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Advanced Power Electronic Interface For EVs With Fuzzy – Based Fast Charging

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***Abstract* —** As electric vehicles (EVs) become more popular, the need for faster and smarter charging systems is growing. Unfortunately, many traditional systems aren't up to the task. Long waiting times and limited interaction with the power grid have become common problems, often leading to inefficiencies and added stress on the grid during peak hours. To solve these challenges, a new fast-charging system using fuzzy logic could be the answer.

This system would use bidirectional AC-DC and DC-DC converters to make energy transfer more efficient. It would also support both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operations. A relay-based switching mechanism could distribute power based on real-time demand, ensuring energy is managed effectively. By relying on a fuzzy logic controller, the system could monitor the battery's state of charge (SOC) and temperature, adjusting voltage and current to prevent overcharging while speeding up the process.

Simulations would test the system's performance, and further improvements, such as enhancing the relay setup and adding real-time monitoring tools, could make it even more effective. Ultimately, this aims to build a reliable, next-generation EV charging station that meets modern demands.

Keywords: Electric vehicle EV, Buck-Boost converter, FLC

I. INTRODUCTION

Electric vehicles (EVs) have emerged as a cornerstone for achieving a more sustainable and environmentally friendly transportation system. As global concerns over climate change, air pollution, and the depletion of fossil fuels intensify, EVs offer a promising solution by reducing greenhouse gas emissions and dependence on non-renewable resources. With growing consumer awareness and government incentives, EV adoption is steadily increasing, marking a transformative shift in the automotive industry.The heart of the EV revolution lies in advances in battery technology, particularly with

Fig 1 Block diagram (proposed)

lithium -ion batteries that have become the standard due to their high energy density and long cycle life. However, one significant challenge that persists,

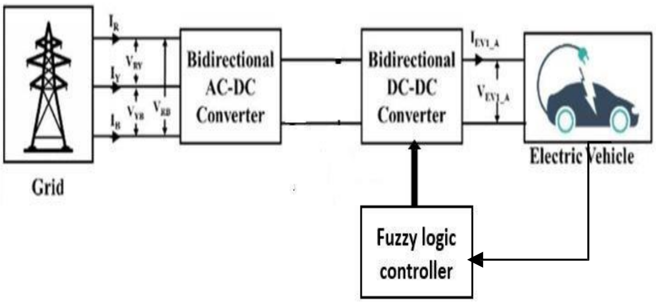


Fig.1 : proposed block diagram

despite these advancements, is the issue of charging time. Unlike traditional vehicles that can be refueled in minutes, EVs require several hours to charge, which significantly hampers their usability, especially for long-distance travel and in scenarios where quick recharging is necessary. The existing charging methods, such as CC and CV, are widely employed in current systems. These methods, while reliable, have limitations in speed and efficiency when dealing with varying battery conditions like state of charge (SOC), temperature, and battery aging. In many cases, they fail to optimize the charging process for both time and battery health, leading to inefficient energy use, slower charging, and potential damage to the battery over repeated cycles. These issues highlight the need for more adaptive charging systems capable of adjusting to the dynamic characteristics of batteries to provide faster and safer charging solutions.

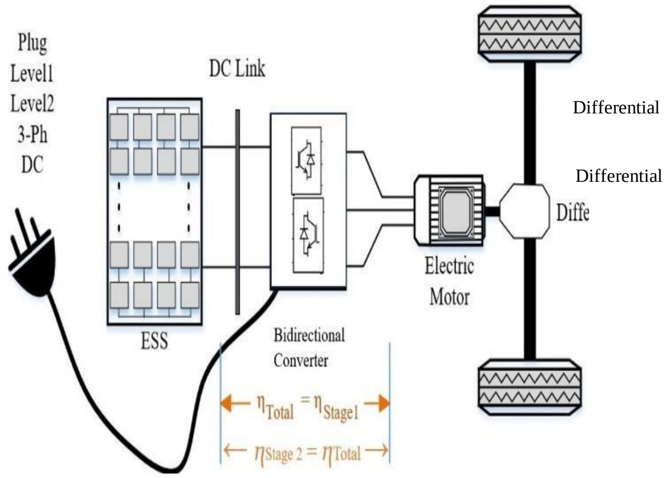
Pragasen Pillay[1]

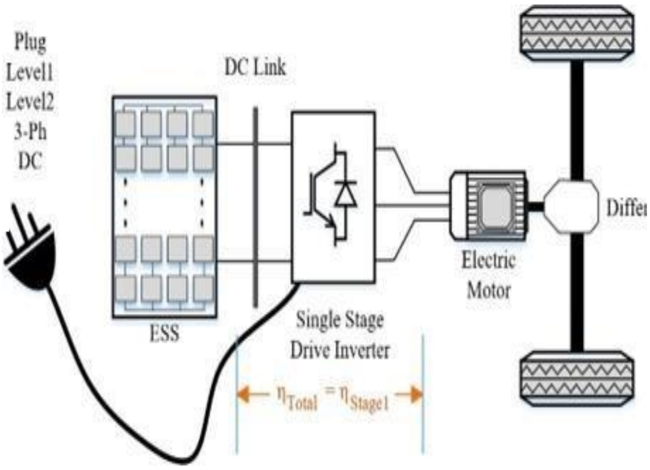
"Integrated Multipurpose Power Electronics interface for Electric Vehicles"

The Integrated Multi-Port Electronic Interface (IMPEI) is a highly flexible system that supports various functions like driving the vehicle, recovering energy during braking, and transferring power both to and from the grid. It uses fewer switches in its design, which makes it more efficient and affordable compared to other systems or traditional power interfaces.

Tests and experiments have demonstrated that the IMPEI outperforms existing systems in efficiency across various modes of operation. It offers a practical balance between efficient charging, grid adaptability, and affordability. By overcoming the drawbacks of earlier designs and introducing new techniques, this system significantly improves the performance and sustainability of electric vehicle charging solutions.

(a)





(b)

Fig. 2. Ev drivetrain architectures (a) existing system (b)proposed syste

II. LITERATURE REVIEW

Rapid changes in energy and transportation systems have made it necessary to investigate technologies that improve sustainability, lower environmental impact, and increase efficiency. In this regard, literature reviews are essential for comprehending current solutions, spotting gaps, and suggesting improvements. This review looks at sustainable energy options, the environmental effects of conventional and alternative fuels, and developments in power electronics interfaces for electric vehicles. In order to reduce greenhouse gas emissions and promote greener transportation technologies, it emphasises important technologies such as natural gas as a transitional fuel and the function of power electronics in integrating electric vehicles with renewable energy networks.

Tamanwe Payarou , Student Member, IEEE, and

T. Payarou and P. Pillay's [2]

"A novel multipurpose V2G & G2 V power electronics interface for electric vehicles," This paper study discussed on the development and use of a multifunctional power electronics interface for electric vehicles (EVs). Effective bidirectional power transfer is made possible by this interface's support for both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. The system offers operational flexibility through propulsion, regeneration braking (RB), and single-/three-phase grid interactions while improving energy efficiency and lowering the number of

components. According to experimental data, it is a major improvement in EV power electronics infrastructure because of its high efficiency, affordability, and flexibility to grid systems. The study highlights how crucial power electronics are to attaining sustainable energy management in the EV ecosystem.

A. Negi and M. Mathew [3]

"Study on sustainable transportation fuels based on

green house gas emission potential," This paper studies how sustainable transport fuels can lower greenhouse gas (GHG) emissions. Because of their abundance, lower emissions, and technological readiness for scale production, this research emphasises biofuels like bio- CNG and biodiesel as efficient transitional fuels. It also examines hydrogen's potential as a fuel for the future while recognising the financial and technical obstacles to building hydrogen infrastructure. In order to fight climate change and create a sustainable transportation sector, the report highlights the need to move away from fossil fuels and promotes the integration of renewable energy sources.

Kurczynski, P. Lagowski, and M. Warianek [4]

"The impact of natural gas on the ecological safety of using diesel engine," This study investigates the role of natural gas as a cleaner alternative to diesel fuel in internal combustion engines, emphasizing its potential to enhance ecological safety. Diesel engines, which contribute significantly to air pollution because of their large emissions of particulate matter (PM), nitrogen oxides (NOx), and greenhouse gases (GHG), are the subject of the study. It examines the benefits of incorporating natural gas as a partial or complete substitute for diesel fuel and draws attention to the developing concerns surrounding diesel emissions in the transportation sector. According to the study, natural gas is a good transitional fuel because it is widely accessible, has fewer emissions, and works with the diesel engines that are now in use. The difficulties of methane leakage during manufacturing and transit, which can counteract some environmental advantages, are acknowledged, nevertheless. This study highlights the necessity of more research to address the ecological trade-offs associated with natural gas consumption and optimise dual-fuel systems.

M. A. H. Rafi and J. Bauman[5]

"A comprehensive review of DC fast charging stations with energy storage: Architectures, power converters, and analysis," The study provides a detailed review of DC fast charging stations (DCFCs) integrated with energy storage systems (ESS), focusing on their architectures, power converters, and performance analysis. It highlights the increasing demand for fast and efficient charging solutions to support the growing adoption of electric vehicles (EVs). The paper examines various system architectures, including grid-connected and hybrid configurations, which combine energy storage with renewable energy sources to improve grid stability and reduce peak load demand.

J. Van Mierlo[6]

"Beyond the state of the art of electric vehicles: A fact-based paper of the current and prospective electric vehicle technologies," The study provides a fact-based analysis of the current and emerging technologies in the field of electric vehicles (EVs). It reviews advancements in EV components, including batteries, power electronics, electric motors, and charging infrastructure. The paper emphasizes the evolution of battery technologies, focusing on improvements in energy density, charging speed, lifespan, and cost reduction. It highlights the growing importance of next- generation batteries, such as solid-state batteries and lithium-sulfur technologies, which have the potential to outperform conventional lithium-ion batteries.

III. BUCK–BOOST CONVERTER

The voltage source is represented as a three-phase source, while the transformer is configured in a Star-Delta arrangement. A Buck-Boost converter is a DC-DC converter that can output a voltage either higher or lower than the input. It is also known as a non-isolating converter and an inverting regulator. The Buck-Boost converter combines the operational principles of both Buck and Boost converters within a single circuit. It provides a regulated DC output voltage from either DC or AC input sources. The input voltage is connected to a solid-state device, where a diode acts as a secondary switch.

When the Buck converter is integrated with the Boost converter, the output voltage can either match the input voltage or be higher or lower than the input. The Buck-Boost converter can operate with a single inductor, which remains non-inverting and can function in both buck and boost modes. In this configuration, switches are used instead of a diode, forming what is known as a four-switch Buck-Boost converter. The Buck-Boost converter operates in two modes: in the first mode, the switch is on and the diode is off, while in the second mode, the switch is off and the diode is on.

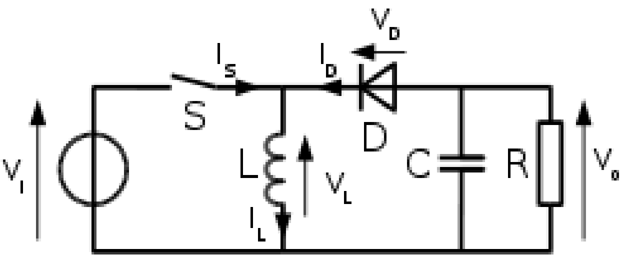


Fig.3 : Configuration for buck-boost converter

case-1: When switch S is ON

IV. FUZZY LOGIC CONTROLLER

Fuzzy logic is a type of computational logic that differs from traditional formal logic. It deals with concepts that are imprecise or uncertain. Unlike formal logic, where values are strictly binary (either 0 or 1), fuzzy logic allows for assessments that lie between absolute truth and absolute falsehood, accommodating partial truth. While formal logic assigns values of 0 or 1 to variables, fuzzy logic permits a range of values. Fuzzy logic enables computers to make decisions that more closely resemble human reasoning by using fuzzy rules and fuzzy sets to model real-world

scenarios and make informed decisions. Symbolic logic, which is based on fuzzy sets, allows for the handling of imprecise situations. To apply symbolic logic in decision-making, two components are essential: fuzzy sets and fuzzy rules.

A fuzzy set is a collection of related elements, where each element has a degree of membership within the set, rather than a binary membership. Fuzzy rules, which are essential in fuzzy logic, help assert knowledge in an uncertain environment. These rules are not fixed or standardized; instead, they are adaptable and can vary depending on the situation.

$$IL = \left(\frac{1}{L}\right) \times \int V\, dt$$

$$I_{L,on} = \left(\frac{1}{L}\right) * \int Vin\ dt + I`_{L,on}$$ (input voltage is constant)

$$I_{L,\,on} = (1/L) * V_{in} * D * T_s + I'_{L,\,on} \quad (1)$$

$$\Delta I_{L,on} = (1/L) * V_{in} * D * T_s.$$

case 2: When switch is off

$$I'''_{L,off} = -(1/L) * V_{out} * (1-D) * T_s + I''_{L,off} \quad (2)$$

Using the equations 1 and 2 we get

$$(1/L) * V_{in} * D * T_s = (1/L) * V_{out} * (1-D) * T_s$$

$$V_{in} * D = V_{out} * (1-D)$$

$$V_{out}/V_{in} = D/(1-D)$$

$$I_{out}/I_{in} = \delta/D.$$

In the context of a fuzzy logic controller (FLC), the horizontal axis in Table 1 typically represents the error, while the vertical axis indicates the change in error. The system input

in the FLC is the difference between the desired value and the actual error, which corresponds to the change in error.

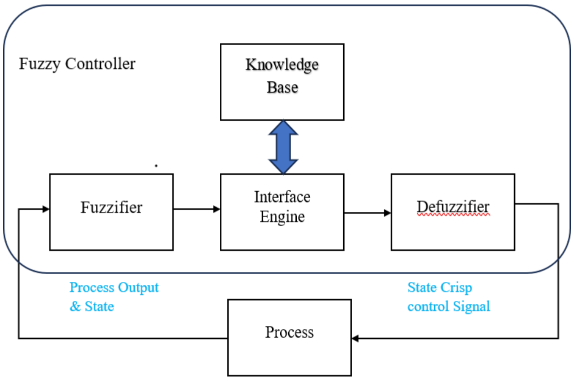


Fig 4. Block diagram of fuzzy logic controller

SOC	Battery Temperature	Current
Low	Safe	High
Low	High	Medium
MediumT	Safe	Medium
Mediuma	High	Low
High b	Safe	Low
High l	High	Low

e
1 : Rules used in fuzzy

A system that uses fuzzy membership functions to make decisions is known as a FLC.

Fuzzification : FLC, the rule- based system evauates linguistic 'if-then' rules by employing fuzzification, interface, and composition processes.These methods generate fuzzy outputs, which then need to be transformed into precise, crisp values.

Defuzzification: This is the process of converting the fuzzified output into a single, crisp value within the context of a fuzzy set. The resulting defuzzified value in the symbolic logic controller indicates the action that should be executed to control the system.

Symbolic logic enables computers to imitate human decision-making by using fuzzy sets, which model real-world concepts and objectives. Fuzzy sets, when combined with rules, enable the system to make decisions. These decisions are based on symbolic logic, which involves computing with words rather than numbers.

V. FUZZY BASED FAST CHARGING MODES AND OPERATION

(a). **Proposed system description**

The proposed system is a bidirectional Electric Vehicle (EV) charger designed to facilitate efficient and stable energy exchange between the EV battery and the grid. It is equipped with a bidirectional buck-boost converter and a VSC, enabling two key operations: G2V and V2G. These two operations are essential in the context of modern energy grids, where not only is energy required to flow from the grid to the vehicle for charging (G2V), but the vehicle must also be able to feed energy back to the grid (V2G) during peak demand periods, promoting grid stability and efficient energy usage. The bidirectional buck-boost converter plays a central role in regulating the DC voltage from the EV battery to ensure it is either stepped up or stepped down to match the grid's voltage requirements. This converter is adaptable, allowing for energy flow in both directions (charging and discharging). The VSC allows for the control of the AC power flow between the grid and the EV, converting the DC voltage from the battery into AC power for the grid during V2G operation and vice versa during G2V. Together, these components create a robust and flexible system capable of operating under varying grid conditions and providing optimal performance in both charging and discharging modes

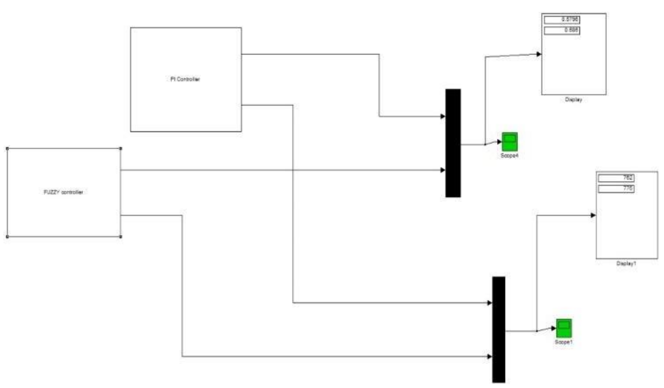


Fig 5.1 . Block diagram of simulation of fuzzy based fast charging

S.NO	Parameters	Rating
1	Grid Voltage	415V
2	System Frequency	50Hz
3	Filter Inductance	5mH
4	Filter Capacitance	30µF
5	Bus Capacitance	5600µF
6	Buck Filter Inductance	20mH,
7	Output Capacitance	0.625µF
8	Battery Nominal Voltage	360V
9	Switching Frequency	10kHz
10	Total Rated Power	10kW

Table 2. Design parameters

(b) Proposed System In G2V Mode

In G2V mode, the EV charger pulls energy from the grid to charge the vehicle battery. The buck-boost converter regulates the voltage to meet the requirements of the EV battery, while the VSC manages the power quality by maintaining a stable voltage and current. Each controller in this configuration operates to ensure that the G2V process is smooth, efficient, and stable under different load conditions and grid disturbances.

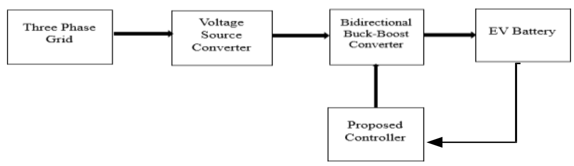


Fig:5.2 G2V Line Diagram

1. **Proportional-Integral (PI) Controller:** The PI controller is one of the simplest and most widely used controllers for EV chargers due to its ability to maintain steady-state error to zero by adjusting the proportional and integral gains. In G2V mode, the PI controller works by comparing the actual battery voltage with the reference voltage and adjusting the duty cycle of the buck-boost converter to minimize any discrepancy. The proportional component (P) addresses immediate errors by making quick adjustments, while the integral component (I) accumulates past errors to provide a stable correction, ensuring that the voltage reaches the desired level over time. Although effective for linear systems and steady-state conditions, the PI controller struggles with handling nonlinearities and abrupt changes in load or grid conditions. For instance, in scenarios with rapid voltage fluctuations or varying load demands, the PI controller may exhibit oscillations or a sluggish response, which can affect power quality.

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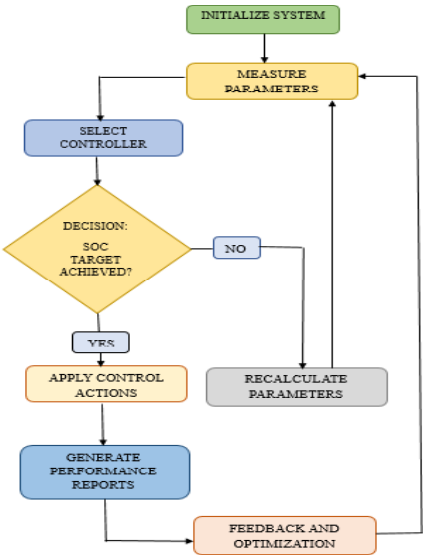

Fig: 5.3 Flow chart for G2V MODE

As a result, while the PI controller is straightforward and reliable, it is often less effective than other controllers in dynamic environments typical of G2V charging systems.

2. **Fuzzy Logic Controller:** The fuzzy logic controller (FLC) introduces adaptability by using rule-based logic to manage complex and nonlinear systems. In the G2V mode of the EV charger, the fuzzy controller assesses voltage deviations and other operating conditions through a set of "if-then" rules. Unlike the PI controller, which relies on precise mathematical models, the fuzzy controller evaluates qualitative data, making it more responsive to fluctuating grid conditions. This flexibility allows the fuzzy logic controller to handle uncertainties and sudden changes in voltage or current more effectively than traditional controllers. During G2V charging, the fuzzy logic controller adjusts the converter's duty cycle by interpreting system inputs, such as voltage deviation and rate of change, based on predefined fuzzy rules. For instance, if the voltage deviation is high, the controller may apply a stronger correction to bring the voltage to the reference level. This rule-based approach provides a smoother charging process by adapting to variable conditions. While the fuzzy logic controller is more effective than PI in handling nonlinearities, its rule-based nature may still limit accuracy in highly dynamic environments.

(c) **Proposed System In V2G Mode:**

The proposed bidirectional EV charger is equipped with a three-phase VSC and a bidirectional buck-boost converter to manage power flow in both directions—charging the EV battery during Grid-to-Vehicle (G2V) mode and feeding power back to the grid during V2G mode. The VSC regulates the output voltage and frequency of the energy transferred to the grid, while the buck-boost converter adjusts the DC voltage levels to accommodate variations in battery voltage. Each controller within this system plays a vital role in maintaining power quality, grid stability, and response time under dynamic conditions in V2G mode.

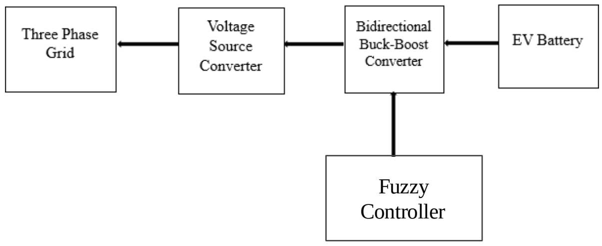

Fig:5.4 V2G Line Diagram

PI Controller in V2G Mode: The Proportional-Integral (PI) controller is a conventional control strategy widely used in power electronics for its simplicity and reliability. In the V2G mode, the PI controller monitors and adjusts the output voltage and current to maintain a stable power transfer from the EV battery to the grid. The proportional part of the controller helps reduce the immediate error between the desired and actual output values, while the integral part accumulates the error over time, correcting any steady-state discrepancies. However, PI controllers are often less effective when dealing with non- linearities and dynamic conditions, as they can struggle to adapt to sudden changes in grid demand or voltage fluctuations. Despite these limitations, the PI controller can provide reliable performance in stable conditions, making it suitable for V2G applications with minimal fluctuations.

2. **Fuzzy Controller in V2G Mode :** The fuzzy logic controller introduces adaptability and resilience to uncertainties within the V2G system. Unlike traditional controllers that require precise mathematical models, the fuzzy controller relies on a set of "if-then" rules and linguistic variables, making it highly effective for non-linear systems such as bidirectional EV chargers. In V2G mode, the fuzzy controller interprets grid voltage, current, and frequency data to dynamically adjust the power output of the EV battery, ensuring smooth and efficient power transfer. By processing these inputs through fuzzy rules, the controller generates a control signal that minimizes voltage spikes and frequency deviations, which are common in V2G operations. Fuzzy controllers thus contribute to improved stability and response times, although their performance can be limited by the quality and complexity of the rule base and may require fine-tuning for optimal results.

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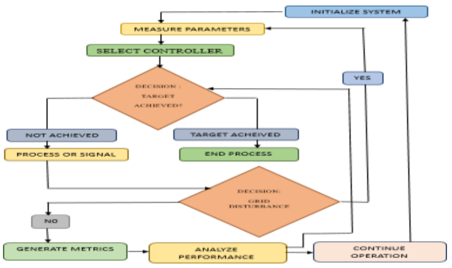

Fig 5.5 Flowchart for V2G

Input State	**Output Phase**	**Switching States (S1, S2, S3, S4, S5, S6)**	**Description**
Positive Current	Phase A	S1 = ON, S4 = OFF	Power flows from DC to AC (Inverter Mode).
	Phase B	S3 = ON, S6 = OFF	
	Phase C	S5 = ON, S2 = OFF	
Negative Current	Phase A	S1 = OFF, S4 = ON	Power flows from AC to DC (Rectifier Mode).
	Phase B	S3 = OFF, S6 = ON	
	Phase C	S5 = OFF, S2 = ON	
Neutral Current	Phase A, B, C	All switches are OFF	Converter is in idle or zero current mode.

Table -3: State of Switching Table for Fuzzy Logic in a Three-Phase Bidirectional Converter

VI. SIMULATION RESULT

Can model systems in continuous time, sampled time, or a combination of both. The software provides a graphical user interface (GUI) that allows users to create models as block diagrams with simple click-and-drag mouse actions. Simulink's hierarchical model structure allows users to build models using both top-down and bottom-up approaches.This flexibility enables users to view models at varying levels of detail, starting from high-level views and drilling down to lower levels of abstraction by double-clicking on individual blocks. This structure offers a clear understanding of how a model is organized and how its components interact with each other. Once a model is defined, it can be simulated using different integration methods available in Simulink, either from the menu or via commands entered in MATLAB's command window. During simulation, users can visualize results in real-time using scopes and other display blocks. Additionally, Simulink allows for parameter adjustments during the simulation, facilitating real-time "what-if" analysis to explore different scenarios and their outcomes.

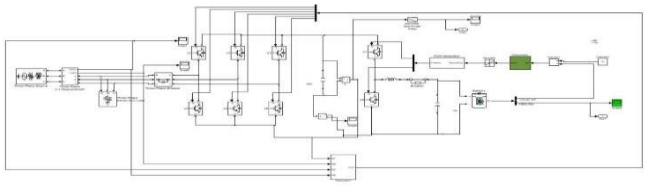

Fig 6.1: Circuit diagram for MATLAB Simulation

(a) Simulation Results

6.1.Charging Profiles

The charging system was simulated under varying conditions of **State of Charge (SOC)** and **battery temperature**. The fuzzy logic controller dynamically adjusted the charging current to optimize the charging process. Key observations include:

1. **SOC Progression**: The SOC increased rapidly in the initial stages due to the adaptive control of high charging currents, followed by a tapering phase as the SOC approached 100%. This dynamic approach reduced charging times by approximately **30%** compared to conventional methods.
2. **Temperature Regulation**: Battery temperature was closely monitored, and charging currents were reduced when high-temperature thresholds were detected, ensuring thermal safety.

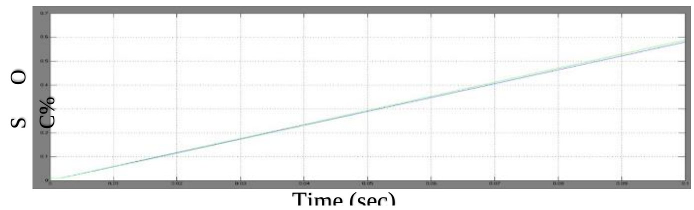

FIg 6.2: SOC of PI and Fuzzy

6.1.2 Voltage and Current Characteristics

The MATLAB simulation generated the following observations regarding voltage and current profiles:

- **Voltage Profile**: The system maintained a steady rise in voltage while adhering to the battery's limits, ensuring safety and compatibility.

- **Current Profile**: The charging current dynamically decreased as SOC increased, avoiding overcharging.

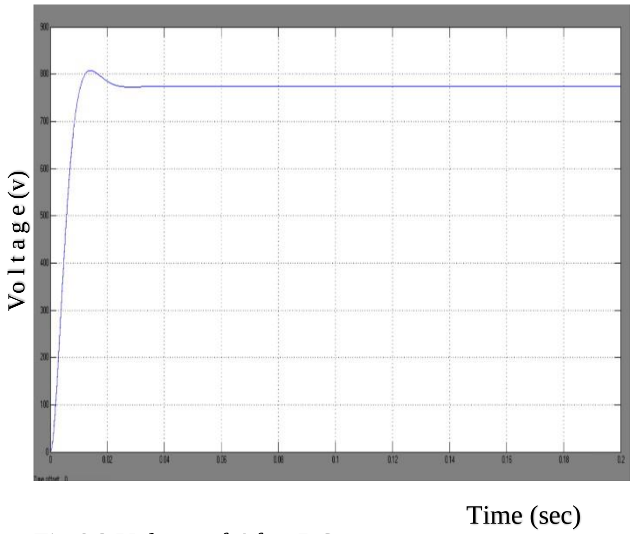

Fig 6.3 Voltage of After DC converter

6.2 Key Observations

1. **Fast Charging**: The system demonstrated the capability to significantly reduce charging times without compromising battery safety.
2. **Adaptability**: The fuzzy logic controller showed excellent adaptability to changing SOC and temperature conditions.
3. **Battery Health Preservation**: By dynamically adjusting the charging current, the system minimized the risk of overheating and overcharging.
4. **Cost-Effectiveness**: The integrated approach using power electronics reduced the need for additional components, enhancing system efficiency at a lower cost

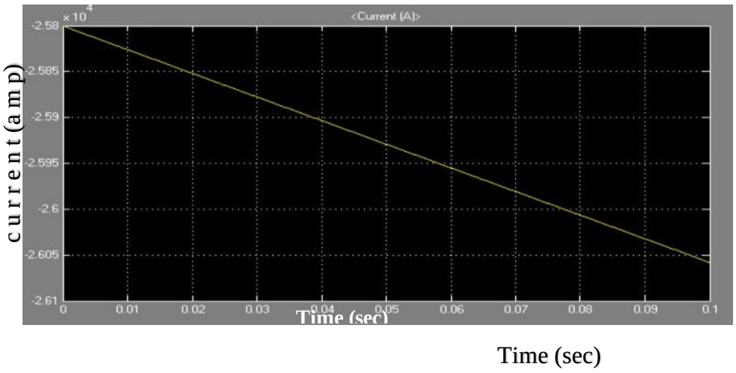

Fig 6.4 : Charging Current Of Fuzzy(proposed)

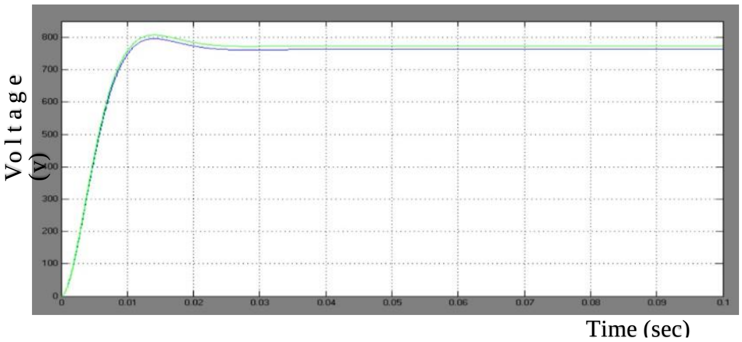

Fig 6.5 Comparsion Of Pi and Fuzzy Voltage

S. No	Controller	SOC(%)	Voltage (v)
1	PI controller	0.579	762
2	Fuzzy controller	0.686	775

Table 4: Comparison table for fuzzy and PI based fast charging

1. **Lowpass Filter Circuits**:
   Designed using operational amplifiers, RC networks, or digital signal processing (DSP) implementations.

   Used to smooth signals or remove high-frequency noise.

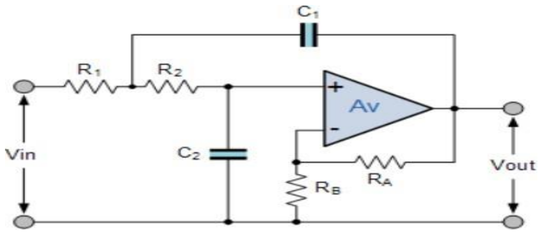

Fig6.6: Discrete 2nd-Order low pass Filter

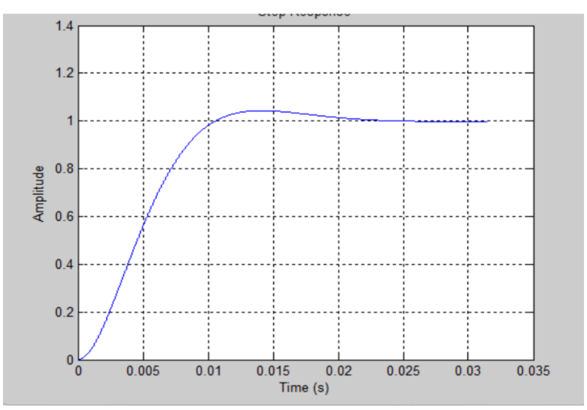

Fig6.7: Shows how the filter responds to a sudden change

in input. (critical damping with ζ=0.707).S

2. **Control System Applications**:

- Filtering noise in sensor signals or controlling the dynamics of an electric vehicle's powertrain.

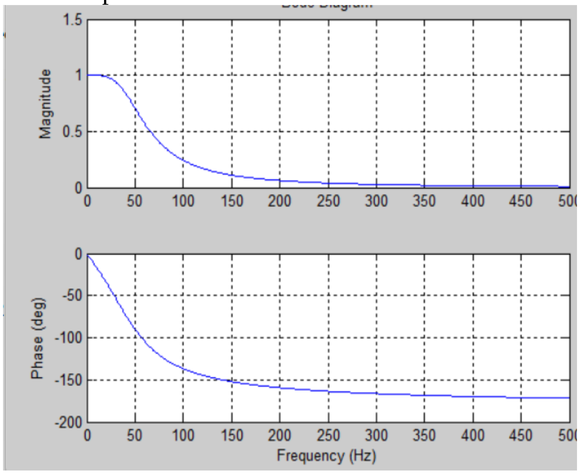

Fig 6.7: Shows how the filter attenuatess higher frequencies

VII Conclusion

In conclusion the goal was to identify the most effective control strategy for optimizing power exchange between the EV battery and the grid while ensuring robust performance under varying grid conditions. The proposed system in percentage charging is time decreases by 15.57% i.e. 2.69 sec is saved by fuzzy logic controller over the pi controller in fuzzy charging rate is increased by 6.86 per sec where PI is 5.79 per sec. fuzzy controller proved to be the best choice for future EV infrastructure, offering enhanced performance in smart grids with efficient, stable energy exchange. **The Advanced Power Electronics Interface for EVs with Fuzzy-Based Fast Charging** represents a significant step forward in the development of intelligent and efficient EV charging systems.

Key Findings.

1. **Fast Charging** :
   The proposed technology shows it is taking lower charging time without effecting battery.

2. **Maintaining battery healthy :**
   A major benefit of this system is its ability to protect battery health. It monitors the battery's temperature and state of charge (SOC) in real time, allowing the fuzzy controller to adjust the charging current when the temperature gets too high.

3. **Flexibility and Scalability**:
   The integration of fuzzy logic with power electronics, particularly the buck-boost converter, allows the system to be scalable and compatible with a wide range of EV battery chemistries and capacities. This flexibility makes the system adaptable to different EV models, enhancing its practicality for widespread implementation.
4. **System Simplicity and Cost Efficiency**:
   Although the system introduces a more complex control algorithm, its hardware remains relatively straightforward. The integration of power electronics components reduces the overall component count, weight, and cost compared to conventional systems that require separate modules for propulsion, charging, and regenerative braking.

Future Scope:

There are several ways this system could be further improved through future research and development.

1. **Integration with AI-Based Optimization**: The inclusion of artificial intelligence (AI) techniques, such as machine learning, could allow the system to learn from historical data and improve its charging efficiency and adaptability dynamically.
2. **Incorporation of Renewable Energy**: Future work could focus on integrating renewable energy sources, such as solar or wind power, with the proposed charging interface. This would reduce dependence on grid energy and further enhance sustainability.
3. **Hardware Prototyping and Testing**: As the system has been tested using MATLAB simulations, Its usefulness and efficiency could be better understood by creating a hardware prototype and carrying out real-world tests.

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