Photovoltaic Charger with Fuzzy Logic Control for Lithium-ion Battery Charging

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Abstract — This paper proposes a Battery charger system (photovoltaic) whose efficiency and safety during the charging of lithium-ion batteries are improved by incorporating fuzzy logic control. With the growing demand for renewable energy, particularly solar energy, lithium-ion batteries are being increasingly used in the present world owing to their high energy density and long cycle life in several applications ranging from electric vehicles to portable devices. The fuzzy logic control system developed in this work will adapt dynamically to changing environmental factors like solar irradiance and the state of charge of the battery, providing energy conversion efficiency with safety to the system for charging the battery.

Keywords: Photovoltaic Charging, Fuzzy Logic Interface, lithium-ion battery, Charging Algorithm, Renewable Energy.

I. INTRODUCTION

The shortage of fossil fuel energy sources and concern over the environment led to a widespread shift from traditional energy sources like coal power to solar energy. Through sunlight captured, the solar panels convert solar energy into electrical energy that can be considered to be friendly to the environment and a green alternative for the generation of energy. Connecting the PV systems with Li-ionbatteries as an energy storage medium grants society with practically complete utility of solar energy by exporting the generated excess energy to the battery and importing the stored one during low irradiance or heavy demand. The proper charge algorithms should be employed for better performanceand longevity of lithium-ion batteries. For this reason, it isusing fuzzy logic. In the traditional charging principle, the control strategies are most times fixed and may not respond well to the changing environmental conditions and battery properties. Fuzzy logic control gives a flexible and adaptive option for operating the charging procedure by taking conditionsof solar irradiance and battery state of charge into account.

Fuzzy Logic Control (FLC) offers a distinct and enhanced solution regarding the charging control of batteries. FLC overcomes non-linear system performance and responds by deciding fast using linguistic methods with the consequence of low computational and mathematical costs which are preferred with complex systems like charging Li-ion batteries. More customers having integrated green energy into their supply have further motivated the application of PV systems (photovoltaic) in our society. Li-ion batteries with their high volumetric energy density and long life extend the time for which solar power can be stored. Taking into consideration this, it is the absolute charging of lithium-ion batteries in the right and safe way that is the factor decisive for their efficiency, maximum effectiveness, and long lifespan of the batteries.

This research work suggests creating and implementing a PV charger system enabled with fuzzy logic control for charging the lithium-ion battery. The fuzzy logic controller will have a dynamic behavior in adjusting charging parameters such as current and voltage to the input variables which can be solar irradiation levels and battery state of charge. The proposed system will focus on improving the charging operation in a way that will get the most out of the PV array and at the same time ensure safe and efficient charging of the lithium-ion batteries.

II. RESEARCH APPROACH

A. Why does this work in this field?

Renewable Energy Advancement: The world is changing to renewable energy sources because of the need to change and reduce the reliance on limited natural resources. PV systems are a specific case of the whole phenomenon, but an environmentally friendly tool contributes to electricity production with their power of solar energy harnessing.

Energy Storage Integration: Being the wide penetration of PV systems, energy storage systems also get their rightful place such as lithium-ion batteries. Energy storage is the key driving force of solar energy utilization, facilitating the storage of excess energy in times of generous solar irradiance and its subsequent release for use during periods of low irradiance or high energy demands.

Charging Efficiency Optimization: Charging time being managed with precision time trips is the vocational way to drive the greatest performance and the lifespan of lithium-ion batteries. The traditional approach might not be successful in overcoming the current environmental condition as well as battery development, resulting in inefficient battery charging systems. Fuzzy logic control performs an adaptive automation role in the charging regulation in which adjustments are made through input properties' sensitivity to change over time.

Maximizing Energy Utilization: The system seeks to control the parameters of the photovoltaic (PV) charger to its optimum to utilize the photovoltaic system to the maximum enabling maximum energy extraction from the PV array. With tracking technology, the system can minimize wastage and ensure that the panels are adjusted to the sun’s path. This improves the conversion of solar energy and hence increases the viability of renewable energy technologies by efficiently utilizing obtainable solar resources.

Longevity and Reliability: Lengthening the lifespan of lithium-ion batteries is what matters since it decreases the system maintenance price and helps to achieve a hundred percent reliability of the PV-battery systems. Fuzzy logic control can take action against the issues that promote the degradation of the batteries.

B. Scope of this research work

Model Design: This paper will create a scope for the development of the system architecture of the PV charger which will include some modular components. The components are a solar PV array, a maximum power point tracker (MPPT), a battery management system (BMS), and a fuzzy logic controller (FLC).

Fuzzy Logic Control Algorithm: The most important part of the research will be the fuzzy logic algorithm creation,These include defining the language variables, formulating fuzzy rules and protocol for control ranging from start/stop of charging to manipulation of the charger's parameters like solar irradiance and battery state of charge.

Simulation and Modelling: The simulation of the PV-Charger system will be exactly replicated by MATLAB tools to explore its output power in those rated conditions only. Within the simulated installation, the efficiency of the battery is anticipated. This estimative performance should be demonstrated in situ irregular solar radiation. Moreover, the performance of the MPPT algorithm is supposed to be presented together with all batterycharacteristics and fuzzy logic control.

Experimental Validation: Although the fuzzy logic controller is idealistically robust, the experimental validation of this model under numerous operational conditions is important In this regard, the proposed system should undergo practical evaluation in different contexts, including fluctuating solar irradiation, extreme temperatures, and charged battery status, among others Practical validation will help determine the flexibility of the proposed controller and confirm its suitability for use.

Impact of Environmental Extremes: Another factor more specific to photovoltaic systems is that due to environmental conditions, they undergo fluctuations in temperature as well as fluctuating irradiance levels. Most of these conditions are expected and due to this; the fuzzy logic controller in the proposed system will accommodate these by offering dynamic charge parameters. However, it requires more real-world testing to check the stability of the system in severe environmental conditions. This shall also enable the system to work efficiently and effectively in real life, especially in areas with some of the worst climates.

Performance Evaluation: The examination will be carried out as a comparative study of the load management system, concerning charging efficiency, power consumption, and the charged batteries in comparison with the control methods of charging center stations, which are used at present. Implementing this control in another charging mode would make us illustrate if fuzzy logic fulfills its work in improving the batteries' charging efficiency well and ensuring their safety.

Scalability and Practical Implementation: The idea behind the photovoltaic charger system as presented in this paper is scalable to accommodate all extents of incorporation in both residential and commercial properties. What is more, the addition of more PV panels or battery storage units means that the system can be scaled up to accommodate increased energy requirements. Because of its adaptive nature, the fuzzy logic controller does not need a lot of tuning during such expansions and so is well suited for any scale of the system.

C. Research survey/ literature review

This author therefore critically evaluates smart control methodologies in photovoltaic systems with a focus on the fuzzy logic MPPT and proportional Integral (PI) control for charge regulation [1]. This work focuses on different battery technologies as applied to electric vehicles and relevant techniques of battery management [2]. This work seeks to address various charging methods and their advantages as well as disadvantages to give an insight into the best and most feasible manner of charging an EV [3]. The design of a new single/multiple output multilevel buck rectifier for an EV-battery charging system is introduced in this paper [4]. This study talks about how the architecture was designed and put into practice, highlighting how balanced charging and discharging may improve battery pack performance and durability [5]. This work provides a critical evaluation of Single Phase Shift (SPS) & Dual Phase Shift (DPS) strategies in the context of DC-DC converting systems employing Dual Active Bridges (DAB), especially in the context of electric vehicle (EV) charging schemes [6]. In this work, a critical assessment is made of the practicality and applicability of AMRIT for a more precise electric driving range by assessing battery discharge characteristics and the Thermal Model for better range estimations [7]. In this work, the existing machine learning-based methods in predicting specific characteristics used in the lithium-ion batteries of electric vehicles such as state of charge (SOC) and state of health (SOH) are critically analyzed [8]. This study contains a thorough analysis of different types of bidirectional converters used in electric vehicles concerning their efficiency, energy density, and cost. It further tries to classify the control techniques such as PWM and hysteresis control and evaluate the effect of these techniques on the voltage and current regulation in EV converters to find the best models and approaches for moving forward in electric transportation [9]. This work proposes an IoT blockchain-enabled microgrid-centric power recovery strategy through peer-to-peer energy-sharing methods to overcome the discussed limits of power recovery strategies during outages [10]. This study aims to a Fuzzy logic algorithm FLC-based MPPT controller is proposed for solar PV powered, battery charging. Comparing all this with our work gives an idea of charging using the FLC MPPT, In this paper, the detailed charging process is tested and explained and results are observed. A constant charging is carried out with the variable input voltage, this will increase the battery life span, efficiency, and Health of the Li-ion battery.

Battery Selection and Management: This section focuses on batteries that are customized for given applications; special interest is given to Lithium-ion batteries, which are suitable for Electric vehicles as well as portable devices; But to achieve higher energy density and very long cycle life, Advanced Battery Management Systems (BMS) which are critical tools, like FLC is employed in this work.

Charging System Design and Control: This paper presents an exhaustive analysis of different charging system architectures, and power control methods to increase the overall performance and modularity. It looks at how fuzzy logic control, proportional-integral (PI) control, or a charged quasi-resonant switch-mode control as tools to manage the charging capacity output. The issues of precise input handling are solved with the help of fuzzy logic control, while the accuracy of charging levels and system stability are provided by PI control. Switch-mode control gets improved with quasi-resonant switch-mode control to minimize the switching losses. The proposed system is expected to enhance the management and utilization of management and charging capacity as well as reduce energy consumption and risks associated with the same.

Renewable Energy and RE Integration: Go Green is a primary factor that reflects the rise of EV charging infrastructure, such as solar energy, especially in the ecosystem. A study on fuzzy-logic PV chargers is considered with the intention of refining the PV harvesting and efficient battery charging of lithium-ion cells.

Smart Control And Strategies: Smart control methodologies like Fuzzy MPPT and PI control approaches are identified as highly competition in charge management in PV systems. Thus these methods are very useful in the long term and they will increase the battery charging capacity.

D. Research Gap

Integration of Multiple Renewable Energy Sources: Some studies highlight a combination of solar PV systems with the charging systems while other related research studies lack efforts to incorporate other renewable energy sources such as wind or kinetic energy. Future studies may be focused on the application of hybrid charging systems that utilize more than one renewable energy source for augmenting charging efficiency and reliability.

Advanced Control Strategies: Although fuzzy logic control and PI control are mentioned in some texts, still more studies are to be done into advanced dynamic control strategies which can be adapted to environmental dynamics and user behavior models to have an upper hand. Machine learning approaches including neural networks or ML model-based learning could be studied to predict chargingalgorithms.

User-centered design and user experience: Analogue to the situation when creating charging stations, user comfort, and ease of use are problems rarely taken seriously. In the future, the design research can be focused on the user-friendly charging interface,andbest schedules based on the preferences of users and itcan enhance the EV of the drivers and their lifestyle.

E. Methodology

The proposed system will consist of the following components:

- Photovoltaic (PV) Panel: Sustainable power.
- DC-DC Converter: A boost/buck converter to transform the available variable output voltage of a PV panel to the desired level for charging the battery.
- MPPT Controller with Fuzzy Logic: The controller proposed here would be based on fuzzy logic, with continuous tracking of the maximum power point of the PV array to be done based on voltage and current readings.
- Lithium-ion Battery is used in this work.
- Battery Management System (BMS) with Fuzzy Logic: This system uses fuzzy logic to regulate battery charging current and voltage based on real-time readings of battery voltage, charging current, and irradiance. The fuzzy logic controller determines whether to use constant current or constant voltage charging and adjusts the output of the DC-DC converter accordingly to optimize battery performance.

Fuzzy Logic Control Design and Fuzzy Interface:

- Input Variables: Under the logic of fuzzy controller, there are most probably two inputs of this controller: the voltage and current (of the battery)
- Membership Functions: Fuzzy sets will be defined for each variable as parameters taking values of states "low," "medium" and "high." (Mamdani)
- Fuzzy Rules: A set of rules will be set up based on battery charging parameters, and other safety orientations. These rules will declare the type of produce obtained due to a particular input type.
- Output Variable: The output of this fuzzy logic controller will act as a feedback signal for the DC-DC converter in response to the charging of current or voltage.

Maximum power point tracker (MPPT) Controller:

- Inputs: These are PV voltage as well as these are PV currents as well.
- Output: The duty cycle of a buck converter is a process of chopping with the help of PWM or Pulse-width modulation.

Charging Regulation Controller:

Inputs: Battery SOC and Voltage/current.
Output: Control Signal for the converter.

F. Block Diagram:

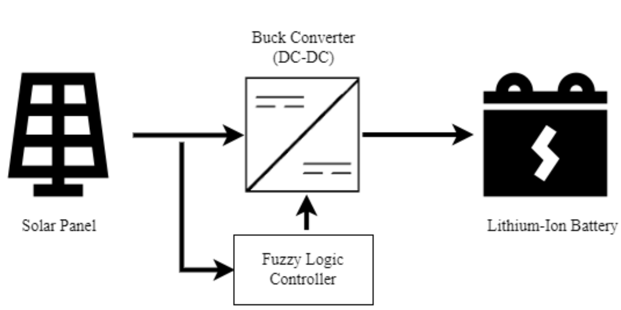

Fig.1 Battery Charger

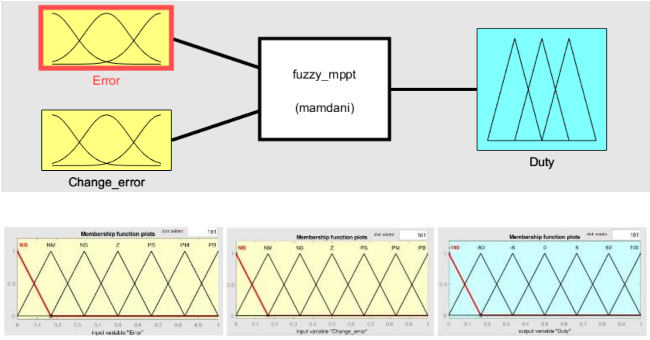

Fig.2 Fuzzy Logic (Duty ratio)

Fuzzy Type: -

In this paper, a Mamdani-type fuzzy inference system is employed. This is the most common one used in control systems and what distinguishes it from others and makes it popular is owing to its interpretable rule base where the inputs can be related to the outputs using fuzzy logic.

Mamdani Fuzzy Inference: A Fuzzy rule-based system of the type zero or first order is of the form 'if A and/or B, then C' where A and B are fuzzy sets of the input variables and C is a fuzzy set of the output variable. The rules are connected using what is referred to as aggregation while the fuzzy set derived is defuzzied to form a sharp set.

Defuzzification Method: -

Defuzzification is the final step of a fuzzy system that involves converting the fuzzy output of the inference system into a single crisp value that can be used in the decision. Among various methods of defuzzification, the Centroid (or Center of Gravity) method is frequently implemented in most of the Mamdani-type fuzzy systems. It computes for the center of the area under the curve of the aggregated fuzzy set which makes the output proportional and directly in the center.

Centroid Method: As for the crisp output, it refers to the point that of which if a vertical line is drawn to the Y-axis, the areal sum of the aggregated fuzzy set curve will be in equilibrium. This method produces an output that is smooth and free from fluctuation, therefore, making it ideal in control solutions. Eq (1) represents the centroid formula.

$$\text{xCentroid}=\sum\mu(xi)xi/\sum\mu(xi) \qquad (1)$$

Membership Functions: -

A membership function gives information on how each of the input variable (s) or output variable (s) and in this case, Error, Change in Error, and Duty Ratio are transformed into fuzzy sets. In general, membership functions are selected in such a manner that there is a possibility for the input values.

Input Variables (Error and Change in Error):

1. NB (Negative Big)
2. NM (Negative Medium)
3. NS (Negative Small)
4. Z (Zero)
5. PS (Positive Small)
6. PM (Positive Medium)
7. PB (Positive Big)

Output Variable (Duty Ratio): The output membership functions often follow the same shape and number as the input membership functions thus providing a way of achieving a fixed relationship between input conditions and the output actions.

The shapes of the membership functions could be:

Triangular: Commonly employed because their computation is relatively easy.

Trapezoidal: Gives a flatter region thus, the system is not very much affected by changes in input.

Table I

Fuzzy Rules

Rule	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NS	Z	PS
NM	NB	NB	NM	NS	Z	PS	PM
NS	NB	NM	NS	Z	PS	PM	PB
Z	NM	NS	Z	Z	Z	PS	PM
PS	NS	Z	PS	Z	PS	PM	PB
PM	Z	PS	PM	PS	PM	PB	PB
PB	PS	PM	PB	PM	PB	PB	PB

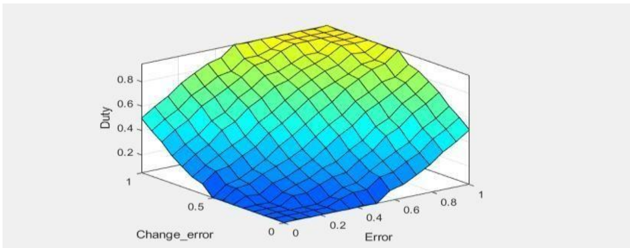

Fig 4. Surface Chart of Fuzzy Rules

G. Design of PV Array

Block Parameters: -

Module –

A10Green technology A10J-M60-225

Max power(W) – 224.985 W

Cell per Module (Ncell) – 60

Open circuit voltage (Voc) – 36.24 V

Short circuit Current (Ioc) - 8.04 A

The voltage at maximum power point (VMP) – 30.24 V

Current at maximum power point (IMP) – 7.44 A

Temperature coefficient of Voc (%/deg.C) - -0.3624

Temperature coefficient of Isc (%/deg.C) – 0.054801

H. Design of Converter

Buck Converter: -

Inductance – 11e-3 H

Capacitor- 10e-6 F

I. Battery parameters: -

Battery type – Lithium-ion Nominal Voltage (V) - 12 V

Rated capacity – 250 Ah

Initial State of charge (SOC) % - 10 %

III. RESULTS AND DISCUSSION

The proposed fuzzy logic-controlled photovoltaic (PV) charger performance, was tested under various irradiance conditions. Two key scenarios were considered: one at a nominal operating condition of 1000 W/m², 25°C and the other at low irradiance of 750 W/m², 25°C.

1) At Ideal condition 1000 W/m2, 25 deg.C :

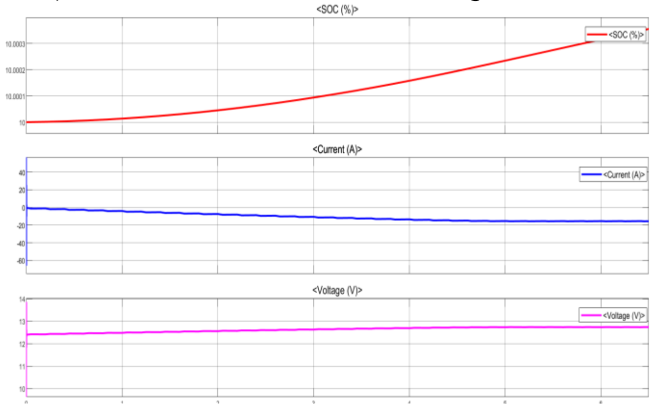

Fig 9. At Ideal Condition 1000W/m2, 25 deg.C

State of Charge (SOC): The fuzzy logic controller was initially set at 10% SOC and was successful in charging the battery at a high voltage of 12.82V which fits perfectly to the battery. At maximum irradiance, the PV panel was able to supply the converter with a steady output voltage of 225V to the converter to show that the system can operate well under high irradiance conditions.

Current Response: This reveals a charging current of -12.80 A, which means that during driving, the current profile of the system was relatively stable, which is vital for its batteries.

2) At Condition 750 W/m2, 25 deg.C:

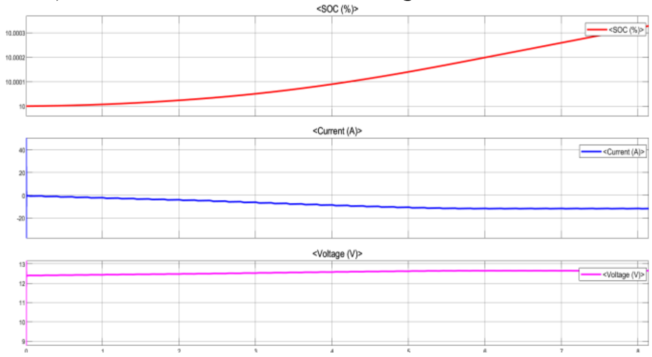

Fig 10. At Condition 750 W/m2, 25 deg.C

State of Charge (SOC): At this lower irradiance, the SOC rises steadily even further with the battery voltage, now slightly higher at 12.6V because of the feedback action taken by the Fuzzy Logic Controller. The PV panel voltage was recorded to be 198.

Current Response: The charging current is at -12.6A, which highlights how the system is designed to accommodate changes in the state of the environment.

3) At Condition 250 W/m2, 25 deg.C:

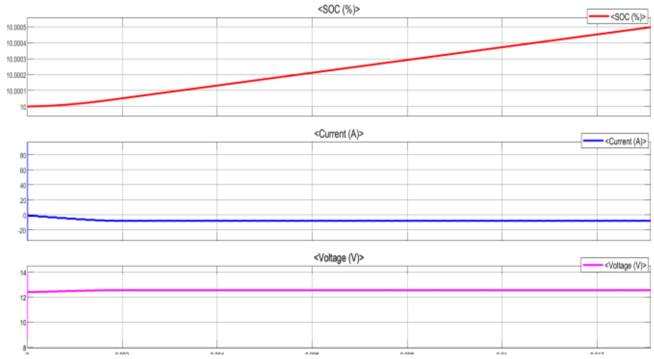

Fig 11. At Condition 250 W/m2, 25 deg.C

The Panel produces a voltage of 170V in this condition as the irradiance in this condition is very low. The battery voltage is 12.46V and the current response is -12.38A. At this lower irradiance, the system showed an adaptive response by slightly increasing the battery voltage while maintaining the stable current.

Performance Across Conditions: From the data in Figures 9, 10, and 11 it was observed that SOC went on increasing with different irradiation levels. Charging voltage was controlled by the FLC and kept within the range of 12V ± 1%; therefore, proving the strong control ability of the FLC in regulating the system voltage in the face of environmental fluctuations.

Voltage Control: The FLC was able to adjust input voltage according to the changes in irradiance and temperature of the environment. The measured panel voltages ranged from 170V at 250 W/m² as shown in Figure 11 to 230 V at 1000 W/m² as shown in Figure 9, this shows that the system can manage voltages well even at varying irradiation levels.

Battery Protection: These actions of the FLC made it impossible for the battery to be overcharged or undercharged hence improving its durability. It is a great safety measure to enhance the longevity and suitability of the battery which powers the entire system.

Enhanced Efficiency: By controlling the energy conversion and storage of the PV array, the FLC achieved the overall improvement of the integrated system's efficiency. It pointed to a way through which the battery could be charged as per need and hence could perform appropriately and achieve successful charging even at low irradiance such as 250W/m² as illustrated in figure 11.

Table II

FLC Model

Irradiation W/m^2 At 25 deg.c	**Voltage(V)**	**Current(I)**
1000	12.82	- 12.80
750	12.6	- 12.6
500	12.54	- 12.52
250	12.46	- 12.38

Table.III

P&O Model

Irradiation W/m^2 At 25 deg.c	**Voltage(V)**	**Current(I)**
1000	12.75	**-** 12.70
750	12.58	**-** 12.55
500	12.48	-12.40
250	12.30	**-** 12.10

When the Fuzzy logic Control (FLC) is compared with the Perturb and Observe (P&O) method in the above table, it becomes clear that FLC performs well than P&O. However, under optimal irradiation of 1000W/m² FLC provides a stable voltage of 12.82V and current of 12.80A, whereas P&O is slightly lower with 12.75V and 12.70A indicating the system was not as accurate in tracking the MPP. At further reduction of irradiance, 500W/m² and 250W/m², FLC remains superior to P&O, with FLC having fixed voltage at 12.54V and 12.50A while the P&O decreases to 12.48V and 12.40A respectively. At this very low level of irradiance 250W/m², the FLC has had 12.46V and 12.38A while the P&O drops to 12.30V and 12.10A. This proves that FLC offers better voltage and current regulation besides greater energy conversion efficiencies throughout the weather conditions thereby making FLC a more reliable recommendation for the PV systems than the P&O.

IV. Conclusion

The Intelligent PV battery charger system for lithium-ion batteries using Fuzzy Logic Control is discussed in this paper. The system demonstrates effective management of varying irradiance and state of charge (SOC) conditions, significantly enhancing energy conversion efficiency and addressing safety and battery life. High irradiance of 1000W/m² was used and the output voltage was steady and the charging current was constant at 12.82A at higher irradiance equals 1000W/m² the controller finds the optimal battery voltage and current response while at Lower irradiance of 750W/m² and 500W/m²,250W/m². Knowledge control in the Fuzzy-Logic-Controlled voltage regulator was accurate within the permissible limit of voltage, 12V ± 1%, and kept constant regardless of the environment and constantly avoided overcharging or undercharging. It is versatile and can be applied in homes and businesses because of its stability. Further research will be directed toward the practical implementation of such approaches in energy management problems, as well as in examining finer aspects of RE and microgrid systems and towards the study of the integration of more than one kind of RE. Also, the ability of the system to scale can provide grounds for optimization in a range of energy conditions.

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