sets using membership functions Figure 4&5 rule base that consists of if-then rules derived from expert knowledge an inference engine that processes these fuzzy sets according to the rule base to generate fuzzy output sets; and defuzzification, which converts the fuzzy output sets Figure 6. back into crisp values

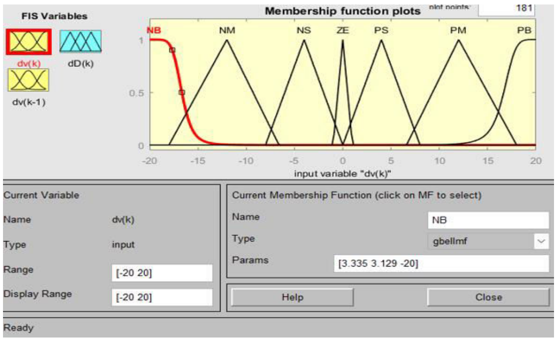

Figure 4. First Input values into fuzzy sets

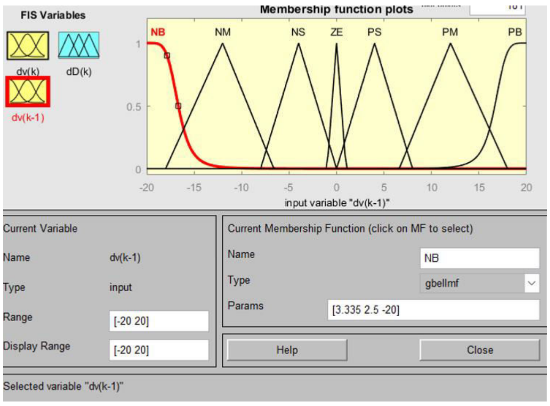

Figure 5. Second Input values into fuzzy sets

In the context of a five-level H-bridge converter, a type of multilevel inverter used to generate high-quality output voltage with lower harmonic distortion, an FLC proves particularly effective. The primary control objectives for the H-bridge converter include maintaining voltage regulation, minimizing harmonic distortion, and balancing the voltage across each H-bridge module.

The FLC uses input variables such as the error (the difference between reference and actual voltage) and the rate of change of error to produce appropriate control signals. These signals then dictate the switching states of the H-bridge inverter stages to adjust the output voltage level to match the desired reference. The FLC's rule base is designed to provide specific outputs based on the input conditions, ensuring smooth control transitions and robust performance under varying operating conditions.

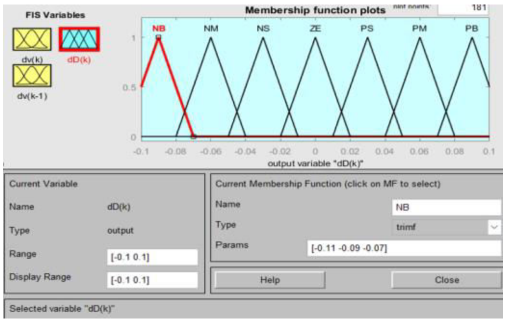

Figure 6. Output values into fuzzy

The benefits of using an FLC for a five-level H-bridge converter include its robustness in handling system non-linearity and uncertainties, its flexibility in adapting the rule base to different control requirements without complex mathematical modelling, and its ability to provide smoother control transitions, which reduce switching losses and improve efficiency. Overall, a Fuzzy Logic Controller offers an effective solution for managing the complex control requirements of a five-level H-bridge converter, enhancing performance in terms of voltage regulation, response time, and harmonic distortion levels. The proposed fuzzy is have 49 set of rules as shown Figure 6.

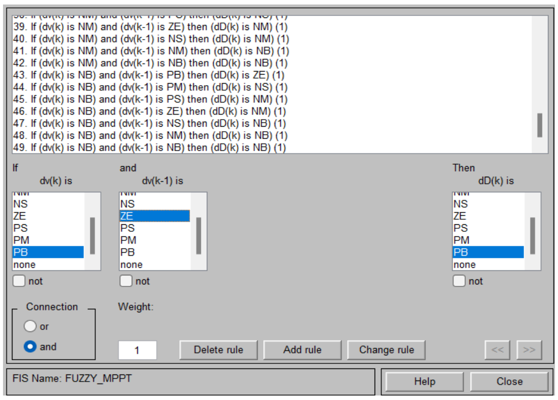

Figure 6. 49 set of rules

5.SIMULATION OF PRAPOSED SYSTEM

The proposed system simulation involves a sophisticated setup designed to charge an electric vehicle (EV) lithium-ion battery using a 230V AC supply. Initially, the AC supply is passed through an LCL filter composed of two inductors and a capacitor.

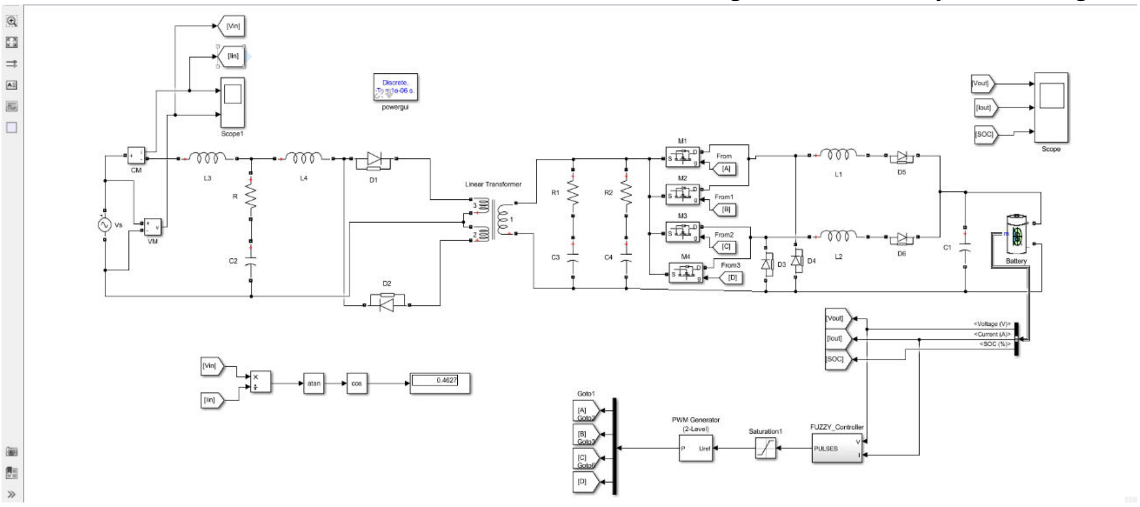

Figure 7. simulation of proposed system

This filter reduces harmonics and smooths the AC signal, mitigating high-frequency noise and improving power quality for subsequent stages. The filtered AC voltage then enters an AC to DC converter, which rectifies the AC signal into DC voltage necessary for battery charging as shown Figure 7.

The rectified DC voltage is further smoothed by an RC filter, which consists of a resistor and capacitor. This filter removes any remaining ripples or noise, ensuring a stable DC output. The stable DC voltage is then fed into a DC-to-DC converter, which adjusts the voltage level to match the required charging voltage for the lithium-ion battery. The converter ensures safe and efficient charging by providing the correct voltage and current levels.

A main component of the system is the fuzzy logic controller, which optimizes the charging process. The controller generates pulse-width modulation (PWM) signals to control the DC-to-DC converter. It processes input parameters such as the state of charge (SOC) of the battery, desired charging current, and other system variables to determine the optimal duty cycle for the converter. This results in high current density, enhancing the charging speed and efficiency of the EV battery.

In MATLAB/Simulink, can model this system by first representing the 230V AC supply with a sinusoidal source block. Then, create the LCL filter using inductors and capacitors, ensuring they are configured to filter out high-frequency components. Implement the AC to DC converter using a rectifier circuit, and then build the RC filter with resistor and capacitor blocks. The DC-to-DC converter can be implemented using a buck or boost converter, configured to step up or step down the voltage as needed. The Parameters of the proposed system is given in Table 1.

S.no	Parameters	Values
1	Input Source	1∅,AC,230V
2	Output voltage	51V
3	Output current	185.5A
4	Input capacitor (C2)	18.5 μF
5	Output capacitor (C1)	320 μF

6	DC inductors (L1, L2)	0.3mH
7	AC inductors (L3, L4)	2.82mH
8	Switching Frequency	35KHz
9	Filter capacitor (C3, C4)	$100\mu F$

Table 1. Parameters of the proposed system

The fuzzy logic controller (FLC) in your system plays a crucial role in optimizing the charging process of the EV lithium-ion battery as shown Figure 8. It is designed to generate pulse-width modulation (PWM) signals that control the DC-to-DC converter. The FLC processes input parameters such as the state of charge (SOC) of the battery and the desired charging current. Using a set of fuzzy rules and membership functions, the controller determines the optimal duty cycle for the DC-to-DC converter.

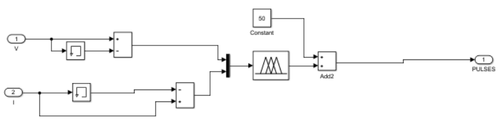

Figure 8. simulation of propose fuzzy control system

This approach allows the FLC to handle the non-linearities and uncertainties inherent in battery charging, ensuring high current density and efficient charging. The fuzzy logic controller continuously adjusts the charging process to maintain optimal conditions, protecting the battery from overcharging and overheating while maximizing the charging speed and efficiency.

By integrating all these components and running the simulation, you can observe the performance of your proposed system, ensuring all elements work together harmoniously for efficient and optimal charging. This comprehensive approach not only facilitates efficient battery charging but also protects the battery from overcharging and overheating.

6. ANALYSIS OF SIMULATION RESULTS

In the proposed simulation model, the system focuses on efficiently charging an electric vehicle's lithium-ion battery using a DC-DC converter controlled by a fuzzy logic controller. Initially, a 230V AC supply with 50Hz serves as the input to the system shown belove Figure 9. This AC supply undergoes filtration through an LCL filter. This component plays a critical role in the process by reducing harmonics and ensuring a smooth AC input. It achieves this by attenuating high-frequency noise components, thereby enhancing the quality of the AC voltage supplied to the subsequent stages of the system.

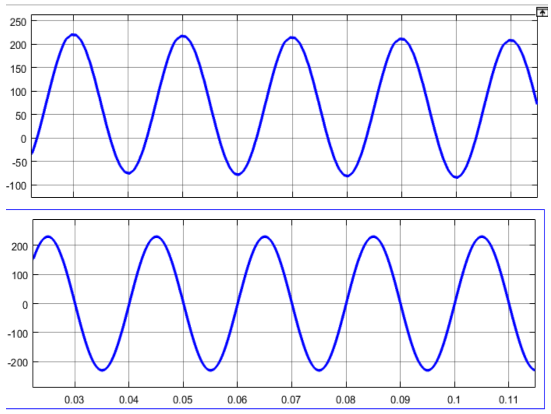

Figure 9. Input to the system

The voltage at the battery terminal is 51V within the typical range for many EV lithium-ion batteries as shown Figure 10. This indicates that the DC-to-DC converter is functioning correctly, providing the appropriate voltage for charging.

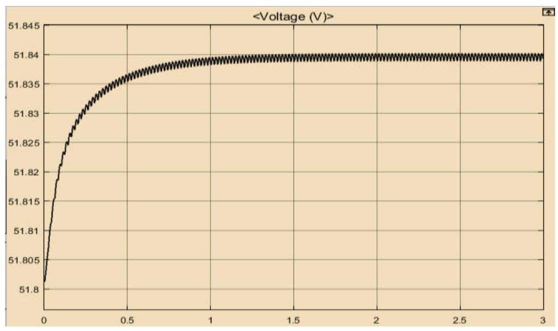

Figure 10. Voltage EV lithium-ion

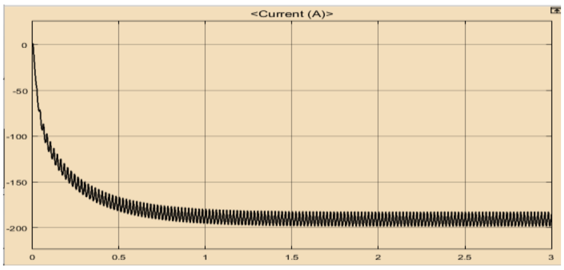

Figure 11. high charging current to the battery

The negative sign of the current indicates the direction of current flow, which is expected during the charging process. A current of -185.5A with high current density is significantly high, which suggests that the system is delivering a high charging current to the battery as shown Figure 11. This aligns with the goal of achieving high current density for faster charging. It crucial to ensure that the battery and the system components can handle such a high current without overheating or damage.

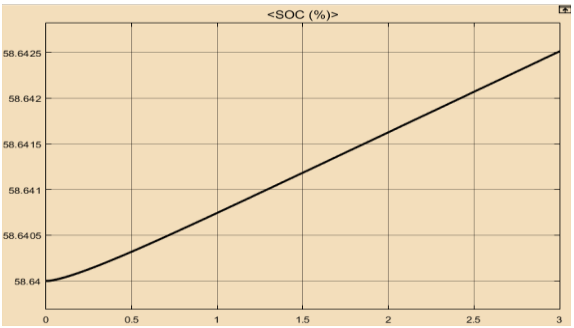

Figure 12. State of charge (SOC)

The increase in state of charge (SOC) shows in Figure 12. it increasing from 58.64% that the battery is successfully charging. The SOC increased, which is a positive sign that the battery is absorbing the energy being supplied. The rate of increase will depend on the battery capacity and the charging current.

A Total Harmonic Distortion (THD) value for a waveform signifies the presence of harmonic components that contribute to approximately 23% of the total signal power, relative to the fundamental frequency. This measurement is crucial in assessing the purity and integrity of electrical signals, especially in power systems and electronic devices where waveform quality directly impacts performance and efficiency. Lower THD values indicate cleaner waveforms with minimal distortion, which are preferred for ensuring stable operation and reducing interference in electrical networks. Engineers and designers use THD measurements to optimize equipment performance, comply with standards, and enhance overall system reliability by mitigating harmonic distortions effectively.

Therefore, a THD value of 0.4405 underscores the importance of managing harmonics to maintain high-quality electrical outputs essential for various industrial and residential applications as shown in Figure 13.

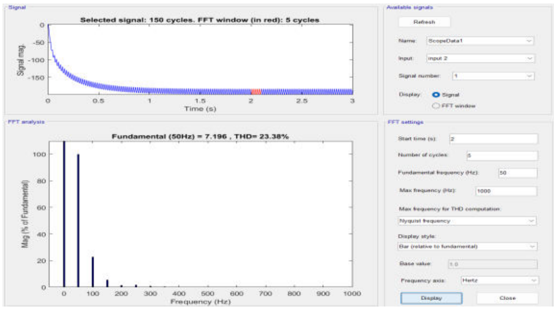

Figure 13. Total Harmonic Distortion (THD)

7.CONCLUSION

The proposed system integrating a DC-DC converter with a fuzzy logic controller for charging lithium-ion batteries in electric vehicles demonstrates significant advancements in efficiency and reliability. Operating at 51.1V and -185.2A current, with the state of charge (SOC) 58.64%, highlights its capability to manage charging dynamics effectively. The fuzzy logic controller plays a crucial role in regulating output voltage and current with minimal overshoot, ensuring stable and optimal charging performance. Moreover, efforts to minimize power loss in active switches and reduce junction temperatures contribute to extended converter lifespan and enhanced system reliability. Analysis under various conditions underscores its robustness and adaptability, while practical validation through a hardware prototype confirms its suitability for real-world EV battery charging applications. The total harmonic distortion of approximately 23%, making it ideal for high-density load currents. Overall, the system represents a promising solution poised to meet the demanding requirements of modern electric vehicle technology, emphasizing efficiency, reliability, and practical feasibility.

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