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Comparative Analysis of Modified PI and Fuzzy Logic Controllers Based High Current Density DC–DC Converter for EV Charging Applications

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Abstract: Two control techniques—modified proportional-integral (PI) controller and fuzzy logic controller (FLC)—used in a high current density DC-DC converter for EV charging systems are compared in this work. Selecting a suitable control method is essential given the growing need for quick, trustworthy EV charging. Under given operating conditions, the modified PI controller is meant to lower output overshoot and power losses while preserving thermal efficiency. By contrast, without exact system modelling, the proposed FLC offers an adaptive, rule-based control approach that can dynamically react to variances in load and input voltage. Under both ideal and non-ideal environments, simulation and experimental evaluations were conducted to investigate converter performance factors including output voltage control, power loss, overshoot, and junction temperature. The FLC beats the modified PI controller in terms of adaptability, thermal stress reduction, and superior efficiency over a wider range of operating conditions even if it stays steady under set settings. The opportunities of fuzzy logic-based control for next-generation, fast-charging electric car infrastructure are underlined by this comparison study.
Keywords: Modified PI controller, high current density, battery charging, power loss reduction, thermal efficiency, adaptive control, and fast charging. Electric vehicles (EVs), DC-DC converters, fuzzy logic controllers (FLC).

I. INTRODUCTION

Electric vehicles (EVs) have grown to be a reasonable replacement for conventional internal combustion engine vehicles (Phillips et al., 2000) thanks to their reduced exhaust emissions, greater power conversion efficiency, and lowered noise and vibration levels. In 1835 Thomas developed the first battery-powered electric vehicle, hence starting the evolution of EV technologies (Lü et al., 2020). Development of EVs depends on the battery, which serves as the primary energy storage component and allows propulsion. Unlike conventional cars running on fossil fuels, EVs run on electricity, which can be generated either internally via fuel cells or outside through off-board charging stations. The fast acceptance of EVs has greatly raised the demand for electric energy, which emphasizes the immediate requirement of scalable and efficient EV charging infrastructure [1-2].

Usually depending on on-board and off-board setups, EV charging systems combine two main power conversion stages: an AC-DC converter for interfacing with the electrical grid and a DC-DC converter for battery charging [3], [4]. Designed either as isolated or non-isolated components, AC-DC converters expose diodes and active switches to higher electrical stress, which generates more thermal dissipation and larger power losses even if they are architecturally simpler. Furthermore, the lack of electrical separation begs safety issues. Reduced junction temperatures let isolated AC-DC converters also enhance component stress, thermal control, and general system reliability [5]. Diode rectifiers, used in conventional AC-DC converters, have many disadvantages including high total harmonic distortion (THD) and power factor degradation resulting from poor power quality and large power losses. Power Factor Correction (PFC) topologies are often employed to correct these shortcomings even with their complexity and cost [6–17]. Another choice is to utilize low-frequency coupled inductors in AC-DC converters and include LCL filters; these have demonstrated to be more efficient and result in reduced power loss. Once AC-DC conversion is complete, the controlled DC voltage is sent into the lithium-ion battery. Usually used for this, conventional closed-loop DC-DC converters compromise the lifetime of the system by means of large power losses connected with conduction, switching, and leakage mechanisms. Furthermore, in these converter overshoots of output voltage and current could compromise the integrity of lithium-ion batteries. By reducing conduction, switching, and leakage power losses as well as voltage overshoot, a modified Proportional- Integral (MPI) controller has been suggested to satisfy these restrictions. This optimal control method not only increases efficiency but also shields switching frequency, thereby retaining small passive component design.

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While conventional DC-DC boost converters can provide high output voltages with somewhat short duty cycles, power switch and diode losses usually limit their efficiency and voltage gain. Investigated as a possible remedy to these constraints are buck converters, more efficient devices with reduced output voltage ripple. Notwithstanding these developments, the great use of electric vehicles causes great demand on the power system during peak charging hours. Indices of inadequate power quality resulting from this demand increase include voltage declines, spikes in peak demand, and power imbalances [18]. Charging electric vehicles using renewable energy sources [19, 20] helps to lower grid stress and boost sustainability.

This work introduces a novel hybrid DC-DC converter driven by a fuzzy logic controller (FLC) to improve the infrastructure for electric vehicle charging. The proposed FLC makes the converter more flexible and efficient by dynamically adjusting to changes in load conditions and input voltages. The FLC tracks load or converter current using fuzzy logic rules grounded on input and output membership functions rather than additional sensor hardware. This distinguishes it from conventional controllers as well. This characteristic ensures seamless running of charging and discharging cycles, hence optimizing power flow in response to demand and supply fluctuations. Excellent for the lifetime and condition of the battery, the FLC also helps prevent overcharging and deep discharge.

This work presents a new hybrid DC-DC converter under control of a fuzzy logic controller (FLC), therefore enhancing the efficiency of charging infrastructure for electric vehicles. The suggested FLC may dynamically change to fit various input voltages and load conditions so enhancing the efficiency and adaptability of the converter. Without more sensor hardware, fuzzy logic rules based on input/output membership functions let the FLC track load current and converter current. In this sense, it stands different from traditional controllers. This feature guarantees flawless operation of the charging and discharging cycles, hence optimizing power consumption in reaction to changes in supply and demand. For its health and lifetime, the FLC helps prevent overcharging or extreme discharge of the battery.

II. PROPOSED SYSTEM

Figure 1 depict the recommended system. On a single-phase AC supply, run with the load as For the LCL network, filtering duties have been located near the AC source. It also permits control of THD and power factor. To control the AC flow to the connected inductor, two diodes D5 and D6 The linked inductor produced ripple DC from its secondary side.

Reduction of the dc ripples comes from the RC3, RC4, C3, and C4. Under load, then, the four MOSFETs M1, M2, M3, and M4 help control the dc output voltage. The dc flow is preserved in part by the additional diodes D1, D2, D3, and D4, elements.

In single-phase AC systems, the alternating nature of the input creates two distinct operating intervals.

During the first half-cycle (0° to 180°), components L3, L4, D5, and L5 conduct, while D6 remains off, resulting in a positive voltage across the output inductor L7, as shown in Figure 2(a).

L6, D6, L4, and L3 become conductive in the second half-cycle (180° to 360°), but D5 is passive once more producing a positive voltage across L7 as shown in Figure 2(b). This two-mode operation guarantees consistent unidirectional output, therefore enabling effective energy transfer even with alternating supply voltage.

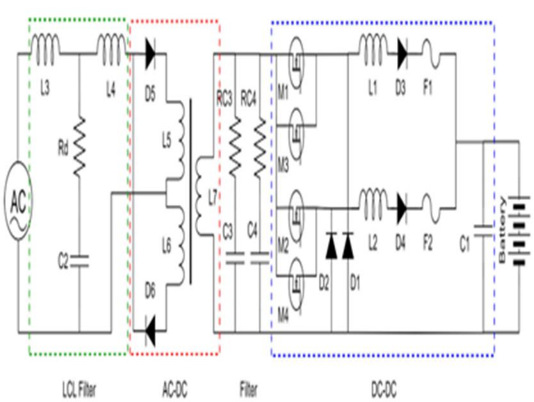


Fig.1: Proposed system

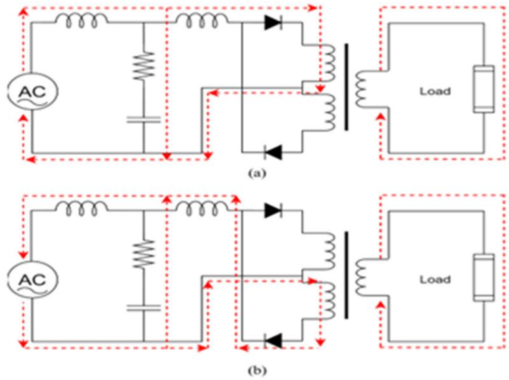


Fig.2: Working modes of the AC-DC converter with LCL filter (a) Mode 1 and (b) Mode 2

A. Fuzzy Logic Controller

Operating within a spectrum of truth values between 0 and 1, Fuzzy Logic Control (FLC) is a symbolic logic-based control approach producing a "grey area" between traditional binary logic values. For complicated and nonlinear systems where perfect mathematical modelling is difficult, FLC is therefore quite successful. Usually involving error (e), the fuzzy inference process starts in an FLC system with fuzzification, whereby membership functions translate the input variables—usually error (e) into fuzzy sets. Linguistic variables such Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) describe these inputs in concert with the output control signal. Every variable fall between -10 and 10. A set of IF-THEN rules is used to carry out the rule evaluation phase once the inputs are fuzzified. The foundation of the FLC strategy is built around these rules, which are derived from expert knowledge and system behaviour. As shown in the below Table 1, A total of 49 fuzzy rules can be constructed to specify the control strategy, with two input variables and seven membership functions per variable.

After that, we will aggregate the rule outputs, which means that all relevant rules will have their results added together to create a fuzzy output. As a last step, defuzzification transforms the output from fuzzy to a clear control signal that the system may use. Since it is easy to incorporate expert information and has an understandable rule structure, the Mamdani-type inference system is frequently utilised in FLC design. The system is able to make rational decisions, regardless of the level of uncertainty, because each rule in this framework connects input conditions to output actions. Central to this control paradigm is a fuzzy inference system (FIS), which maps inputs to outputs using these IF-THEN principles. One of FLC's strengths is that it can change its rules to fit new needs without changing the control algorithm's structure. In addition, FLC boosts the efficiency of applications such HES battery charging, especially when it comes to controlling the State of Charge (SoC). It is a perfect controller for high-tech power systems, such as EV chargers, because it can withstand nonlinear and dynamic situations.

TABLE 1:
FUZZY RULE

CE/E	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NZ	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PB	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

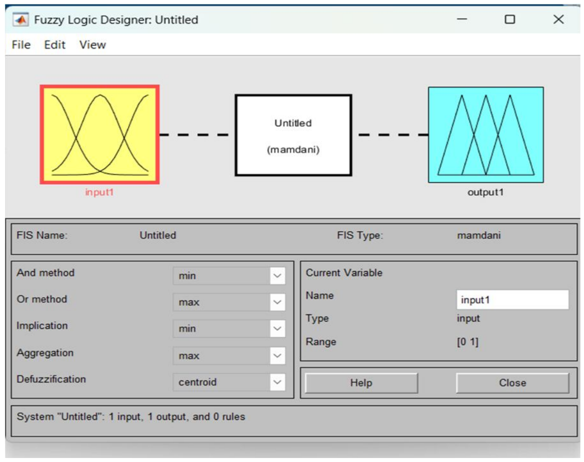


Fig.3: MATLAB Fuzzy Logic designer interface displaying Mamdani-Type FIS with input and output membership functions

Figures 3, 4, and 5 show MATLAB Fuzzy Logic Designer interface-based design and configuration of a Mamdani-type Fuzzy Inference System (FIS). Using a single input and a single output, both shown by their respective membership functions within a Mamdani framework), Figure 3 displays a simple FIS configuration. As shown by the 49 rules defined in the system, Figure 4 broadens this model by include two input variables (`E` and `CE`,) and one output, therefore enabling more sophisticated rule-based decision-making. At last, Figure 5 shows the exported configuration FIS to the MATLAB workspace under the variable `dcvehi`, therefore enabling simulation and additional integration. All three figures show the main features and user-friendly interface of MATLAB's fuzzy logic toolbox in building and operating Mamdani-type FIS models.

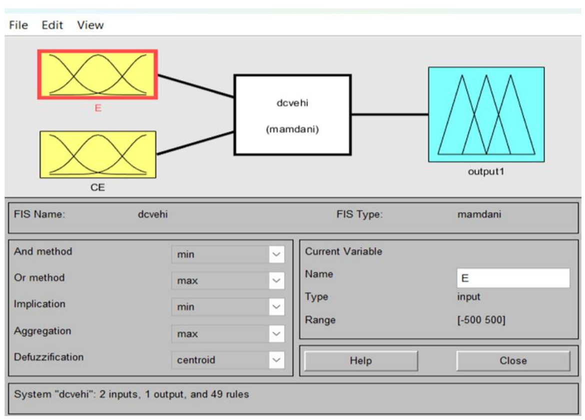


Fig.4: Design interface of Mamdani-Type Fuzzy Inference System (FIS) in MATLAB with two inputs and one output

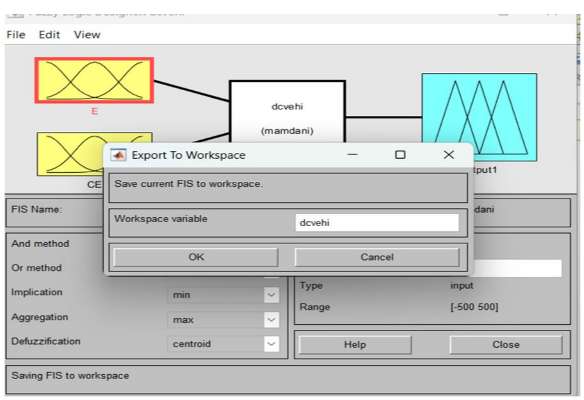


Fig.5: MATLAB Fuzzy Logic Designer Configuration of Mamdani-Type Fuzzy Inference System with two inputs and one output

B. Modified PI-Controller

A closed-loop logic architecture is used by the Modified Proportional-Integral (MPI) controller. Previous research has confirmed that this modified PI method is effective [25], [26]. The reference output voltage in this system is specified as:

$$V_{ref}\ (\mathrm{t}) = \mathrm{nu(t)}$$

This reference voltage is further refined by a sample-and-process unit, formulated as:

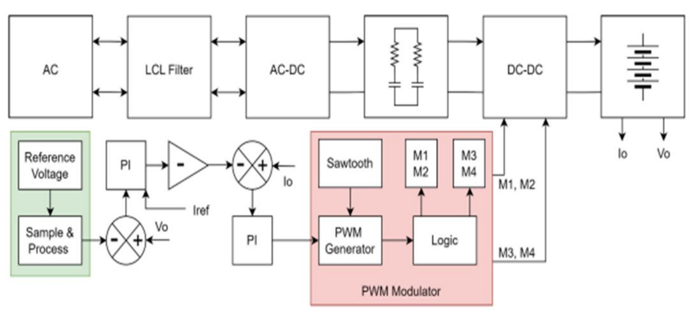
$$\mathrm{V'}_{ref}(\mathrm{t}) = \frac{n}{m}r(t-0) - \frac{n}{m}r(t-m)$$

where *n* represents the target battery voltage and *m* corresponds to the system's settling time. Since the revised reference value corresponds to the actual output voltage, the resultant error is fed into the first PI controller aiming at the desired output current. This controller produces an inverted output that is subsequently compared with the real current to produce an error signal for the second PI controller. The Pulse Width Modulation (PWM) block generates switching pulses employing a sawtooth waveform reference from the second PI output. To get best performance, both PI controllers are tweaked with the Ziegler–Nicholls technique. Through a logic block, the output pulses drive MOSFETs 1 and 2, which are active during the first conduction cycle, and MOSFETs 3 and 4, which conduct during the second. All switches are kept off during non-conductive durations.

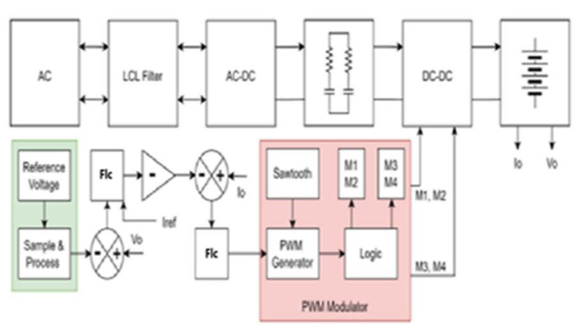
III. SIMULATION SETUP

A. Simulation Environment

Using (a) a PI controller and (b) a fuzzy logic controller (FLC), assessed via MATLAB/Simulink, Figure 6 displays the block diagram of the closed-loop converter system and the key parameters of the system are summarised in Table 2. Built to generate 54 V output voltage and 154 A charging current, the converter is connected to a single-phase AC grid. The system sequence consists in an AC input, LCL filter, AC-DC converter, DC link capacitor, DC-DC converter, and battery or load. Reference voltage generation starts the control loop; next are sampling, error computation, and modulation. Under a PI-based system, the control signal is produced by a Proportional-Integral controller. By contrast, the FLC generates an adaptive control signal from error and change in error as inputs. Both approaches run the switches (M1–M4) using a PWM modulator—sawtooth generator, PWM generator, or logic). Offering superior control than the conventional PI controller, the FLC shows better dynamic reaction and decision-making ability.



(a)



(b)

Fig.6: Block diagram of the closed-loop proposed system using (a) PI and (b)Fuzzy Logic controllers

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TABLE 2:
SPECIFICATION OF PARAMETERS

Parameters	**Value**
Source	Single-phase AC (Grid)
Output voltage	54V
Output current	154A
Switching frequency	31KHz
DC inductor (L1, L2)	0.2mh
AC inductor (L3, L4)	2.47mH
Output capacitor (C1)	300 µF
Input capacitor (C2)	14.5 µF
Filter capacitor (C3, C4)	100 µF

The effectiveness of the suggested converter was evaluated by means of MATLAB/Simulink in a simulation model. Drawing power from a single-phase AC grid, the system is supposed to generate a voltage of 54 V and an output current of 154 A.

B. Simulation Results

The system's performance was evaluated using two control strategies: Modified PI Controller and Fuzzy Logic Controller.

1) Modified-PI Controller

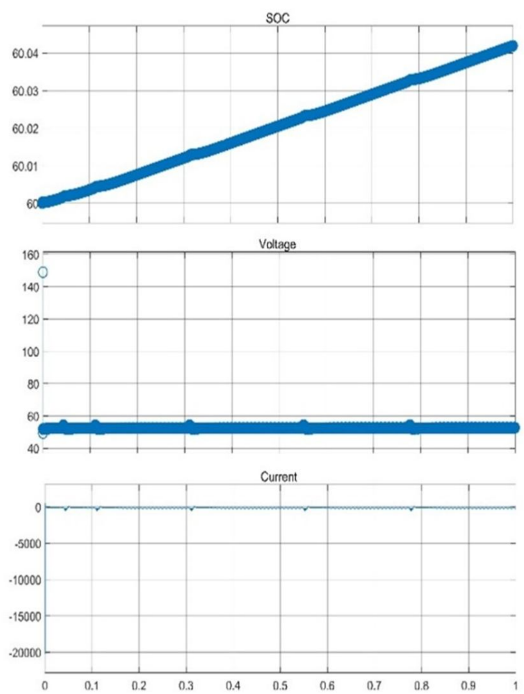

Fig.7: Modified PI Controller simulated properties of SoC, Battery Voltage, and Charging Current

Figure 7 shows the battery charging system's simulated behaviour under the altered PI controller. Indicating slower charging accumulation, the State of Charge (SoC) shows a modest rise from 60% to 60.04% for one second. The output voltage is seen to remain almost 54 V, with minor changes in current.

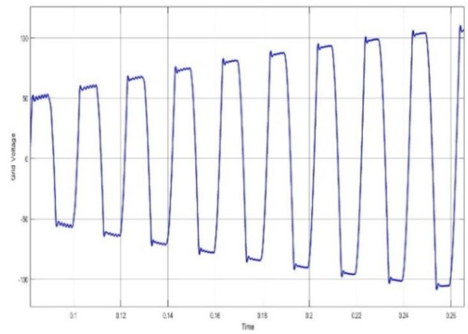

Fig.8: Simulated consequence of the Grid voltage using Modified PI Controller

The figure 8 shows how dynamically the grid voltage under control by a modified Proportional-Integral (PI) controller responds. With fast transitions between voltage levels, the waveform shows a nearly square wave pattern that shows the controller's capacity to minimise steady-state error and accomplish fast tracking. As the system advances, the voltage magnitude exhibits higher consistency, therefore suggesting increased stability and lowered oscillations

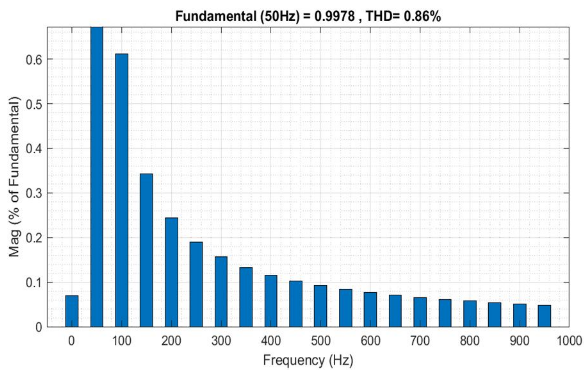

Fig.9: Simulated THD in terms of grid current using Modified PI Controller

As shown in the Figure 9 ,Modified PI Controller recorded a current THD of 0.86%, indicating the presence of minor distortions that could impact charging efficiency over time.

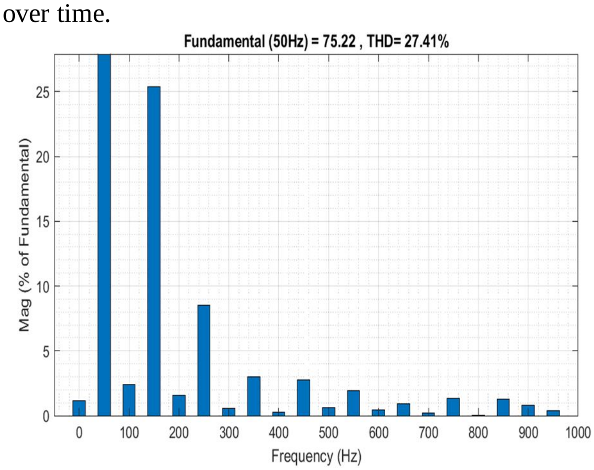

Fig.10: Simulated THD in terms of grid voltage using Modified PI Controller

As shown in the Figure 10, There is huge harmonic distortion in the voltage waveform. With a computed voltage THD of 27.41%, poor waveform quality and a strong degree of harmonic content are indicated.

2) *Fuzzy Logic Controller*

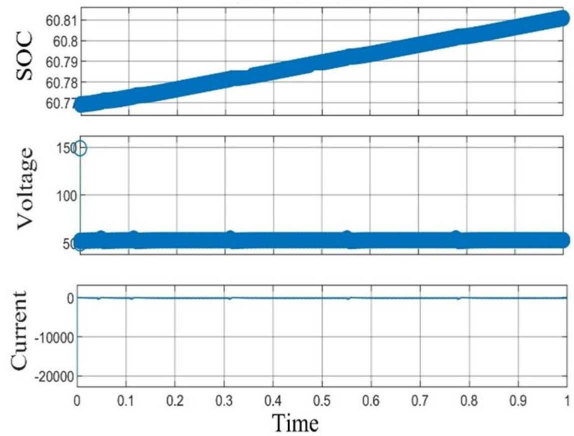

Fig.11: SoC, battery voltage and charging current simulated properties

Figure 11 displays the SoC, battery voltage and charging current response under the Fuzzy Logic Controller. The Fuzzy controller gives greater voltage control and smoother charging behaviour than the PI controller.

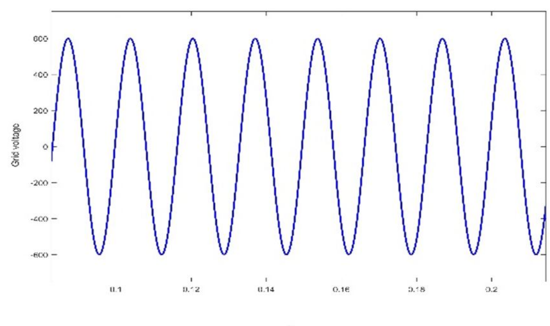

Fig.12: Simulated consequence of grid voltage using Fuzzy Logic Controller

The simulated grid voltage under Fuzzy Logic Controller (FLC) control is shown in figure 12. Reflecting the controller's capacity to preserve consistent and balanced grid settings, the voltage waveform shows a smooth, sinusoidal profile with constant amplitude and frequency. The absence of obvious distortion or oscillatory disturbances emphasises how well the FLC achieves exact and steady voltage control. This consistent response shows how well the controller handles nonlinearities and uncertainty usually found in grid-connected systems, hence proving its great adaptability and strength.

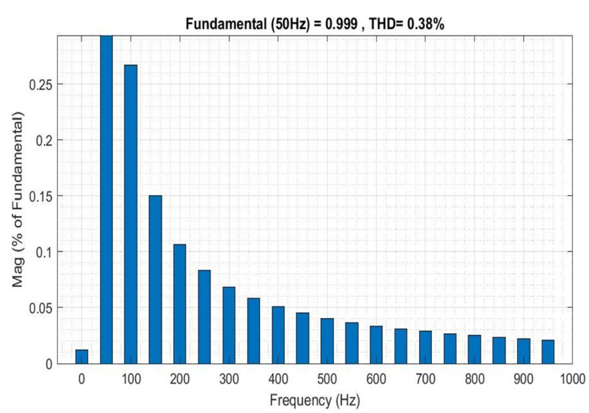

Fig.13: Simulated THD in terms of grid current using Fuzzy Logic Controller

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As shown in the Figure 13, The Fuzzy Logic Controller's lowering of the current THD to 0.38% has resulted in more steady and free of ripples current sent to the battery.

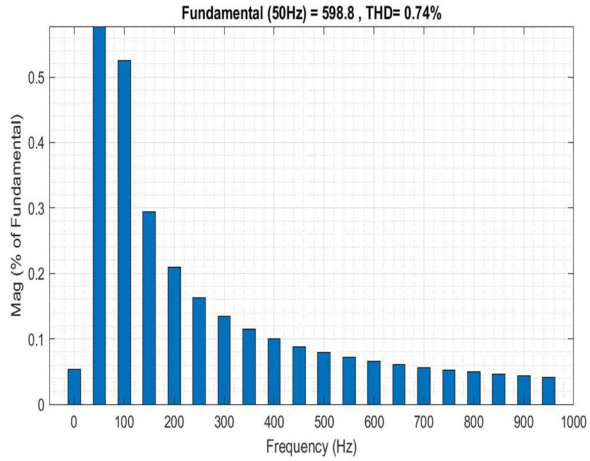

Fig.14: Simulated THD in terms of grid voltage using Fuzzy Logic Controller

As shown in the above Figure 14, By lowering the voltage Total Harmonics Distortion (THD) to 0.74%, the Fuzzy Logic Controller greatly improved the voltage waveform's quality. This result emphasizes the great ability of the fuzzy controller to control nonlinearities and dynamic fluctuations in the system, therefore ensuring a significantly more consistent and reliable voltage output**.**

C. THD Analysis

As indicated in Table 3, the findings of the Total Harmonic Distortion (THD) analysis for both voltage and current are shown.

TABLE 3:
THD ANALYSIS

CONTROLLER	CURRENT THD %	VOLTAGE THD %
PI	0.86	27.41
FUZZY	0.38	0.74

IV. RESULT ANALYSIS

Using important performance criteria such as transient response, total harmonic distortion (THD), charging current stability, state of charge (SoC) behaviour, and battery voltage regulation, a thorough comparative study was carried out between the fuzzy logic controller and the modified PI controller. In comparison to the modified PI controller, which showed a slower increase from 60.00% to 60.04%, the fuzzy logic controller showed a better dynamic response, with the Soc growing smoothly from 60.77% to 60.81% within 1 second. The improved PI controller exhibited higher fluctuations around the same voltage level, while the fuzzy controller kept the terminal voltage constantly around 50 V with minor oscillations.

With little ripples and a fast settling period of about 20 milliseconds, the current profile under fuzzy logic control was quite stable and indicated great transient performance. On the other hand, the modified PI controller highlighted its inferior current control and slower stabilisation by showing notable current ripples and deep negative spikes reaching about -5000 A. Further supporting these results is harmonic distortion study, in which the fuzzy controller outperformed the modified PI controller recording a voltage THD of 27.41% and a current THD of 0.86%. The fuzzy controller obtained a voltage THD of 0.74% and a current THD of 0.38%.

The results demonstrate that the fuzzy logic controller provides superior energy management, improved voltage and current quality, quicker transient response, and markedly reduced harmonic distortions in comparison to the modified PI controller. As a result, the fuzzy logic approach presents itself as a more robust, efficient, and reliable control strategy for battery charging applications that require high performance and power quality.

V. CONCLUSION

In this study, a comprehensive comparison between the Fuzzy Logic Controller (FLC) and the modified PI controller was performed, focusing on critical performance parameters such as State of Charge (SoC) dynamics, terminal voltage regulation, charging current stability, transient response, and Total Harmonic Distortion (THD). The Fuzzy Logic Controller outperformed the modified PI controller in all aspects evaluated.

While the redesigned PI controller showed a slower climb, the FLC displayed better dynamic behaviour and achieved a constant increase in SoC within a fraction of seconds. Under these fuzzy logic techniques, voltage control was more steady with fewer oscillations than in the modified PI controller, which showed more variations.

Moreover, the FLC kept a very constant current profile with fast settling times and little ripples, which is absolutely important for reliable and effective battery charging. By contrast, demonstrating its poor performance in current control, the modified PI controller displayed notable current ripples and instability. After comparing the FLC to the modified PI controller, the harmonic distortion study confirmed its advantages. When compared to other control strategies, the fuzzy logic controller is superior because it improves energy management, voltage and current quality, transient reaction time, and significantly reduces harmonic distortions. These results bring attention to the FLC as a strong option for high-performance battery charging applications, highlighting its possibilities for uses that demand fast and dependable regulation and very high power quality standards.

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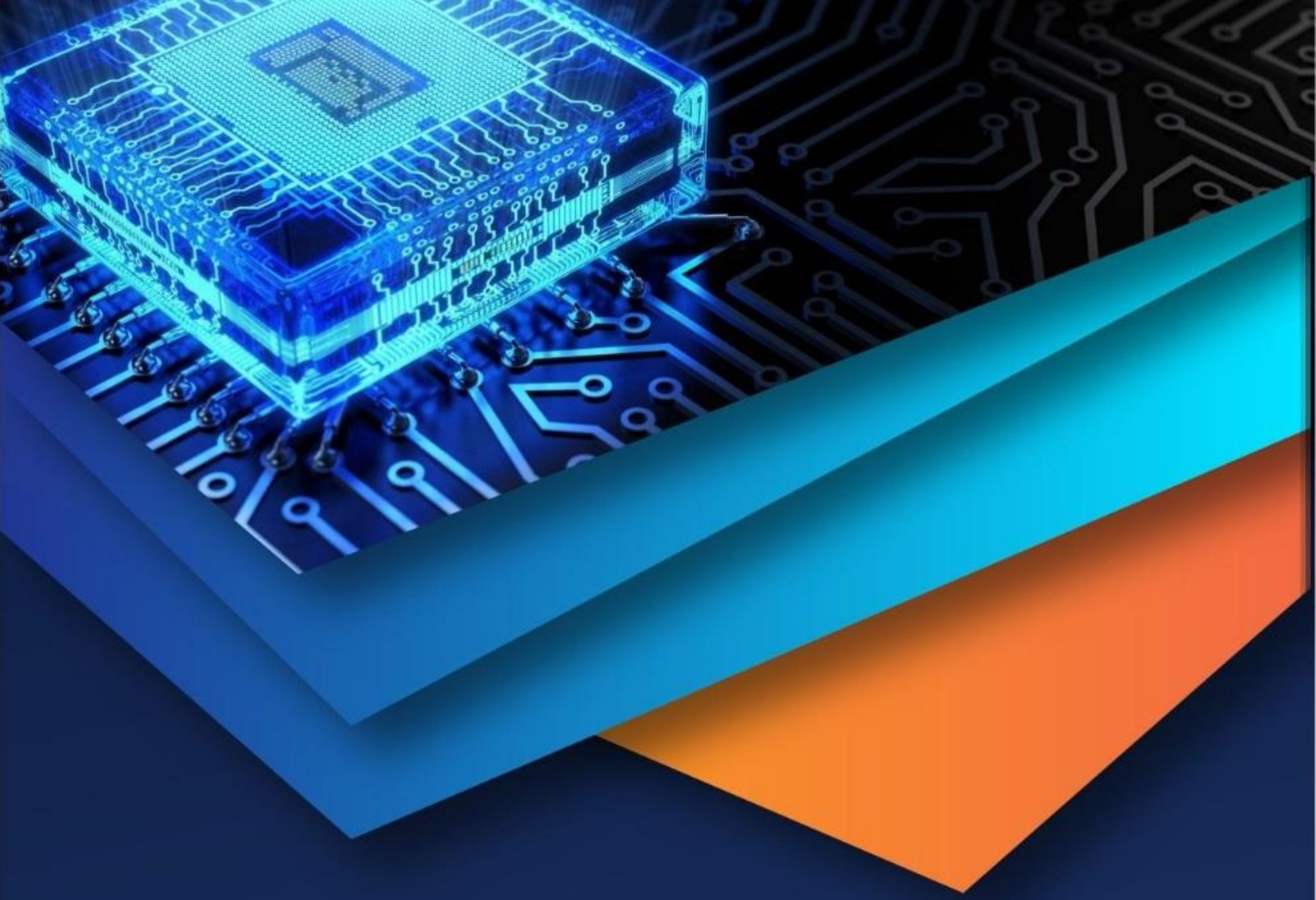

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