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Abstract— **Implementing a Battery Management System (BMS) in Electric Vehicles (EVs) offers several benefits that enhance the efficiency, security, and durability of the vehicle's battery system. The BMS oversees and controls the performance of each cell in the battery pack, guaranteeing that they function within predetermined voltage and temperature thresholds to maintain safety. In this paper, an intelligent BMS for an EV model powered by a solar PV array was proposed using a fuzzy logic (FL) controller. The proposed method was applied to EVs consisting of four Lithium-ion batteries. The simulation results are achieved using MATLAB/Simulink software. The estimation of the state of charge (SOC) for each battery was used as input to the FL which controls the discharging/ charging mode for each battery via power semiconductor switches. Three different scenarios are used to verify the suggested method. A full control FL operation was obtained, and the batteries were protected successfully against overcharging and over-discharging.**

Keywords— Battery management system, Solar PV, Fuzzy logic, State of Charge, Electric vehicle.

I. Introduction

The integration of a Photovoltaic (PV) system with a Lithium-Ion (Li-ion) battery in an EV offers several advantages, including extended range, reduced dependence on grid electricity, environmental benefits, off-grid capability, emergency charging, and showcasing innovative technology [1]. PV systems generate electricity from sunlight, which can be used to charge the Li-ion battery, extending the vehicle's range. Solar power is a clean and renewable energy source, contributing to a reduction in greenhouse gas emissions. PV-equipped EVs can also provide grid support through Vehicle-to-Grid (V2G) technology, allowing excess energy stored in the Li-ion battery to be fed back to the grid during high-demand periods [2-6]. A Battery Management System (BMS) is a crucial component in EVs to ensure the safe and efficient operation of the battery pack. Key aspects of a BMS include cell monitoring, thermal management, fault detection and diagnostics, overcurrent and overvoltage protection, charge control, and discharge control [7-9]. It also provides real-time data and commands for optimal battery performance [10]. Cell balancing ensures uniform charge levels, while predictive maintenance uses algorithms to predict potential issues or degradation in battery performance. In addition, the energy efficiency optimizes the use of energy within the battery pack to maximize range and overall efficiency. The design and implementation of a BMS are crucial for the performance, safety, and longevity of an electric vehicle's battery system. Several different kinds of BMS are used in EVs. Each of these BMS is intended to meet a particular set of duties and criteria [11, 12]. The most prevalent kinds of BMS that are used in electric vehicles are centralized, distributed, Passive, Active, and Smart BMS techniques. The choice of BMS type depends on factors such as the size and configuration of the battery pack, the specific requirements of the electric vehicle, cost considerations, and the desired level of sophistication in terms of features and capabilities [13, 14]. The authors in [15, 16] summarized the current state of the art in BMS and this study's objective is to show the design of a passive cell balancing network for lithium-iron-phosphate ($LiFePO_4$) batteries. Several significant simulation and hardware findings are shown in order to illustrate the state of charge (SOC) estimate accomplished via the use of the Coulombs counting technique and the battery cell balancing mechanism. [17] presented a novel technique using neural network (NN) with fuzzy logic (FL) technique. The suggested method provides several benefits that are not available with conventional BMS systems. These benefits include a decentralized control architecture, the capacity to function without constant contact, and enhanced dependability. The used BMS control system comprises an adaptive virtual admittance, which modifies the value of the virtual admittance depending on the current SOC of each battery cell. In [18] an efficient BMS was suggested based on a formula for calculating the efficiency of the battery. The formula for calculating battery efficiency that has been presented takes into account the charging time, the charging current, and the capacity of the battery. By using the suggested SOC and state of health (SOH) computations, an algorithm that is capable of precisely determining the status of the battery has been developed. The open circuit voltage (OCV) measurement is very suitable for estimating initial SOC and accurate way to determine SOC under no load condition. This method helps to eliminate the initial inaccuracy that occurs when using the coulomb counting method (CCM). The conventional method for evaluating the parameters of a battery is not only expensive but also time-consuming and requires a significant amount of computer power. To solve this issue, a strategy that is based on heuristic optimization approaches has been proposed in [19]. Different heuristic optimization strategies that are considered to be state-of-the-art were used to evaluate the suggested BMS model. An evaluation of the parameters has been carried out by comparing the projected voltage curves from the model to the curves obtained from the manufacturer's catalog.

The authors in [20,21] proposed Fuzzy Logic based BMS for PV/Battery solar system in EV model. The suggested approach robust control scenarios with simulation and experiment tests to prove the suggested study. A fuzzy logic controller (FLC) has been used in the BMS technique that is recommended for the purpose of managing the charging and discharging cycles of a Li-ion battery system. Also, control BMS is connect to electric vehicle (EV) load that is supplied by solar panels.The BMS keeps the battery from being overcharged or depleted. The study discussed the BMS strategies, which include safe charging, battery protection, and SOC (State-of-Charge), among others. In this paper, an efficient BMS based FL method is proposed to protect the EV li-ion batteries from overcharging or over discharging conditions. The proposed BMS contributions can be summarized as follows:

- Proposes an efficient fuzzy logic control for EV battery.
- Protect the EV batteries from overcharging or over discharging conditions.
- Modelling EV model with real model parameters.

II. Material and Methods

A. Proposed System Structure

The proposed system configuration was shown in figure 1. The BMS used based FL method. The main source of the system is fed from the PV solar array via DC/DC converter. The supplied four li-ion batteries are estimated based on their SOC. The switches such as MOSFETs or IGBTs are used to control the charging or discharging the bank of the batteries. The PWM signals is send from BMS to these gates of the switches to open/close the circuit. The Fuzzy Logic (FL) is proposed by measuring the SOC for each battery and sent it to fuzification process and then do the proper output with low or high signal. In this study, a constant DC voltage 50V has been applied to charge the batteries of four electric vehicles which have rated voltage (48V, 200Ah). Each electric vehicle needs 2000 W which make a total of 8000 W. Therefore, the power rating of PV is 8500 W to supply demand load So, the output voltage is controlled based on the speed of the EV.

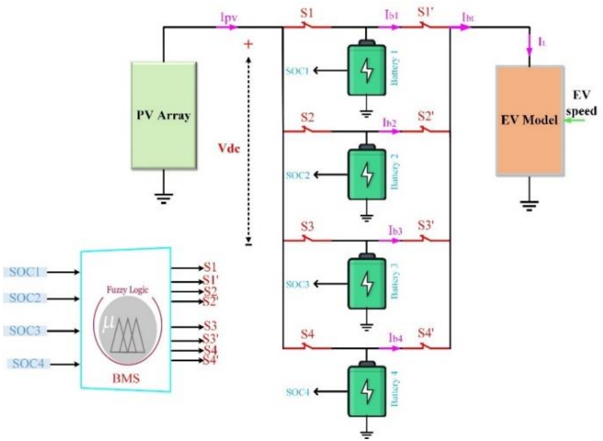


Fig. 1. Pproposed system circuit.

The solar PV array are used to supply the EV by charging the batteries via DC/DC converter. The array current for the cells can be modelled as follows [22]:

$$I_i = I_{ph} - I_d \left(exp\left[\frac{(V + IR_S)}{Aa} \right] - 1 \right) - \frac{(V + IR_S)}{R_{SH}} \quad (1)$$

Where, I_i is the module's current, V is the module's voltage, I_{ph} is the photo current of the module, I_d is the diode current at case of saturation, R_S represents internal resistance of solar module , R_{SH} is representation of the shunt resistance that results from defects or irregularities in the solar cell, a is the diode constant, A is the thermal voltage. The solar PV system is shown in Fig.2. as shown in this figure, the DC/DC converter is controlled by the duty ration which comes from the MPPT algorithm that maximize the energy of the PV array. The MPP is different based on the solar irradiance and temperature. As a result, this MPPT is used to the matching between the input impedance and output impedance.

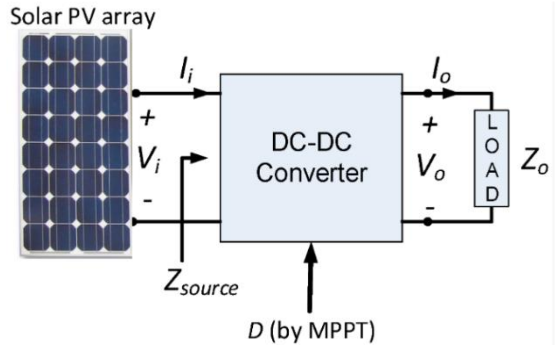


Fig. 2. Solar PV System.

B. Electric Vehicle Modelling

The EV model can be expressed based on the total traction forces (F_T) that can be determined as in equation (2).

$$F_T = F_r + F_{ad} + F_g + F_{ac} \quad (2)$$

Where, F_r is the resistance force of rolling, F_{ad} represents the force of aerodynamic, F_g is the force of gravity and F_{ac} is acceleration vehicle force. These forces are shown in Fig.3 [23,24]. These forces can be expressed as follows:

$$F_r = \mu_{rr} M_v\, g \quad (3)$$

$$F_{ad} = 0.5\, \rho\, v^2 A_f\, C_d \quad (4)$$

$$F_g = M_v\, g \sin(\emptyset) \quad (5)$$

$$F_{ac} = M_v\, a = M_v \frac{dv}{dt} \quad (6)$$

Where, μ_{rr} is the rolling friction coefficient (0.05 and 0.005 for radial and EV tires), M_v is the vehicle mass, g represents the acceleration of gravity, ρ is the density of air, $\emptyset$ is the road slope, v is the speed of vehicle, A_f is the frontal area, C_d indicates to coefficient drag of aerodynamic in the range (0.19 to 0.3), $\emptyset$ is the road slop and a is the acceleration of EV.

However, the load power that produced by the traction engine (EV drivetrain) on the DC link ($P_L(t)$) is written as follows [25]:

$$P_L(t) = F_T(t) \times v(t) \times \eta_t \quad (7)$$

Where, η_t is the mechanical transmission efficiency.

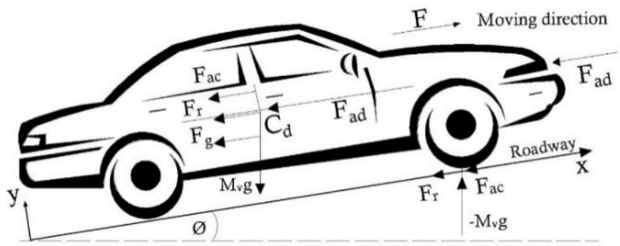


Fig. 3. Proposed system circuit.

C. Battery management system

Fuzzy logic is often used in BMS for EVs due to its ability to handle uncertainty, imprecision, and non-linearity. It excels at handling unpredictable and varying conditions, allowing for more flexibility in modeling complex systems. FL based BMS also allows for the integration of human expertise, linguistic variables, rule-based control, adaptive control, reduced sensitivity to measurement noise, multi-objective optimization, and simple implementation and interpretation. In this study the FL based BMS is used to control the SOC of the four EV batteries [26,27]. It is particularly useful in managing batteries under different and unpredictable scenarios, such as changes in SOC. However, its effectiveness depends on the used rules, and the decision to use fuzzy logic in a BMS can be shown in Fig.4. In this work, the four inputs (SOC1, SOC2, SOC3, and SOC4) for the batteries (Battery1 , battery 2, battery 3, and batter 4) are used. The membership functions of the fuzzy are designed to estimate the SOC and fed the results to the power switch to disconnect or connect the switch based on the decision of the fuzzy output. The membership functions for the input and the outputs can be shown in Fig.5. As seen, in Fig (5a), the input range of the battery SOC is from 0 to 30 % at the low membership (L) and from 30 to 90% high SOC. However, the output of fuzzy control as seen in Fig (5b).

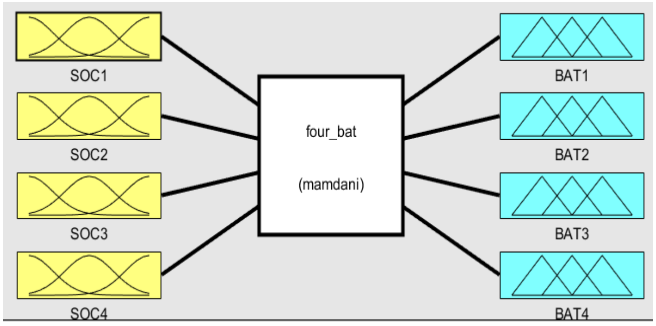
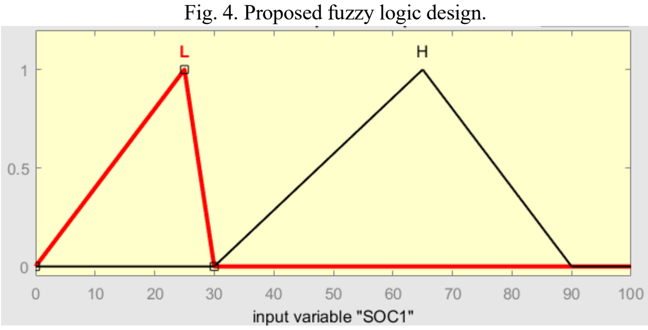
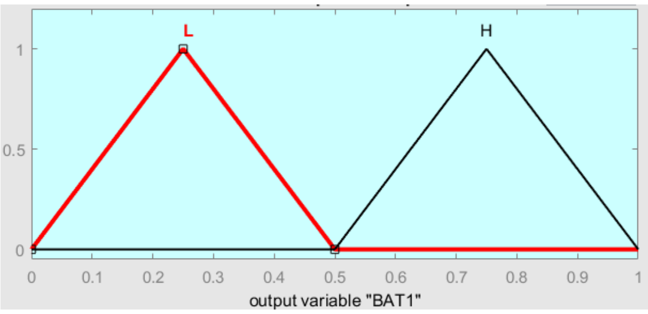


Fig. 4. Proposed fuzzy logic design.



(a)



(b)

Fig.5. (a) Input membership function of the SOC (b) output membership function of the battery.

The output values of the fuzzy are sent to the PWM block diagram which is controlled by the primary and secondary switches. the low value of the output is between the 0-0.5 while the high value of the output is (0.5-1). If the SOC_N for the battery is low , the output fuzzy is HIGH, so the primary switch is ON. This makes the battery stays in charging mode due to the low value of the SOC for this battery. Against, when the batteries have high SOC such as greater than 30%, this makes the output of the fuzzy is Low and the secondary switch is active ON which is reverse (NOT gate) PWM with primary switch. The flowchart of the proposed BMS is displayed in Fig.6. as shown, in this figure, based on the value of the SOC,N (where N is the number if the batteries), the decision of charging or discharging is done to protect the batteries. In order to determine if the output is more than 0.5, the battery is linked to a DC-DC converter for the purpose of charging. The output is compared with the charging and discharging situation, which means that it is compared to 0.5. It is necessary to connect the battery to the EV in order to discharge it if the output is less than 0.5. Effectively overcoming charging and discharging circumstances of the batteries is accomplished by the use of FL controller.

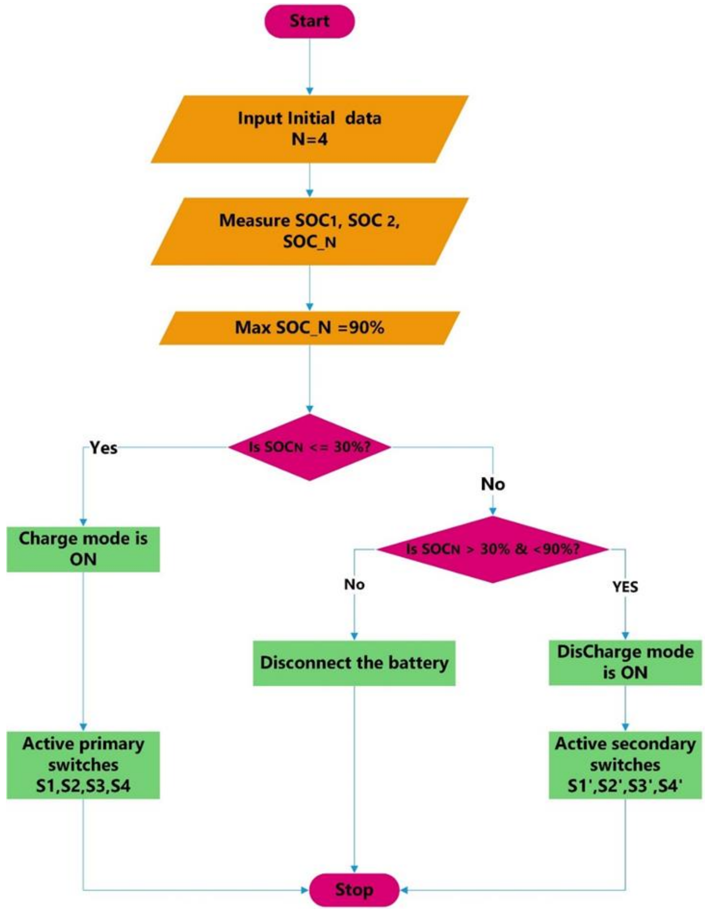


Fig.6. Flowchart of the proposed method.

Based on the above flowchart the output value of the FL controls the switches according to the comparison with 0.5 value . If the output greater than or equal to 0.5, the batteries will charge from the DC bus. While the output value is less than 0.5 (LOW), the PWM is zero and the primary switches are OFF and the batteries will discharge the energy from DC bus to the EV side. The output voltage of the EV is 48 V. Fig. 7 represents the calculation of the error between the first and second charge rates relative to the first battery in the fuzzy logic controller (FLC). Fig.8 presents the rules of the fuzzy control used in this work. As seen, when the SOC is low, the output membership value is high according to the triangle membership functions.

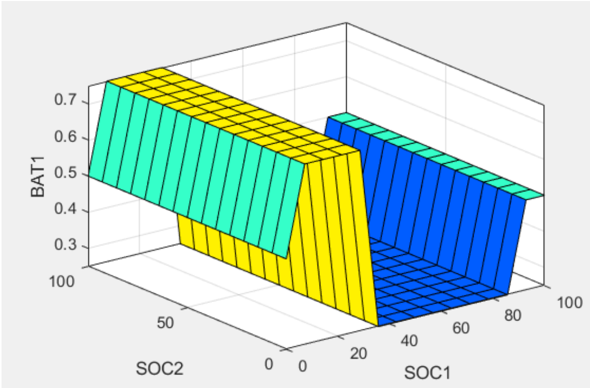


Fig. 7. Error view of the first battery with respect to other batteries.

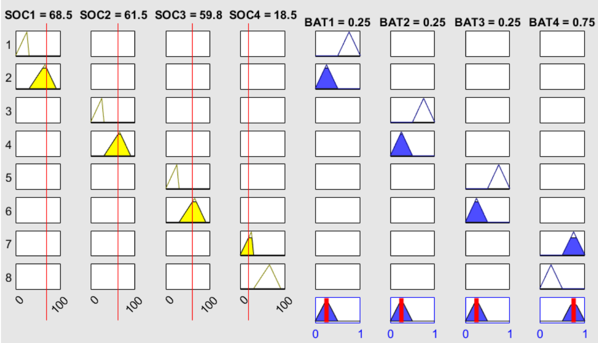


Fig. 8. Rules of the fuzzy control.

III. Simulation Results

In this work, the MATLAB simulation has been used to verify the suggested BMS. The simulation model is done using Simulink in MATLAB version 2021a via personal computer (PC), Intel(R) Core(TM) i7-10750H CPU @ 2.60GHz, and RAM 16.0 GB. The EV model was modelled via the motor current of the EV. The motor current profile of the EV is shown in Fig.9. The output voltage (EV voltage) is 50 V which is displayed in Fig. (9-b). The motor current was varied from 5.5 A to 4 A from time 0s-1.5s. after that, the motor current varies from 4 A to a maximum value of 7 A at time 3s and then it is reduced to 5.5 A. The output voltage of the batteries is constant at 50V. In this case, the BMS controls the charging or discharging modes based on the SOC values.

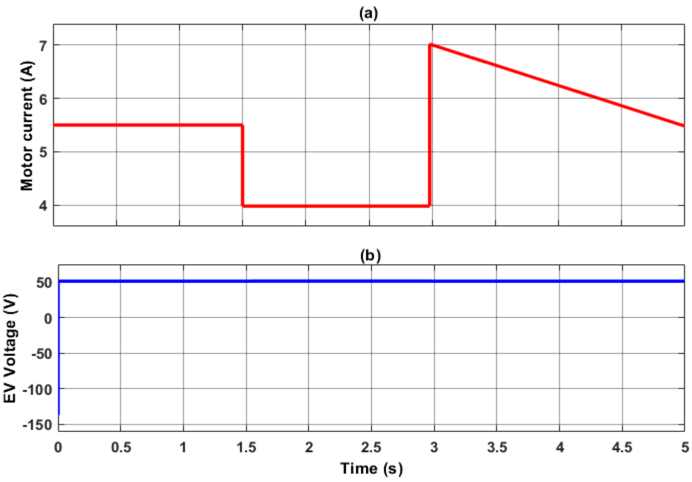


Fig.9. (a) Motor current for EV (b) Output voltage.

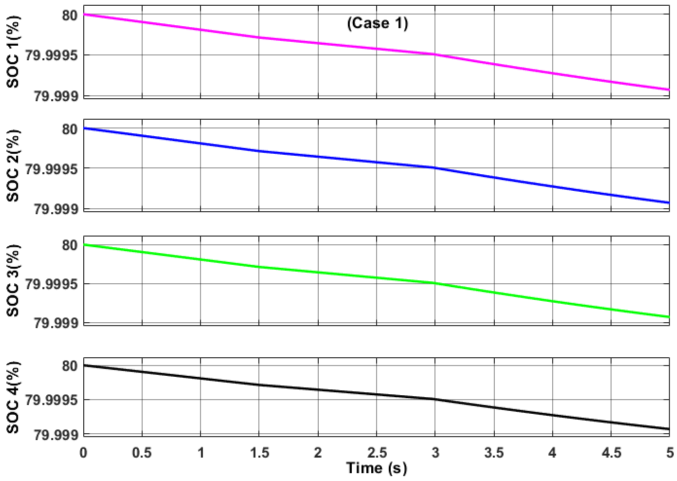


Fig.10. SOC for each battery in case (1).

SOC is a crucial parameter in controlling and managing batteries, especially in the context of EV. SOC represents the current charge level of a battery. Battery health may be negatively impacted by overcharging and over discharging; monitoring SOC helps avoid this phenomenon. As a result, the SOC of the used batteries can be shown in Fig.10. The first case in this study is done by SOC1=SOC2=SOC3=SOC4=80%. The output value of the fuzzy is low for all batteries. As a result, overall batteries in discharging mode due to the SOC is high. The output current for each battery in this case can be shown in Fig.11. As seen in this figure, the output current value is 1.4 A for each battery. The total discharge current will equal the output EV current. The variation in the discharging current occurs due to the motor current profile.

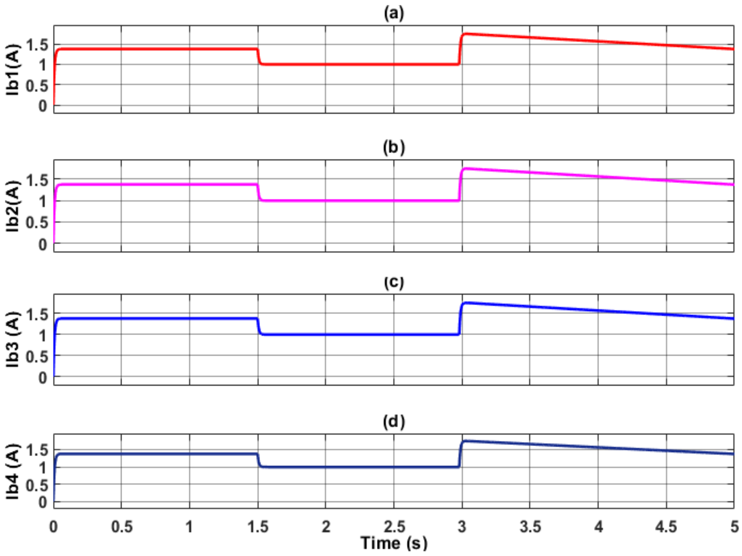


Fig.11. Output current for each battery in case (1).

Fig. 12 displays the SOC of the used batteries. Presenting SOC1= SOC2=20%, and SOC3=SOC4=70%. In this case two batteries will operate in charging mode operation due to their SOC are low. The other two batteries that have SOC=70 % will supply the EV load. The fuzzy output in the first and second batteries are high (0.75) and so the secondary switches S1’ and S2’ are opened with zero PWM value. The fuzzy output is low in the third and fourth batteries due to the SOC are high (70%). Therefore, the switches of these batteries (S3’ and S4') are closed. Fig. 13 shows the current output for each battery in this scenario.

The first and second batteries have an output current value of zero, as seen in Fig.13. Based on the EV current, the third and fourth batteries will supply or discharge the EV load based on their SOC. In this case, the output discharge current from these batteries is 2.75A at the starting and this value will be varied according to the motor current as displayed in Fig. 13. In case 2, two batteries are in discharging mode and two batteries at charging mode based on the values of the SOC.

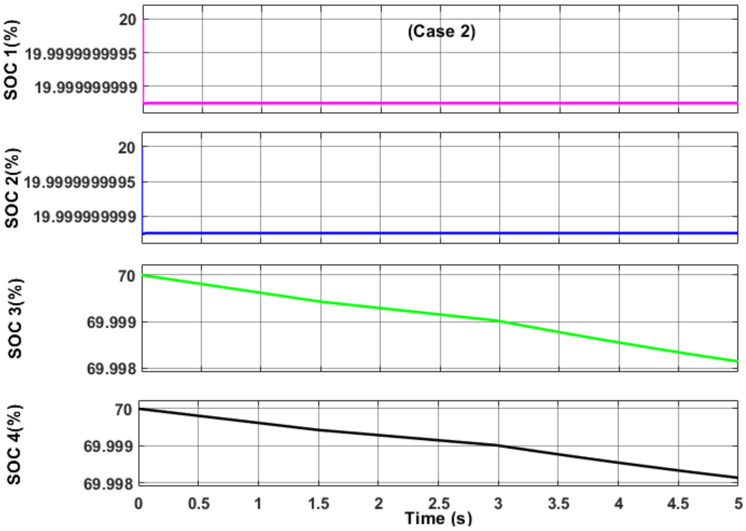


Fig.12. SOC for each battery in case (2).

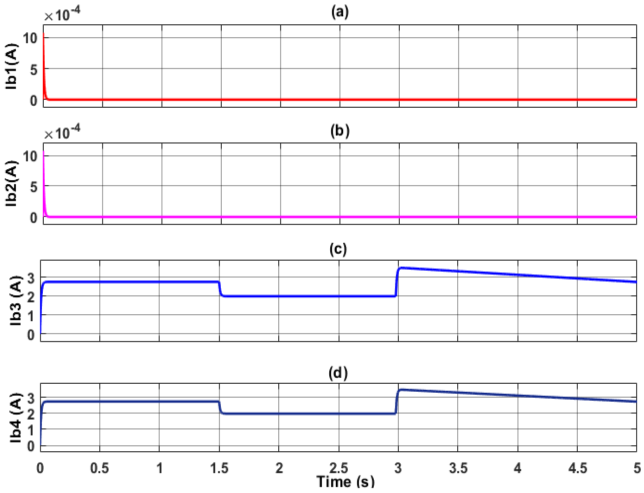


Fig.13. Output current for each battery in case (2).

In case 3, the first, second, and third batteries are in discharging mode operation due to the SOC1=50%, SOC2=60%, and SOC3=47%. The fourth battery has a SOC is 10%. As a result, this battery will stay in charging mode and this state was controlled by the BMS via the output of the fuzzy logic which is equal to 0.75 (HIGH). The SOC values of this case can be shown in Fig.14. The achieved battery currents can be seen in Fig.15.

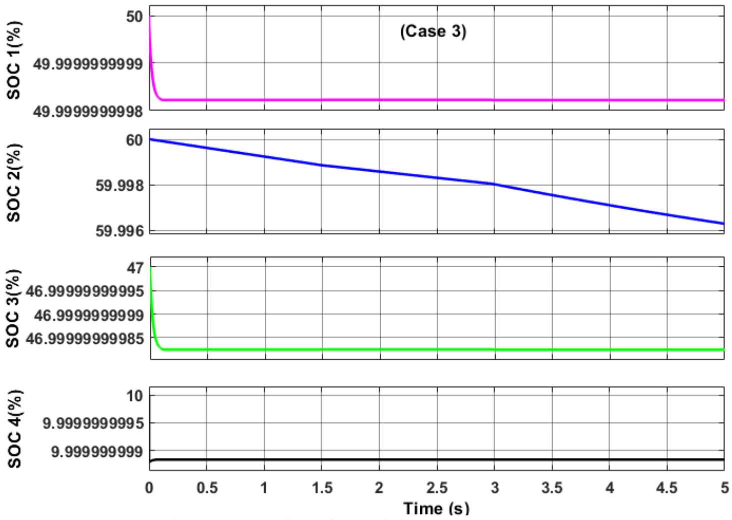


Fig.14 SOC values for each battery in case (3).

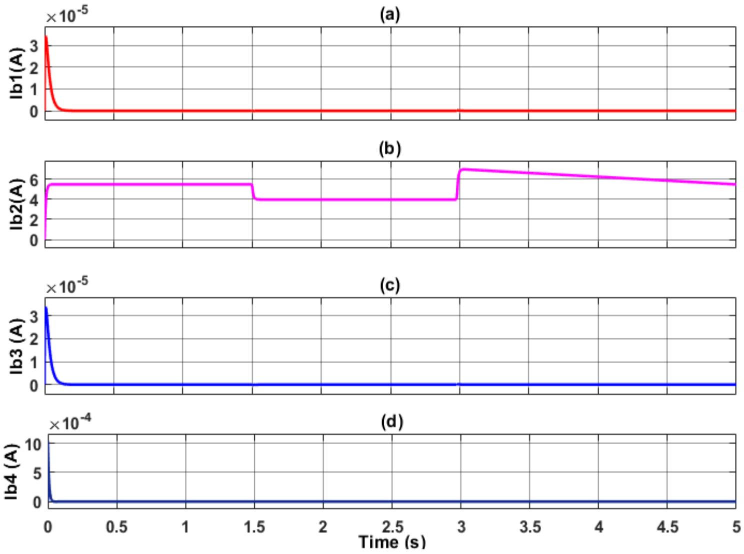


Fig.15. Battery currents for each battery in case (3).

To clarify the novelty of the work, Table 1 shows the numerical results of the used BMS. In this table the comparison between the used case studies is presented. The SOC value for each battery the fuzzy logic output, and the operation of the battery are displayed.

TABLE I. Comparison of SOC with Fuzzy logic control.

Case study	SOC NO.	SOC value	Fuzzy output	Mode of battery
Case 1	SOC1	80%	0.25	Discharging
	SOC2	80%	0.25	Discharging
	SOC3	80%	0.25	Discharging
	SOC4	80%	0.25	Discharging
Case 2	SOC1	20%	0.75	Charging
	SOC2	20%	0.75	Charging
	SOC3	70%	0.25	Discharging
	SOC4	70%	0.25	Discharging
Case 3	SOC1	50%	0.25	Discharging
	SOC2	60%	0.25	Discharging
	SOC3	47%	0.25	Discharging
	SOC4	10%	0.75	Charging

IV. CONCLUSION

This work presents a proposal for an intelligent Battery Management System (BMS) for an Electric Vehicle (EV) electrified by a Photovoltaic (PV) system. The suggested BMS utilizes a fuzzy logic (FL) controller. The suggested approach was implemented on an electric vehicle with four lithium-ion batteries. First, the mathematical analysis for the PV, and EV models are presented. The EV model represent some of four forces: resistance force of rolling F_r, the force of aerodynamic F_{ad}, force of gravity F_g and the acceleration vehicle force F_{ac}. Then the overall system is modelled using MATLAB/Simulink. The state of charge (SOC) was estimated for each battery and it is used as input for the FL sets. The FL regulates the discharging/charging mode for each battery via PWM signals. Three distinct situations are used to validate the recommend technique. An outcome of great precision was achieved, and the batteries have been effectively safeguarded against both overcharging and over discharging.

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