PERFORMANCE ANALYSIS OF FUZZY LOGIC-CONTROLLED OFF-BOARD EV CHARGERS WITH PV INTEGRATION

[1]Jhansi Rani,[2]Fathima Rasi
[12]Students
Department Of Electrical and Electronics Engineering

ABSTRACT

The growing popularity of electric cars (EVs) is driving up demand for sustainable and effective charging infrastructure. In this paper, a photovoltaic (PV) array-powered off-board electric vehicle battery charging system with fuzzy logic control is proposed and examined. Solar energy integration lessens reliance on traditional grid-based power while also promoting environmental sustainability. A fuzzy logic controller (FLC) is included into the suggested system to regulate the PV array's non-linear features and fluctuating output, guaranteeing optimum power transmission to the EV battery under a range of load and climatic circumstances. By dynamically modifying charging settings in response to real-time input circumstances, the FLC is intended to improve charging efficiency, control output voltage, and preserve battery safety.

According to simulation data, the fuzzy logic-controlled charger performs better in terms of energy efficiency, stability, and flexibility than traditional fixed-logic systems. The technology is positioned as a possible option for next-generation EV charging stations because to its high interoperability with smart grid technologies. In order to provide a greener and more effective option for future transportation requirements, our study advances intelligent, renewable-powered EV charging systems.

I.INTRODUCTION

The rapid uptake of electric vehicles (EVs) has increased the need for efficient, sustainable, and flexible charging infrastructure. The power grid is the primary source of electricity for traditional EV charging systems, which presents problems with peak load management, energy costs, and environmental effects. The incorporation of renewable energy sources, namely photovoltaic (PV) systems, into EV charging infrastructures has drawn a lot of interest as a solution to these problems.

Off-board charging solutions provide more flexibility in terms of power regulation, scalability, and maintenance since they retain the charger outside the car. However, efficiently regulating the charging process is made more difficult by the intrinsically fluctuating nature of solar energy. The dynamic external factors that influence PV production, such as variations in temperature and irradiance, are often difficult for conventional control systems to react to.

This paper suggests a fuzzy logic-based control strategy for off-board EV charging utilising solar PV electricity in order to get around these restrictions. Because fuzzy logic control (FLC) can tolerate imprecise inputs and include human-like reasoning, it is especially well-suited for non-linear and uncertain systems. More consistent and effective energy transmission from the PV array to the car battery is ensured by the suggested system, which uses fuzzy logic to control charging parameters like voltage and current.

Designing, simulating, and evaluating the operation of an off-board EV charging system driven by a PV array using fuzzy logic is the aim of this study. The system seeks to promote sustainable energy integration, improve charging safety, and maximise energy efficiency. This work supports worldwide initiatives to encourage green travel and lower carbon emissions by advancing the development of sophisticated, environmentally friendly EV infrastructure.

II.LITERATURE SURVEY

The increasing popularity of electric cars (EVs) has made the construction of dependable, sustainable, and effective charging infrastructure necessary. Numerous technologies and control schemes have been investigated in this area of study to enhance the efficiency of EV charging systems, especially when renewable energy sources like photovoltaic (PV) arrays are included.

1. Integration of Renewable Energy and EV Charging

To lessen dependency on the grid and cut carbon emissions, a number of studies have looked at integrating renewable energy, especially solar PV, into EV charging stations. Solar-assisted EV chargers have the potential to drastically lower energy costs and enhance environmental sustainability, as shown by Kumar et al. (2019). Their study did, however, also draw attention to the difficulty in controlling power variations brought on by fluctuating solar irradiation.

Intelligent control algorithms and hybrid energy storage systems have been presented as solutions to this problem. In order to guarantee reliable power supply, Alizadeh et al. (2021) investigated the use of PV systems in conjunction with battery energy storage. Effectively controlling this hybrid arrangement under changing environmental settings was still a major challenge, however.

2. Systems for Off-Board Charging

Compared to on-board systems, off-board chargers provide a number of clear benefits, including higher power capacity, improved thermal control, and simpler upgradeability. Off-board systems are excellent candidates for intelligent control techniques like fuzzy logic as they enable the implementation of sophisticated and adaptable control algorithms without being constrained by weight or space (Zhao et al., 2020).

3. Power Electronics Fuzzy Logic Control

The potential of fuzzy logic control (FLC) to manage non-linearities, uncertainties, and real-time decision-making in complex systems has drawn a lot of attention recently. Mamdani and Assilian (1975) employed fuzzy logic, a mathematical representation of vagueness first proposed by Zadeh (1973), to control systems.

Researchers like R. Priya et al. (2018) and S. Patra et al. (2020) have used FLC to control battery charging processes in the context of power electronics and energy systems, enhancing reaction times, voltage management, and system flexibility. These studies demonstrate how fuzzy logic may improve charging systems' performance and dependability under a variety of load and environmental scenarios.

4. PV and Fuzzy Control Combined for EV Charging

Fuzzy logic has just begun to be included into PV-based charging systems. A fuzzy-based MPPT (Maximum output Point Tracking) controller was used by Sharma et al. (2022) to manage the charging profile of EV batteries and maximise output from the PV system. Their findings demonstrated less battery stress and better energy use.

The majority of the material now in publication, however, either concentrates on PV-based systems without intelligent control or fuzzy control alone. The performance of off-board EV chargers with fuzzy logic and PV integration has not been fully examined in many research, particularly with regard to energy efficiency and real-time flexibility under dynamic climatic circumstances.

III. PHOTOVOLTAIC MODULE:

The foundation for computer simulation of an actual system is modelling. It is often predicated on a theoretical examination of all the variables affecting the many physical processes taking place in the system. The single diode circuit model, which depicts the electrical behaviour of the pn-junction and is shown in fig. 1, is the most often used model to forecast energy generation in solar cell modelling. How a photovoltaic system operates is seen in the figure. One diode makes up the perfect solar module.

The fundamental component of a solar panel is a solar cell. Numerous solar cells are connected in parallel and series to make a photovoltaic module. Using a current source, a diode, and two resistors, it is possible to mimic a single solar cell. This type is referred to as a solar cell single diode model.

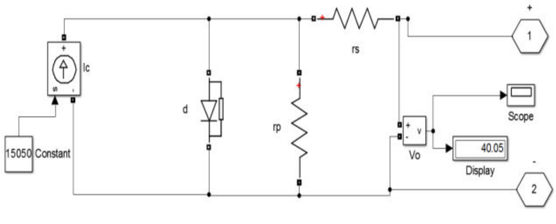


Figure 1: Single diode model of a solar cell

3.1 Introduction to fuzzy

The range and quantity of fuzzy logic applications have grown dramatically in recent years. Applications include industrial process control, medical instruments, decision support systems, portfolio selection, and consumer goods including cameras, camcorders, washing machines, and microwave ovens. You must first grasp what fuzzy logic is in order to see why its usage has increased.

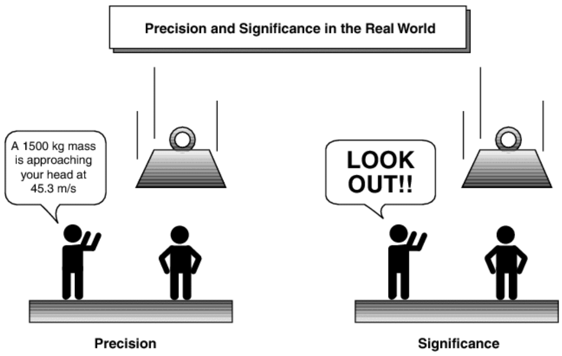
There are two distinct definitions for fuzzy logic. Fuzzy logic, in its strictest definition, is a logical system that is an expansion of multivalve logic. But in a broader sense, fuzzy logic (FL) is almost the same as fuzzy sets theory, which deals with classes of objects with hazy borders where membership depends on degree. According to this viewpoint, fuzzy logic in its strictest form is a subset of FL. Fuzzy logic is conceptually and substantively different from conventional multivalve logical systems, even in its more limited description.

In every way, the fuzzy logic toolbox is really outstanding. Because of this, fuzzy logic is a useful technique for creating intelligent systems. The fuzzy logic toolkit is user-friendly and simple to learn. Finally, but just as importantly, it offers a current and approachable overview of fuzzy logic technique and its many uses.

What is fuzzy logic?

The main idea behind fuzzy logic is the relative value of accuracy: how crucial is it to get it absolutely correct when a tentative response would suffice?

To solve fuzzy logic issues, you may utilise the Fuzzy Logic Toolbox program in conjunction with MATLAB technical computing software. Because fuzzy logic effectively balances significance and precision—trade-offs that humans have been doing for a very long time—it is an intriguing field of study. Fuzzy logic is both ancient and new in this sense because, despite the fact that fuzzy logic as a contemporary, rigorous discipline is still in its infancy, its premise is based on long-standing human reasoning abilities.



IV. OPERATION OF THE PROPOSED SYSTEM

A PV array, a sepic converter, a half-bridge BIDC, an EV battery, a backup battery bank, and a controller make up the suggested PV-EV battery charger, as seen in Fig. 1. To provide a steady output voltage at the dc link, the controller generates the gate pulses that are sent to the sepic converter. In order to run the BIDC in boost mode, which charges the backup battery from the PV array, and in buck mode, which charges the EV battery from the backup battery, gate pulses are also produced to the BIDC switches. The auxiliary switches Sa, Sb, and Sc receive gate pulses from the controller as well. All auxiliary switches are turned on during periods of strong solar radiation in order to connect the dc connection to the PV array via the sepic converter, the dc link to the backup battery via the BIDC, and the dc link to the EV battery. Switch Sa isolates the PV array and sepic converter from the dc connection when solar irradiation is low. In contrast, when solar power is not enough to charge the backup battery, the switch Sc is switched OFF to separate the

BIDC and backup battery from the dc connection. As described in this part, the suggested system functions in three modes: mode 1, mode 2, and mode 3.

Mode 1

All of the auxiliary switches are turned on to charge the backup battery and EV battery concurrently from the PV array using a BIDC and a sepic converter, respectively, during the hours of greatest sunlight, when the power supplied by the array is highest. When in this mode, BIDC increases the dc link voltage to charge the backup battery by moving ahead.

Mode 2

When there is little solar radiation and no sunlight, the electricity from the PV array is not enough to charge an EV battery. As a result, the switch Sa is turned off, and switches Sb and Sc are turned on, connecting the EV battery to the backup battery via BIDC. This disconnects the PV array from the dc connection. In order to charge the EV battery, BIDC steps down the backup battery voltage in this mode.

Mode 3

Switches Sa and Sb are turned on and switch Sc is turned off to separate the BIDC and backup battery bank from the DC connection when the electricity provided by the PV array is enough to charge just the EV battery.

4.1 DESIGN OF THE CONVERTERS USED IN THE PROPOSED CHARGER

Sepic converter

By modifying its duty ratio using the PI controller, the sepic converter in the suggested charging system maintains a steady output voltage independent of the PV array voltage. As shown in Fig. 2, the sepic converter is made up of one IGBT switch, one diode, two inductors, and two capacitors. The sepic converter's main benefits are as follows: (i) it can function in both boost and buck modes based on the duty ratio; and (ii) unlike buck-boost and cuk converters, it produces an output voltage with the same polarity as the input voltage [16]. The following formula provides the sepic converter's voltage gain:

$$\frac{V_{dc}}{V_{PV}} = \frac{D}{1-D} \quad \text{.........................} (1)$$

where Vdc is the dc link voltage, VPV is the PV array voltage and D is the duty ratio of the sepic converter. The values of inductors and capacitors of the sepic converter are chosen as per (2)–(4) [17]:

$$L_a = L_b = \frac{V_{PV_{min}} D_{max}}{2\Delta i_{PV} f_{sw}} \quad \text{................} (2)$$

$$C_1 = \frac{I_{dc} D_{max}}{\Delta V_{C1} f_{sw}} \quad \text{...................} (3)$$

$$C_2 = \frac{I_{dc} D_{max}}{\Delta V_{dc} f_{sw}} \quad \text{........................} (4)$$

Where VPVmin is the minimum PV array voltage, ΔiPV is the input current ripple, fsw is the switching frequency, Idc is the dc link

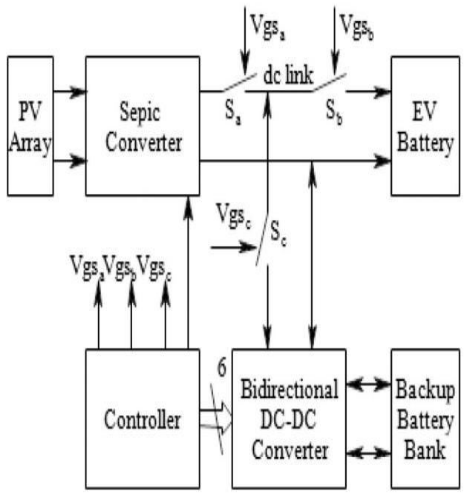


Fig. 2 Block diagram of the EV battery charger

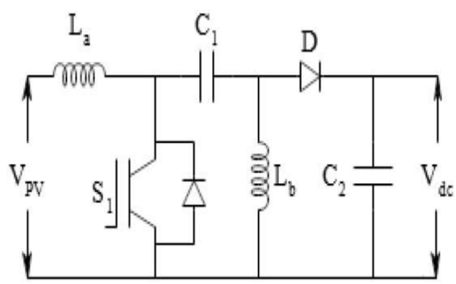


Fig. 3 Schematic diagram of sepic converter

current, ΔVC1 is the capacitor, C1 voltage ripple, ΔVdc is the output voltage ripple, and Dmax is the maximum duty ratio calculated as follows:

$$D_{max} = \frac{V_{dc} + V_D}{V_{PVmin} + V_{dc} + V_D} \quad \text{..................} \textbf{(5)}$$

Where VD is the diode voltage drop.

4.2 BIDIRECTIONAL INTERLEAVED DC–DC CONVERTER

The schematic design of the BIDC used in the suggested charging method is shown in Fig. 3. The dc link is on the converter's low voltage side, while the backup battery bank is on its high voltage side. When moving forward, this converter works in boost mode; when moving backward, it works in buck mode. While SU1, SU2, and SU3 are the active switches in buck mode, switches SL1, SL2, and SL3 are the active switches in boost mode. Every switch used in this converter has a parallel snubber capacitor and an anti-parallel diode. In buck mode, the inductors L1, L2, and L3 function as a low-pass filter; in boost mode, they function as boost inductors. The smoothing energy buffer components of this converter are the capacitors CL and CH. Current ripples are reduced using interleaved inductor currents. In [20], the functioning of a single leg converter is examined in order to analyse the converter's modes of operation. (6) and (7), respectively, provide the voltage conversion ratio of BIDC in boost and buck modes.

$$\frac{V_{BackupBatt}}{V_{dc}} = \frac{1}{1 - D_{Boost}} \quad \text{..............} (6)$$

$$\frac{V_{dc}}{V_{BackupBatt}} = D_{Buck} \quad \text{.....................} (7)$$

Where V Backup Battery is the backup battery voltage and D Boost is the duty ratio of BIDC in boost mode and D Buck is the buck mode duty ratio. The values of inductors are considered less than the critical inductance values in both boost and buck modes to operate the converter in discontinuous conduction mode to improve efficiency

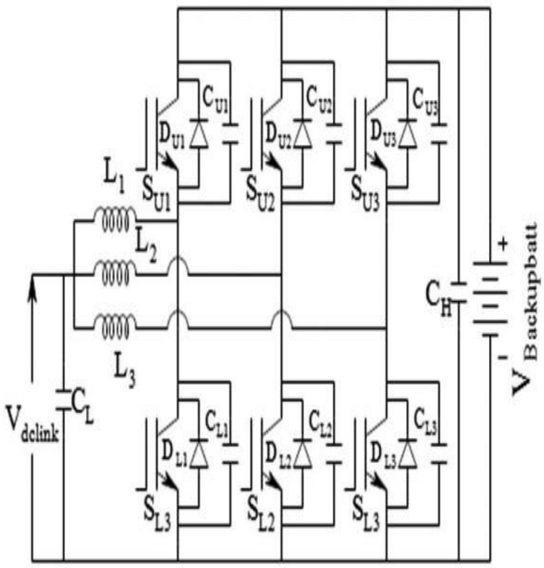


Fig.4 Schematic diagram of half-bridge BIDC [20]. the critical inductance value is calculated in boost and buck modes using (8) and (9), respectively.

$$L_{cric} = \frac{3V_{BackupBatt}^2 D_{Boost}(1 - D_{Boost})^2}{2Pf_s} \quad \text{......} (8)$$

$$L_{cric} = \frac{3V_{dc}^2(1 - D_{Buck})}{2Pf_s} \quad \text{..........} (9)$$

Where P is the Backup battery power. The values of the capacitors on the low and high voltage side of BIDC are considered based on the following equations:

$$C_H = \frac{D_{Boost}P}{2f_sV_{BackupBatt}^2} \quad \text{.............}(10)$$

$$C_L = \frac{V_{BackupBatt}D_{Buck}(1 - D_{Buck})}{8f_s^2 L\Delta V_{dc}} \quad \text{.......}(11)$$

4.3 DESIGN OF CONTROLLERS

The proposed charger's controller sends gate pulses to the three auxiliary switches, the BIDC, and the switches in the sepic converter. Fig. 4 displays the algorithm used to turn the auxiliary switches on and off. The controller calculates the PV array power after sensing the voltage and current. The controller creates gate pulses to activate all auxiliary switches so that the EV battery and backup battery bank may be charged concurrently from the PV array if the PV array power exceeds the EV battery rated power, or PR. PM, the switch, Sc is switched OFF, disconnecting the backup battery from the charging system, and switches, Sa, and Sb are turned ON to charge the EV battery alone from the PV array if the PV array power is less than the rated power of the EV battery but more than the minimum needed power. The switch, Sa, is switched off to isolate the PV array and sepic converter from the charging system if the PV array power is less than the minimum needed power, PM. The backup battery may now charge the EV battery since the switches Sb and Sc are switched on. To maintain a steady voltage at the dc link regardless of changes in the PV array voltage, the PI voltage controller is used in the suggested charging system to provide gate pulses to the MOSFET in the sepic converter. Three legs make up BIDC, and each leg has two switches. The two switches in the same leg must receive gate pulses with a 180° phase offset from one another. Depending on the PV array power, the controller in the suggested system sends six gate pulses to the BIDC. Gate pulses are sent to the BIDC switches to put it in boost mode and increase the dc link voltage in order to charge the backup battery bank if the PV array power surpasses PR. In this mode, the leg 1 switches get gate pulses with a phase shift of 0°, the leg 2 switches receive a phase shift of 120° from the leg 1 switches, and the leg 3 switches receive a phase shift of 240° from the leg 1 switches. The gate pulses are produced appropriately to run the BIDC in the event that the PV array power is less than PM.

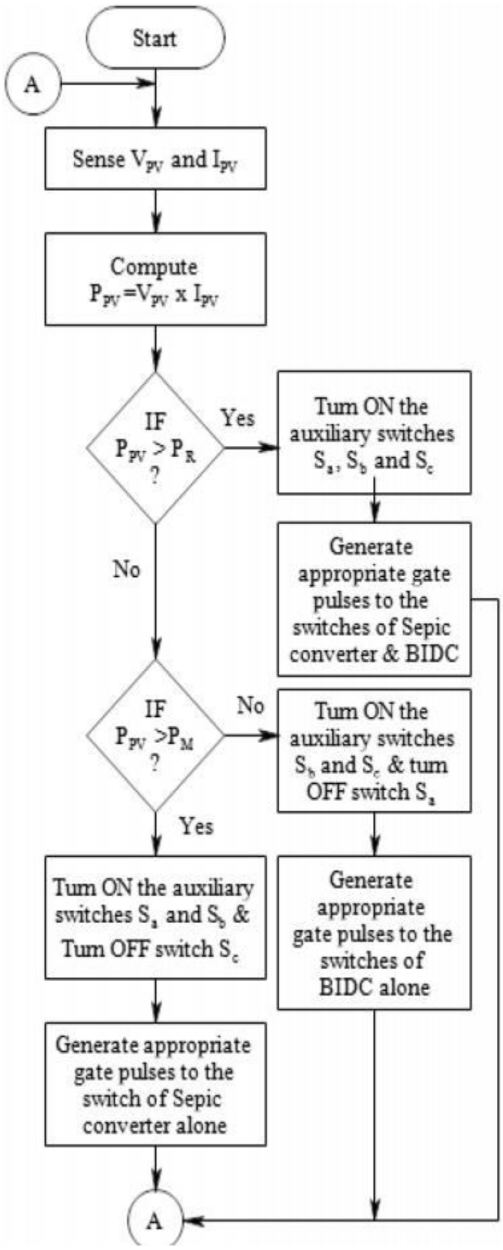


Fig. 5: Flowchart of gate pulses generation for the auxiliary switches

Buck mode, which generates a step-down voltage at the dc connection that is enough for the backup battery to charge the EV battery. In this mode, the leg 3 switches get gate pulses with a 0° phase shift, whereas the leg 2 and leg 1 switches receive gate pulses that are 120° and 240° phase displaced, respectively, relative to the leg 3 switches.

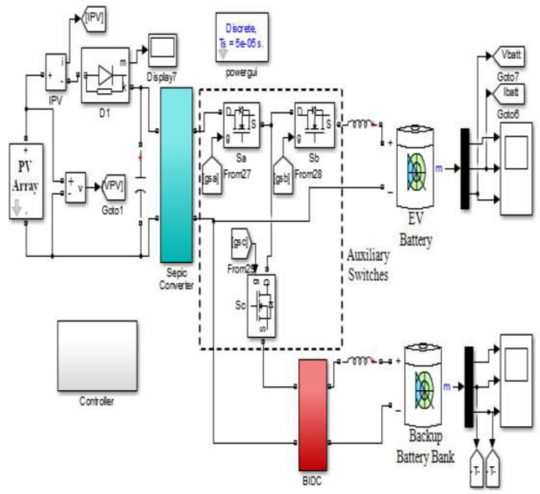


Fig.6 Simulation model of the proposed charger

4.4. MATHEMATICAL MODELLING OF PROPOSED SYSTEM

Mathematical model of the proposed system is obtained by combining the state-space average model of Sepic converter and Bidirectional DC–DC converter. It is derived by considering the ON and OFF switching period of the converters [26, 27]. The state space matrices of the sepic converter, state matrix 'A', input matrix 'B', output matrix 'C', feed forward matrix 'D' are found to be

$$A = \begin{bmatrix} 0 & 0 & \frac{-(1-D_s)}{L_a} & \frac{-(1-D_s)}{L_a} \\ 0 & 0 & \frac{D_s}{L_b} & \frac{-(1-D_s)}{L_b} \\ \frac{(1-D_s)}{C_1} & \frac{-D_s}{C_1} & 0 & 0 \\ \frac{(1-D_s)}{C_2} & \frac{(1-D_s)}{C_2} & 0 & \frac{-1}{C_2 R_{eq}} \end{bmatrix}$$

…….(12)

$$B = \begin{bmatrix} \frac{1}{L_a} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

….. (13)

C = [0 0 0 1]…… (14)

D = [0]…… (15)

Where Req is equivalent impedance at the dc link and Ds is the duty ratio of Sepic converter. Similarly, the state-space matrices of the BIDC, state matrix 'A1 ', input matrix 'B1 ', output matrix 'C1 ', feed forward matrix 'D1 ' are found to be

$$A_1 = \begin{bmatrix} \frac{-(R_{lp}+R_{dson})}{L} & 0 & \frac{-(1-D_{BIDC})}{L} \\ \frac{-1+2D_{BIDC}}{C_L} & 0 & 0 \\ \frac{(1-D_{BIDC})}{C_H} & 0 & \frac{-1}{C_H R_{eq1}} \end{bmatrix}$$

……

(16)

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \end{bmatrix}$$

…… (17)

C_1 = [0 0 1]…… (18)

D_1 = [0]…… (19)

where L = (L1/3), Rlp = (RL1/3), Req1 is equivalent impedance across capacitor CH, Rdson the MOSFET turn on resistance, RL1 is the parasitic resistance of inductor, L1 and DBIDC is the duty ratio of BIDC. Transfer functions of the converters are obtained from the above state-space models and they are combined to produce the overall transfer function of the proposed system. Frequency response of the proposed system exhibits the positive gain margin and phase margin which in turn indicates that the proposed system is stable. Simulation studies of the proposed charger are carried out and the results are furnished in the following section.

V.SIMULATION RESULTS

The simulation studies of the suggested system are conducted using Simulink in the MATLAB program. Its classical equation is used to describe PV arrays [28, 29]. Power MOSFETs, inductors, and capacitors from the Sim Power Systems Block set in the Simulink library are used to mimic the Sepic and BIDC converter. The Simulink library's PWM generator, pulse generator, logic gates, comparator, multiplier, and PI controller are used in the development of the controller. The PV array model incorporates the

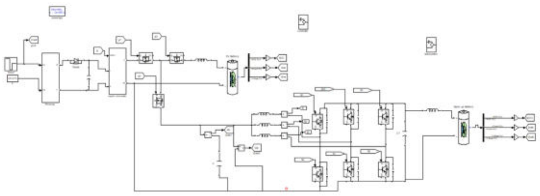


Fig.7 Simulation model of (a) Sepic converter, (b) BIDC with Fuzzy

Developed sepic converter and BIDC along with the battery models available in Simulink library for developing the proposed charging system as shown in Fig. 5. The developed simulation model of sepic converter and BIDC shown as subsystems in Fig. 5 are depicted in Figs. 6a and b, respectively. The dynamic response of the system was investigated using the developed simulation model for PV array irradiation of 850, 100 and 500 W/m2 in mode 1, mode 2 and mode 3, respectively. The simulation results showing PV array voltage and current waveforms along with the gate pulses to the auxiliary switches are depicted in Fig. 7. Irradiation waveforms are shown in the scale of 1 for 1000 W/m2 in Fig. 7. Thus, both EV battery and backup battery gets charged simultaneously in this mode. Whereas at low irradiation of 100 W/m2 , the gate pulses of auxiliary switches, Vgsb and Vgsc are high and gate pulse, Vgsa is low as PV array power is insufficient for charging EV battery. Thus, the backup battery bank discharges through BIDC to charge EV battery in this mode. During irradiation of 500 W/m2 , the auxiliary switches Sa and Sb are ON and switch Sc is OFF disconnecting backup battery from the system. Since PV array power is sufficient only for charging EV battery, backup battery is isolated and not charged in this mode. Fig. 7 shows that the gate pulses to the switch Sb is always high as the EV battery is constantly charged in all the three modes. If the EV battery is fully charged, EV battery is isolated from the

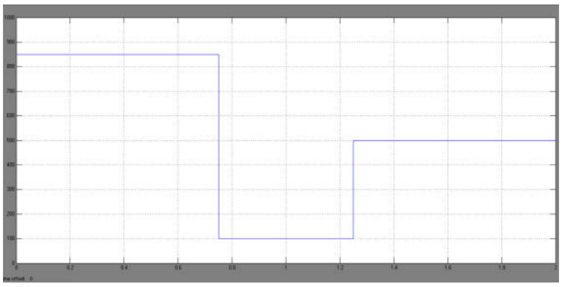


Fig: Irradiance

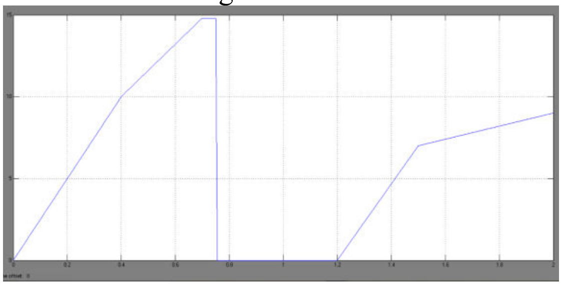


Fig: Ipv

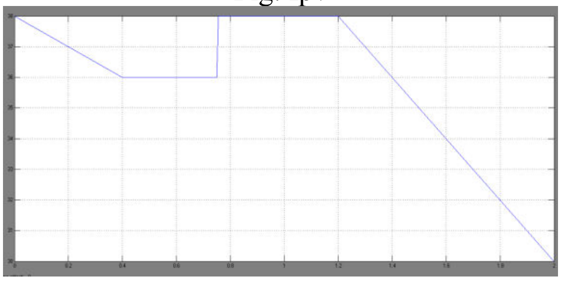


Fig: Vpv

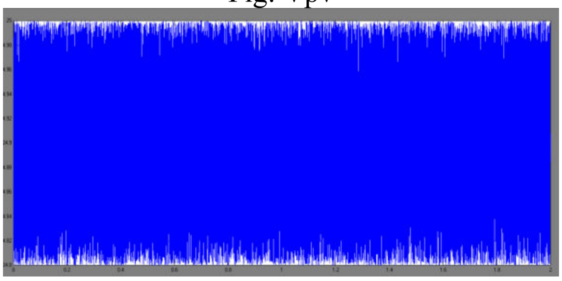


Fig: Vdc

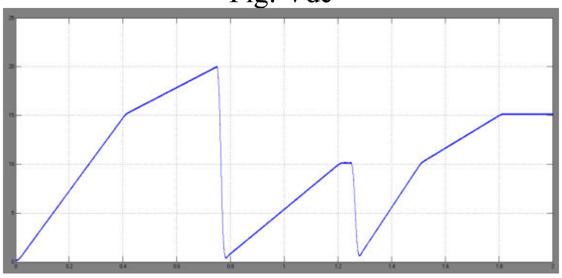


Fig:Idc

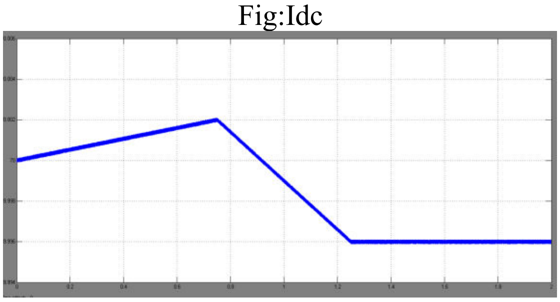


Fig: Battery-Soc

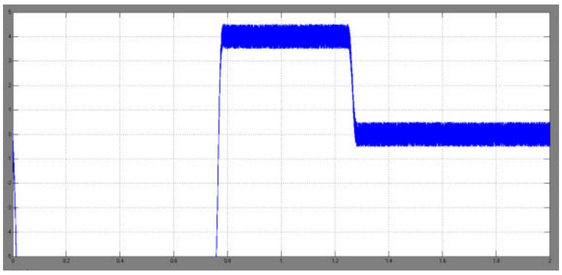


Fig:Ibat-b

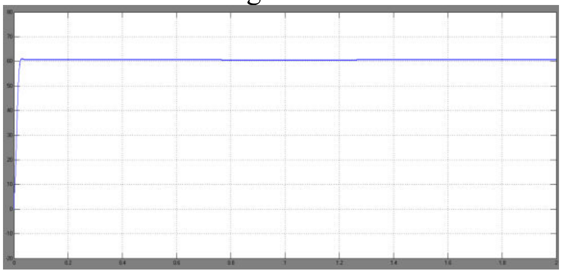


Fig:Vbat-b

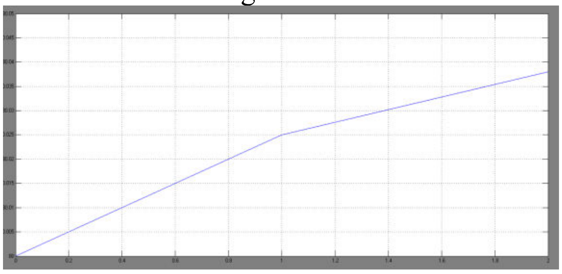


Fig: Soc-battery-a

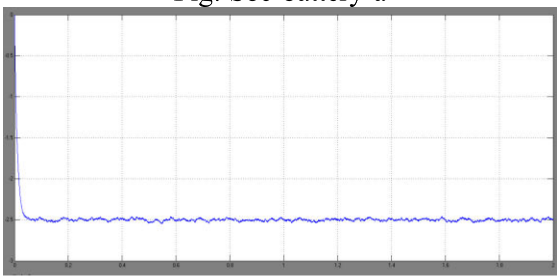


Fig:Ibat-a

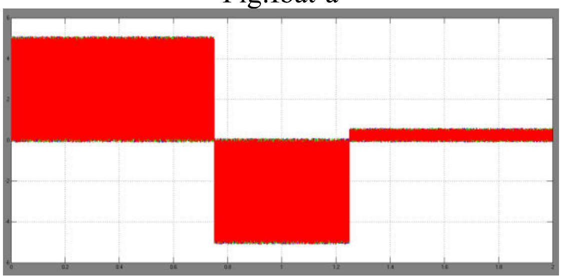


Fig:Ila,ilb, ilc

V.CONCLUSION

Fuzzy logic control is a viable way to improve charging efficiency, system dependability, and sustainable energy use in off-board electric vehicle (EV) chargers that are powered by photovoltaic (PV) systems. In comparison to conventional control techniques, this research has shown that fuzzy logic controllers (FLCs), with their capacity to manage non-linearities and uncertainties, greatly enhance the charging system's dynamic responsiveness and power quality.

The suggested solution efficiently handles the sporadic nature of solar energy while guaranteeing peak charging performance in a range of load and environmental circumstances according to a thorough performance study. The findings support grid stability by showing greater load sharing between the PV source and the utility grid, decreased total harmonic distortion (THD), and enhanced voltage control.

Furthermore, by facilitating adaptive decision-making in real-time without the need for intricate mathematical models, the usage of FLCs aids in intelligent energy management. Incorporating renewable energy sources helps minimise carbon emissions and reliance on fossil fuels while also promoting green mobility efforts.

Overall, this study represents a major advancement towards intelligent, effective, and sustainable e-mobility solutions by highlighting the technological and environmental benefits of integrating PV-integrated EV charging infrastructure with fuzzy logic-based control systems.

REFERENCES

[1] Santhosh, T.K., Govindaraju, C.: 'Dual input dual output power converter with one-step-ahead control for hybrid electric vehicle applications', IET Electr. Syst. Transp., 2017, 7, (3), pp. 190–200

[2] Shukla, A., Verma, K., Kumar, R.: 'Voltage-dependent modelling of fast charging electric vehicle load considering battery characteristics', IET Electr. Syst. Transp., 2018, 8, (4), pp. 221–230

[3] Wirasingha, S.G., Emadi, A.: 'Pihef: plug-in hybrid electric factor', IEEE Trans. Veh. Technol., 2011, 60, pp. 1279–1284

[4] Kirthiga, S., Jothi Swaroopan, N.M.: 'Highly reliable inverter topology with a novel soft computing technique to eliminate leakage current in grid-connected transformerless photovoltaic systems', Comput. Electr. Eng., 2018, 68, pp. 192–203

[5] Badawy, M.O., Sozer, Y.: 'Power flow management of a grid tied PV-battery system for electric vehicles charging', IEEE Trans. Ind. Appl., 2017, 53, pp. 1347–1357
[6] Van Der Meer, D., Chandra Mouli, G.R., Morales-Espana Mouli, G., et al.: 'Energy management system with PV power forecast to optimally charge EVs at the workplace', IEEE Trans. Ind. Inf., 2018, 14, pp. 311–320
[7] Xavier, L.S., Cupertino, A.F., Pereira, H.A.: 'Ancillary services provided by photovoltaic inverters: single and three phase control strategies', Comput. Electr. Eng., 2018, 70, pp. 102–121
[8] Krithiga, S., Ammasai Gounden, N.: 'Investigations of an improved PV system topology using multilevel boost converter and line commutated inverter with solutions to grid issues', Simul. Model. Pract. Theory, 2014, 42,pp. 147–159
[9] Sujitha, N., Krithiga, S.: 'RES based EV battery charging system: a review', Renew. Sustain. Energy Rev., 2017, 75, pp. 978–988
[10] Farzin, H., Fotuhi-Firuzabad, M., Moeini-Aghtaie, M.: 'A practical scheme to involve degradation cost of lithium-ion batteries in vehicle-to-grid applications', IEEE Trans. Sustain. Energy, 2016, 7, pp. 1730–1738
[11] Zubair, R., Ibrahim, A., Subhas, M.: 'Multiinput DC–DC converters in renewable energy applications – an overview', Renew. Sustain. Energy Rev., 2015, 41, pp. 521–539
[12] Duong, T., Sajib, C., Yuanfeng, L., et al.: 'Optimized multiport dc/dc converter for vehicle drive trains: topology and design optimization', Appl Sci., 2018, 1351, pp. 1–17
[13] Santhosh, T.K., Natarajan, K., Govindaraju, C.: 'Synthesis and implementation of a multi-port dc/dc converter for hybrid electric vehicles', J. Power Electron., 2015, 15, (5), pp. 1178–1189
[14] Hongfei, W., Peng, X., Haibing, H., et al.: 'Multiport converters based on integration of full-bridge and bidirectional dc–dc topologies for renewable generation systems', IEEE Trans. Ind. Electron., 2014, 61, pp. 856–869
[15] Shi, C., Khaligh, A.: 'A two-stage three-phase integrated charger for electric vehicles with dual cascaded control strategy', IEEE J. Emerging Sel. Topics Power Electron., 2018, 6, (2), pp. 898–909.