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Fuzzy Logic Controller Based Charging and Discharging Control for Battery in EV Applications

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ABSTRACT- The present research addresses the fuzzy charging and discharge control method for batteries made with lithium-ion utilized in EV applications. The proposed fuzzy-based solution takes into account available parameter to charge or discharge the store within the safe functioning area. To analyses and control battery performance, a variety of controlling methods have been used, but each has its own set of drawbacks, such as the inability to stop two charging conditions, the difficulty of the controller, the lengthy charge time. Due to the lack of mathematical calculations, a fuzzy controller is also simpler to construct, has less additional sensing components, and fewer deep discharging and overcharging protections, making it more efficient in terms of speed and complexity. The effectiveness of the suggested charging-discharging controller system is demonstrated through numerical simulations employing load demand and generation. Performance of the suggested controller is evaluated under simulated load conditions. The model's ability to regulate battery charging and discharging is confirmed by the trial's successful conclusion. The output shows that the battery's state of charge (SOC) never goes above the 20% to 80% safe range for that specific type. A new fuzzy model and an operational real-time system for regulating battery charging and discharging are the major results of this research.

General Terms: Battery Management System, Fuzzy Logic Controller.
Keywords: Charging–discharging; Fuzzy Logic Controller; State-of-Charge; Li-ion and MATLAB/Simulink.

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1. INTRODUCTION

As a new paradigm in transportation, the electric vehicle (EV) is essential to cutting down on emissions of greenhouse gases and promoting greener, more efficient modes of transportation today [1]. Electric automobiles, nevertheless, are viewed by power grids as a brand-new major duty that must be introduced without sacrificing influence quality [2] or power grid constancy [3]. To convert the alternating current (ac) from the power grid into direct current (dc) for charging the EV's batteries, on-board or off-board EV battery chargers are required [4], [5]. The charger that is integrated into the electric car can recharge the battery over the grid. On-board chargers with a power output of less than 6.6 kW are referred to as "slow chargers" in the literature [6][4]. The off-board EV battery chargers, which are installed at specific charging places for the EV [7][8], contain an external power converter (ac-dc). Fast chargers, often referred to as off-board chargers, are frequently described as having outputs greater than 50 kW in the literature. Bidirectional EV battery chargers make it possible to send some of the energy collected from charging electric vehicles back to the grid. The literature identifies this method of operation, which is prevalent with EV battery chargers, as vehicle-to-grid (V2G). Faster charging is achieved with the use of external EV battery chargers. So, the fact that you may switch between sending power back to the grid and using power from the grid to charge your battery is irrelevant. An analysis of the benefits and drawbacks of both on-board and remote systems is provided in [9]. Both on-board and off-board EV charging systems typically consist of two power stages [10]: an ac-dc converter to interact with the power grid and a dc-dc converter to communicate with the batteries.[11]. The ac side must have a sinusoidal current and a unitary power factor, while the dc side's voltage and current must be under control, regardless of the EV battery charging technology. Battery charging needs can be met and power quality can be preserved with the help of these features.

Several pieces of research have looked into FLC-based charging-discharging while taking into account characteristics including state-of-charge (SoC), voltage, and power. In [12], a fuzzy-based dc MG energy management system is explored, with the goal of extending the battery's useful life to greater than 50% SoC in [13], the authors offer a FLC based energy management technique that takes the PV into account. In order to boost MG's efficiency, nonlinear load disturbance was taken into account by Baghaee et al. [14].

However, all studies suffer from the same restriction of evaluating the FLC multi-input SOC set point by concentrating only on the safe operating zone (20%-80%) [16]. In light of the investigation into the direct impact of SOC, for superior power quality and efficient MG control, our research intends to improve these designs and simplify the existing FLC technology. A literature review table shows that the suggested FLC is superior to alternative controlling methods and current FLC technology in keeping the battery SOC within the safe operating area. Also, in contrast to more conventional controller methods, the FLC's output is dependent on fuzzy rules, reducing the likelihood that it may produce inaccurate results. While the CC, CV, and CC-CV charging methods described in the literature are straightforward, overcharging and over discharging the battery remain unchecked. Calculating the PI controller's two proportional and integral parameters adds computational complexity. High repair bills and confusing software are problems for other controllers, too.

The present research's primary objective, compared to the previous studies, is to propose a novel FLC that controls the efficient charging-discharging of the battery predicated on the accessible power, the load request, and the battery's state of charge. The developed controller is demonstrated to be successful in both hardware and simulation implementations of the suggested system, where it is demonstrated to be able to go around the limitations of the multi-input and safe SOC limits that are now in place.

The following is an outline of the main points made in this article.

- The proposed FLC can prevent deep discharging and overcharging of the battery by accounting for variations in load, available power, and the state of charge of the battery at any given time; this eliminates the need for a PI or other conventional controller.
- The research helps get us closer to our aim of dissipating or absorbing excess energy in batteries, so that we may have a more stable and reliable power supply.
- The suggested approach enables the charging and discharging of batteries to run smoothly and continuously in response to changes in both the supply and demand of electricity.
- Because FLC runs and generates the output based on the fuzzy rules formed from the input and output membership functions (MFs), there are no additional sensing components needed to determine the current at load or the resultant converter current.
- In reality, FLC does not rely on the input or output values, but rather on the parameter values themselves. As a result, you won't need any more sensors to monitor the input and output.

The limitations of frequency-based control methods are lessened because FLC does not rely on traditional filters.

In addition, the past has no bearing on FLC because it simply takes into account the current state of affairs.

In this manuscript *section-1* describe the introduction, *section -2* explains the battery modeling, *section -3* gives control method and section-4 follows the results and finally conclusion. The model's ability to regulate battery charging and discharging is confirmed by the trial's successful conclusion. The output shows that the battery's state of charge (SOC) never goes above the 20% to 80% safe range for that specific type. A new fuzzy model and an operational real-time system for regulating battery charging and discharging are the major results of this research.

2. BATTERY MODELLING

The basic goals of lithium-ion battery modelling are to determine its internal state variables, external electrical properties, and mathematical model. Then, based on external factors such as battery current, voltage, and temperature, state variables (internal) such as SOC, internal resistance, and internal voltage are calculated. The volume of research on battery SOC estimation and electric vehicle simulation is rapidly increasing. The accuracy of battery models, particularly those pertaining to Li-Ion batteries, must be improved in order to keep up with the field's expanding interest. Electrochemical models and electrical models are the two types of models utilized in battery modelling. Li-Ion batteries are frequently modelled using electrical models

2.1 Electrical equivalent circuit model

Here we will go over the basics of electric EEC for a Li-ion battery. It explains how a battery's charge and discharge properties change depending on the pace at which it is charged or discharged. *Figure 2* [17-19] depicts the most usual, simple EEC for a Li-ion battery. The open circuit voltage (Vs), the internal resistance (Rint), which has two values (R1 and R2), and the effective capacitance (C1) are the three variables that make up the EEC model. To determine the circuit characteristics for various charge/discharge rates, use this model. The final voltage values predicted by this model are compared to the actual terminal voltage values supplied by the battery suppliers in order to confirm their accuracy. Under constant current charging circumstances, R1, R2, C1, and Vs are represented mathematically in *eq.* 1-4 [20]. As a result of charge/discharge percentage, state-of-charge (SOC) for charging situations, and depth-of-discharge (DOD) for discharging scenarios, the battery variables are expressed as equations based on polynomials.

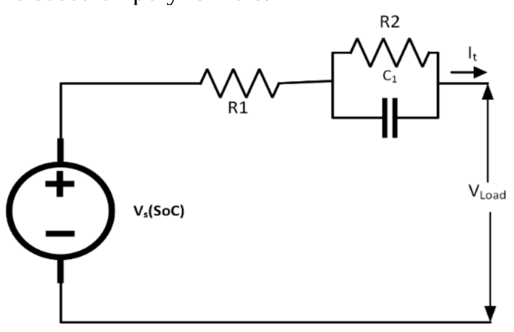

Figure 1. General Block Diagram of Battery model

$$R_1 = (a_1 + a_2 \times C_r + a_3 \times C_r^2) \times e^{-a_4 \times SOC} + (a_5 + a_6 \times C_r + a_7 \times C_r^2) \quad (1)$$

$$R_2 = (a_8 + a_9 \times C_r + a_{10} \times C_r^2) \times e^{-a_{11} \times SOC} + (a_{12} + a_{13} \times C_r + a_{14} \times C_r^2) \quad (2)$$

$$C_1 = -(a_{15} + a_{16} \times C_r + a_{17} \times C_r^2) \times e^{-a_{18} \times SOC} + (a_{19} + a_{20} \times C_r + a_{21} \times C_r^2) \quad (3)$$

$$V_s = (a_{22} + a_{23} \times C_r + a_{24} \times C_r^2) \times e^{-a_{25} \times SOC} + (a_{26} + a_{27} \times SOC + a_{28} \times SOC^2 + a_{29} \times SOC^3) - a_{30} \times C_r + a_{31} \times C_r^2 \quad (4)$$

Eq. 5-8 provides the polynomial formulae for the discharge conditions.

$$R_1 = (a_1 + a_2 \times D_r + a_3 \times D_r^2) \times e^{-a_4 \times DOD} + (a_5 + a_6 \times D_r + a_7 \times D_r^2) \quad (5)$$

$$R_2 = (a_8 + a_9 \times D_r + a_{10} \times D_r^2) \times e^{-a_{11} \times DOD} + (a_{12} + a_{13} \times D_r + a_{14} \times D_r^2) \quad (6)$$

$$C_1 = -(a_{15} + a_{16} \times D_r + a_{17} \times D_r^2) \times e^{-a_{18} \times DOD} + (a_{19} + a_{20} \times C_r + a_{21} \times D_r^2) \quad (7)$$

$$V_s = (a_{22} + a_{23} \times D_r + a_{24} \times D_r^2) \times e^{-a_{25} \times DOD} + (a_{26} + a_{27} \times DOD + a_{28} \times DOD^2 + a_{29} \times DOD^3) - a_{30} \times D_r + a_{31} \times D_r^2 \quad (8)$$

Battery terminal voltage can be calculated for a range of charge/discharge rates once the polynomial coefficients have been determined using FLC. *Eq.9* [21] provides the time-dependent terminal voltage of a charging battery under a constant current.

$$V_{bc}(t_c) = \left[\left[\frac{Q}{C} + I_c \times R_2\right] \times exp\left[-\frac{t_c}{R_2 \times C_1}\right]\right] + V_0 - (I_c \times (R_1 + R_2)) \quad (9)$$

In a similar manner, *Eq. 10* provides the battery terminal voltage for the scenario of a discharge.

$$V_{bc}(t_d) = \left[\left[\frac{Q}{C} + I_d \times R_2\right] \times exp\left[-\frac{t_d}{R_2 \times C_1}\right]\right] + V_0 - (I_d \times (R_1 + R_2)) \quad (10)$$

Maximum energy retrievable from a battery at a certain charge/discharge rate, SOC and temperature is referred to as the battery's capacity [22]. Li-ion batteries' capacity degrades over time because of the unintended reactions that take place during overcharging and excessive charge/discharge cycles. As a result, the rate of charging and discharging has a direct impact on the battery's capacity over time [23]. Trial and error are usually used to determine capacity fading. Models of electric vehicle drive trains, often known as G2V simulations, must account for the reality that the battery will undergo various rates of charge and discharge in real life. Therefore, mathematical models are useful. The fading of battery capacity at various charge/discharge rates can be calculated using straightforward mathematical modelling techniques. The Arrhenius equation serves as the basis for the mathematical model of capacity fading. given as [24].

$$Q_{loss} = A \times exp\left[-\frac{E_a}{R \times T}\right] \times t^z \quad (11)$$

In order to determine capacity decay at a constant charge/discharge rate, we can use the following formula. In reality, however, the charge and discharge rates shift depending on the state of the grid. Capacity degradation is proportional to charge/discharge rate, state-of-charge, and temperature [25].

3. CONTROL METHOD

3.1. Fuzzy Logic Controller (FLC)

A symbolic logic way of thinking, Fuzzy Logic Control (FLC) establishes a grey area between the ideal values of zero and one, where a logical assertion of nonzero is nevertheless viable. Fuzzy inference is process by which input computations of fuzzy variables are fuzzified utilising membership functions which is shown in Figure 2. Technical issues can be resolved by membership function approach, which assigns a truth value in range [0,1]. FLC will take place over following four steps: (1) Fuzzification of input variables, (2) Rule Evaluation, (3) Aggregation of Rule Outputs (4) Defuzzification. The rule-based system not only explains how to respond to incoming signals, but also reflects information from outside world. Specifically, the controller design suggests Mamdani-type rules as they provide a natural framework for incorporating expert knowledge, rules are composed of a succession of basic IF-THEN statements. An input and output variable mapping system, a fuzzy interference system (FIS) uses if-then principles to make decisions. A defuzzification unit transforms a fuzzy variable into a crisp variable, and a fuzzy set with an arbitrary input and output serves as controller in a FIS. If there are nuances to FLC, it will aid in smooth operation of HES through application of a variety of constraint rules. The battery SoC can be made better with use of FLC. The FLC is a smart algorithm that works effectively with complex systems for which mathematical models are difficult to create. The FLC algorithm is highly resilient in nonlinear and time-varying systems. In addition, FLC is flexible since fuzzy rules can be easily adjusted to meet new requirements.

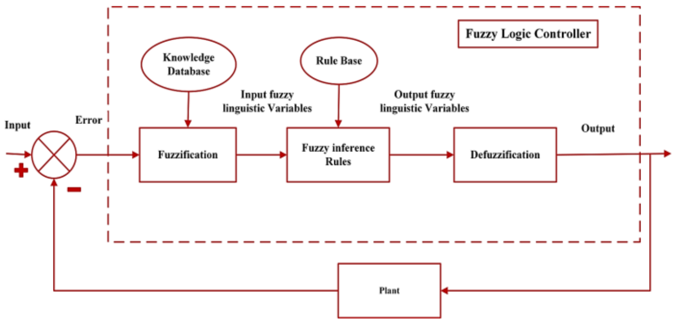

Figure 2. Fuzzy Interference System (FIS)

The suggested FLC takes V(K) and I(K) as inputs for fuzzification, with the resulting out variable being used to feed battery. The dP/dV ratio is established by the chopper's pulse width modulation.

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The battery can be used as an on-demand power supply. It is charged when there is a surplus of generated power over consumption and discharged when the load demand exceeds the supply. *Figure 3* is a schematic representation of the research process as a whole. According to the flowchart, charging will start as soon as the battery's state of SoC falls below a specific cut-off point. The battery will discharge in accordance with the load, but, if the state of charge (SOC) is already at its maximum. The battery's SoC prepares not go above that limit. Therefore, the battery operates within the safe working range between the minimum and maximum threshold, charging and discharging in accordance with the accessible power and load condition. Inputs Prerequired (the distance between the available power and the loads) and SOC_{diff} (the difference between SOC_{pre} and SOC_{ref}) were used in the development of FLC to control the SOC of the battery. Since the controller's output is current, it will govern the variation of battery conditions. By using the pulse width modulation (PWM) technique to regulate the buck-boost converter's duty cycle, this controller setup offers improvements over the standard control schemes. The inductance (L_b) and capacitance (C_b) values of the bidirectional buck-boost converter are 5mH and 1020F, respectively. When being charged, the buck-boost converter is in its buck mode, and when being discharged, it is in its boost mode. Each variable of FLC is partitioned into five fuzzy subsets in the proposed FLC: VS, MS, N, ML and VL (Very Big). To reduce computational complexity, the controller's input and output MFs are normalized to the range 1 as shown in Figure 5.

The charging and discharging rates of a battery are affected by a number of factors, including the SOC of the battery, the available power, and the load demand. The battery's built-in safeguards against overcharging and over draining remain active only within this safe operating range, which sets higher (80%) and lower (20%) limits on SOC, respectively. As the SOC rises or falls above or below the predetermined limit, the fuzzy controller will halt charging or draining the battery, respectively.

Table 1: Rule Table

Error/Change in Error	VS	MS	N	ML	VL
VS	VS	VS	VS	MS	N
MS	VS	VS	MS	N	ML
N	MS	VS	N	ML	NB
ML	N	MS	ML	VL	VL
VL	ML	N	VL	VL	VL

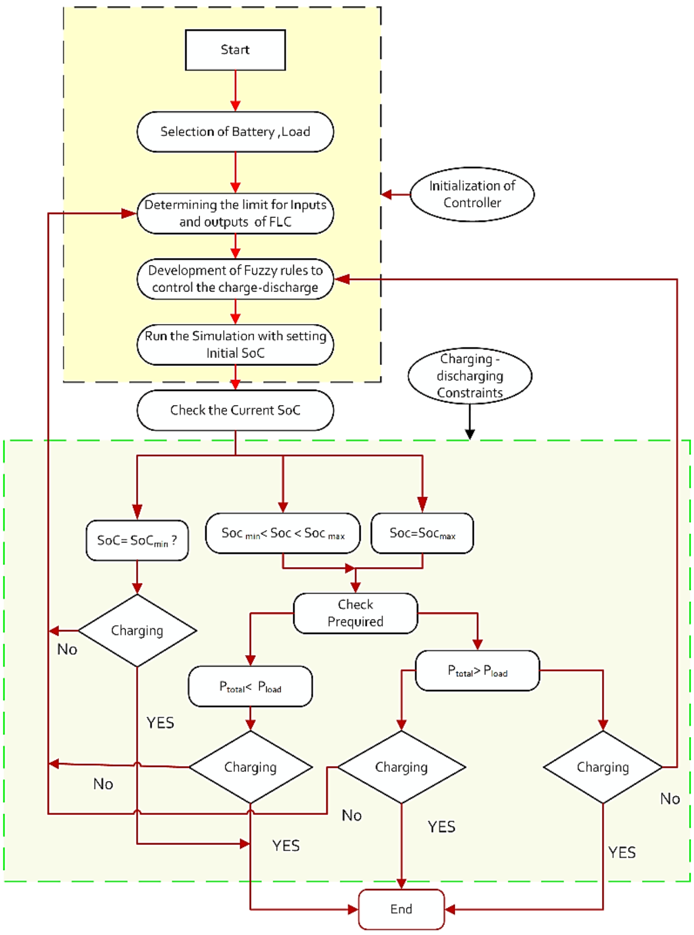

Figure 3. Flowchart of charging–discharging controller

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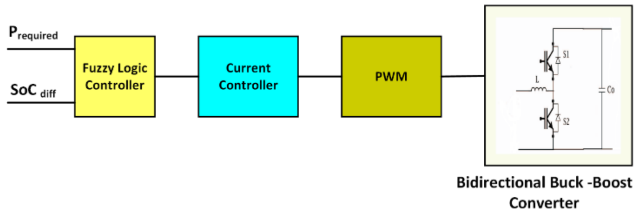

Figure 4. Controller for the proposed fuzzy-based charging–discharging model

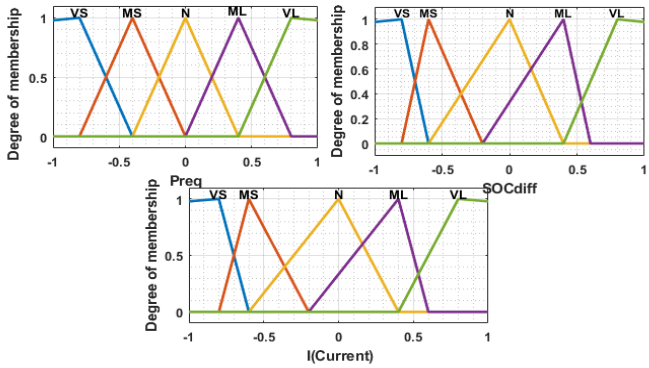

Figure 5. MFs for input variables $P_{required}$. (b) MFs for input variables SOC_{diff}. (c) MFs for output variables current.

4. SIMULATION RESULTS

In order to verify the charging-discharging characteristics of the proposed FLC, the results of comparisons of performance between the PI simulation outcomes (in unrelated mode) and FLC outputs have been presented in this section.

4.1.Performance of Battery during Discharging

During discharging of batter, the results of SoC (%), Battery Voltage and Power variation with PI and Fuzzy Logic Controller shown in Figure 6 and Figure 7 respectively.it is observed the SoC of Battery is 45% and the output voltage of battery is 25.6V when the reference Voltage is det to 28V. The battery output current is 22A and Battery Power is 550W. the load Power is -440W with PI controller. With Fuzzy Logic controller it is observed the SoC of Battery is increased to 65% and the output voltage of battery is 24V when the reference Voltage is det to 28V. The battery output current is 200A and Battery Power is 5.6kW. the load Power is -2.5W. So that using FLC during discharging of Battery obtained more power and Load variation also improved.

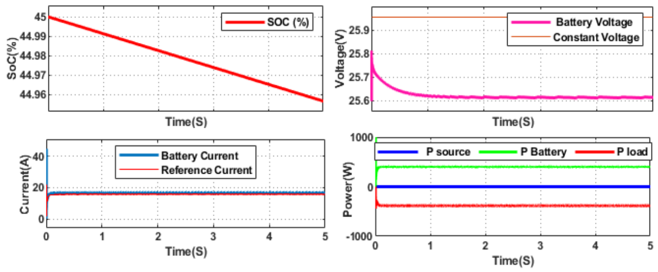

Figure 6. The results of Soc (%), Battery current, Battery Voltage and Power variation with PI

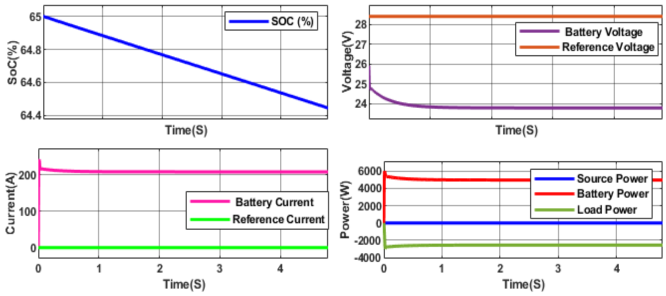

Figure 7. The results of Soc (%), Battery current, Battery Voltage and Power variation with FLC

4.2.Performance of Battery during charging

Ref voltage is 25.95 of battery which is fully charged. voltage saturation of this PI is the max ref current which is 22 A max charging current of battery. During charging of batter, the results of soc (%), Battery Voltage and Power variation with PI and Fuzzy Logic Controller shown in Figure 8. and Figure 8 respectively.it is observed the SoC of Battery is 45% and the output voltage of battery is 25.6V when the reference Voltage is det to 28V. The battery output current is -18.5A and Battery Power is -1777W. the load Power is -330W with PI controller. With Fuzzy Logic controller it is observed the SoC of Battery is increased to 65% and the output voltage of battery is 24V when the reference Voltage is det to 28V. The battery output current is -230A and Battery Power is -6.4kW. the load Power is -3.5W. So that using FLC during charging of Battery obtained more power and Load variation also improved.

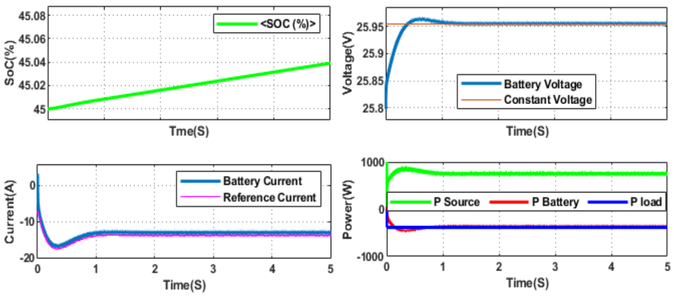

Figure 8. The results of Soc (%), Battery current, Battery Voltage and Power variation with PI

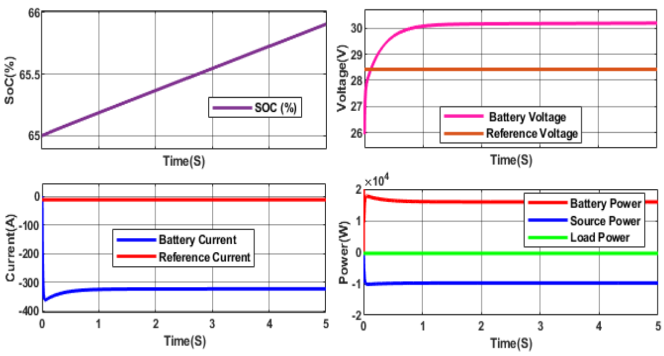

Figure 9. The results of SoC (%), Battery current, Battery Voltage and Power variation with FLC

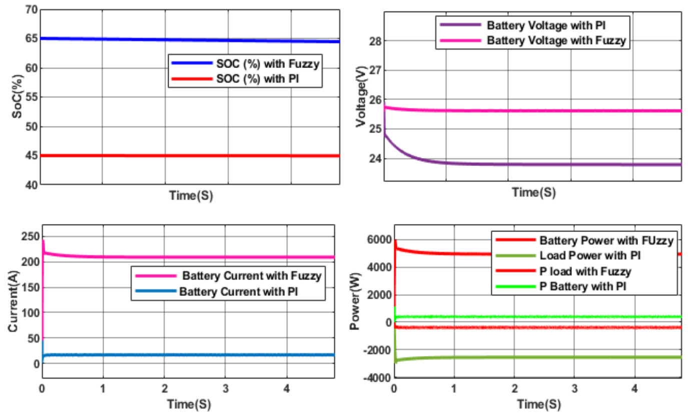

Figure 10. Comparison results of Soc (%), Battery current, Battery Voltage and Power variation at Discharging Mode

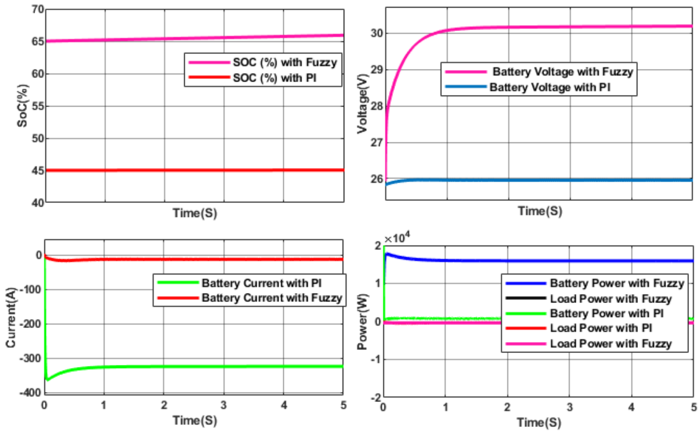

Figure 11. Comparison results of Soc (%), Battery current, Battery Voltage and Power variation at charging Mode

Figure 10 and *figure 11* depicts the comparison results of Battery parameters with PI and FLC based Charging–Discharging Control for Lithium-Ion Battery in EV applications.

5. CONCLUSIONS

This paper introduces a FLC to balance battery charging and discharging with load demand, power output from renewable sources, and state-of-charge (SOC) in a storage system. Since the FLC model is a smart method for assessing the SOC and can be easily implemented, it is used. To keep the battery's charging and discharging cycles within their safe operating range, a fuzzy controller was developed. In total, 25 rules that take into account the load requirement, available Battery power, and battery SOC have been devised. It has been observed that SOC shifts in response to a variety of factors. The successful simulation outcome indicates the controller's effectiveness in preserving the SOC's secure operating area. When the load demand exceeds the available power, the battery goes into draining mode. When the load demand is lower than the power produced by the MG, the battery, nevertheless, is in the charging mode. The fuzzy model also established a range of 20% to 80% as the safe battery SOC limit. In conclusion, the findings of this article show how successfully the FLC regulates ESS charging and discharging for EVs. The fundamental contribution of this study is the real-time implementation and verification of the proposed fuzzy controller, which can control the battery charging and discharging in EVs. The research's concentration, which is limited to evaluating the fuzzy controller's effectiveness in typical operating conditions, does not include accounting for the unknowns or drawbacks of the proposed EV topology.

Table 2: Comparison Table FLC

Controller	Parameters		
	Battery current	Battery Power	%SoC
With PI (during Charging)	60A	1.2kw	Constant
With Fuzzy (During Charging)	130A	2kw	Constant
With PI (during Dis-Charging)	40A	1.3Kw	Decreasing 65
With Fuzzy (During Dis-Charging)	180A	5Kw	Decreasing 45

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