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Current and future prospective for battery controllers of solar PV integrated battery energy storage systems

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Solar photovoltaic (PV) microgrids have gained popularity in recent years as a way to improve the stability of intermittent renewable energy generation in systems, both off-grid and on-grid, and to meet the needs of emergency settings during natural catastrophes. Over the last several decades, researchers have been interested in improving the efficiency of photovoltaic (PV) systems. Solar-battery charge controllers based on various algorithms are continuously and intensively employed to improve energy transfer efficiency and reduce charging time. This paper presents state-of-the-art solar photovoltaic (PV) integrated battery energy storage systems (BESS). An overview of and motivations for PV-battery systems is initially introduced, followed by the survey methodology and its contributions. In addition, this study classifies residential solar PV systems and battery charge controllers with their corresponding references in the review structure, which also provides details on battery charger topologies. Subsequently, an analytical review of the PV-Battery charge controller and the failure probability of such systems is discussed to determine the system components that mostly fail and their importance in the system. Finally, recommendation amendments to the existing charge controller that potentially contribute to increasing the system efficiency, reducing the failure probabilities, and reducing the cost are presented as future design concepts for the entire system.

KEYWORDS

daily energy, PV system with battery storage, voltage balancing, solar-battery, charge controller

1 Introduction

In recent years, photovoltaic (PV) microgrids have gained attention as a potential solution for enhancing the reliability of intermittent renewable energy generation in systems, off-grid stand-alone or on-grid, and during unexpected emergencies resulting from natural disasters. Due to the severe energy crisis and environmental pollution in recent years, solar energy has received major consideration. One of the most popular sources of electrical energy today is photovoltaic technology, which converts solar radiation directly into electricity. They can be utilized in stand-alone mode to supply some islanded loads or in grid-connected mode to support the network. Because weather circumstances (such clouds and fog) have a substantial impact on the solar energy received by a PV array, the PV alone cannot serve loads in stand-alone mode. Batteries and other energy storage devices are so necessary. The batteries and PV array are both DC sources, thus they are joined to the DC bus by DC-DC converters.

Over the last several decades, photovoltaic (PV) systems and their efficiency improvements have become a core research field. In addition to efficiency improvement, it is very important to be able to transfer and store energy correctly and effectively. Continuous and intensive efforts have been made to productively manage energy transfer. One of the most crucial actions is to reduce the charging time using solar-battery charging controllers based on different algorithms. A key aspect of PV-powered microgrids is the energy conversion efficiency during the daytime by maintaining the local charging voltage, which is highly influenced by load and generation fluctuations. The charge controller plays a vital role in controlling the voltage to charge the battery to an appropriate voltage level equivalent to its full state of charge (SOC). It also prevents reverse current flow when solar power is not available, and overcharging when the PV energy exceeds the electrical load demand.

Designing a supervisory controller that can increase battery lifespan, reduce self-discharge rate, and produce high energy concentration is one of the key difficulties for battery energy storage systems. A regulatory State of Charge (SOC) calculation based on PV-Battery Management System (BMS) that best handles these problems (Yonis Buswig et al., 2020). A standalone PV integrated battery system has a number of significant concerns including the output voltage quality, system price, system on/off mode, battery charge and discharge pattern, battery lifetime, system weight, suitable protection strategy, MPPT capacity, controllability, efficiency, *etc.* These characteristics are influenced by the control strategy, energy management system, configuration, DC-DC converter type, battery and PV array size, control strategy, and MPPT algorithm. Therefore, adjusting and choosing the aforementioned parameters correctly is the most important duty for designers of PV systems; hence, PV charge controller (Sabry et al., 2015; Bogno et al., 2017; Salman et al., 2018; Al-Quraan and Al-Qaisi, 2021; Kumar et al., 2021; Sabry and Hussein, 2021; Aboagye et al., 2022).

The high initial cost of the system is the main barrier to deploying battery integrated PV technology in the residential sector. However, if the system's design analysis is carried out in terms of the system's components, failure probability, and longevity, it could ultimately prove to be a useful solution. PV electricity utilization is still in its infancy in developing nations. People may be persuaded to support the development of this technology in the nation by the right design and user-friendly provision of photovoltaic electricity. Under order to provide the necessary electrical energy for a small residential dwelling in the climatic conditions, this research concentrates on the design topologies analysis and failure probability for an off-grid and on-grid PV system.

2 Survey methodology

Several studies have been conducted for purposes similar to those proposed in this study. Each approximation and advance are unique. When conducting an effective survey on a research topic, it is critical to begin by adopting a precise approach. Some techniques have been proposed in the literature to conclude meaningful systematic conditions of art (Denyer and Tranfield, 2009; Kluge et al., 2019). The approach used to create the state-of-the-art solar PV-integrated Battery Energy Storage system (BESS) is described in

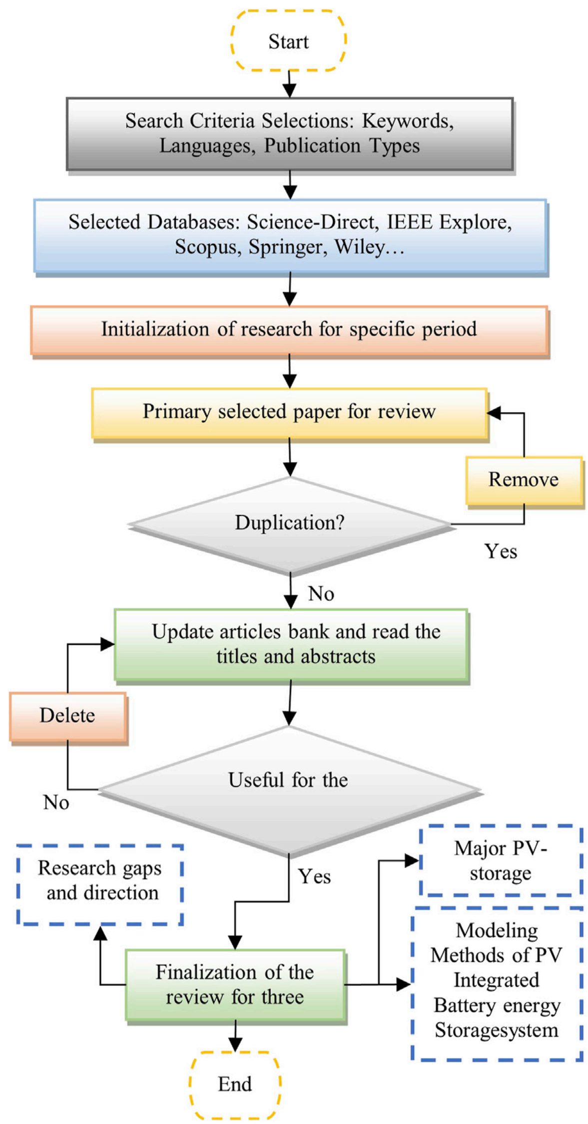

FIGURE 1
Methodology flowchart for reviewing process.

the next section. The search was limited to online published items such as research articles, review papers, conference proceedings, scientific books, and standards. To complete this review, databases such as Scopus, IEEE Explore, Science Direct, Springer, Taylor & Francis, and Wiley publishers were thoroughly searched. Keywords and scientific terms used in the search stage include "power system blackout," "power outages," "power system emergencies," "cascading events," and "methods for blackouts and cascading events". Studies published in ISI and Q1, Q2, and Q3 journals have been investigated in detail to avoid missing any useful and helpful data. In addition to the aforementioned sources, IEEE conference materials were combined for helpful information, and IEEE standards and reports from other countries' energy sectors were scrutinized. Several studies have reported similar results. A meticulous simplification process was performed to avoid repetition. As a result of detailed research, the most related content was

TABLE 1 Literature survey references classification.

Publication type	Number	Percentage
Research articles	174	77.67
Conference paper	44	19.64
Website	1	0.446
Books or chapters	5	2.232

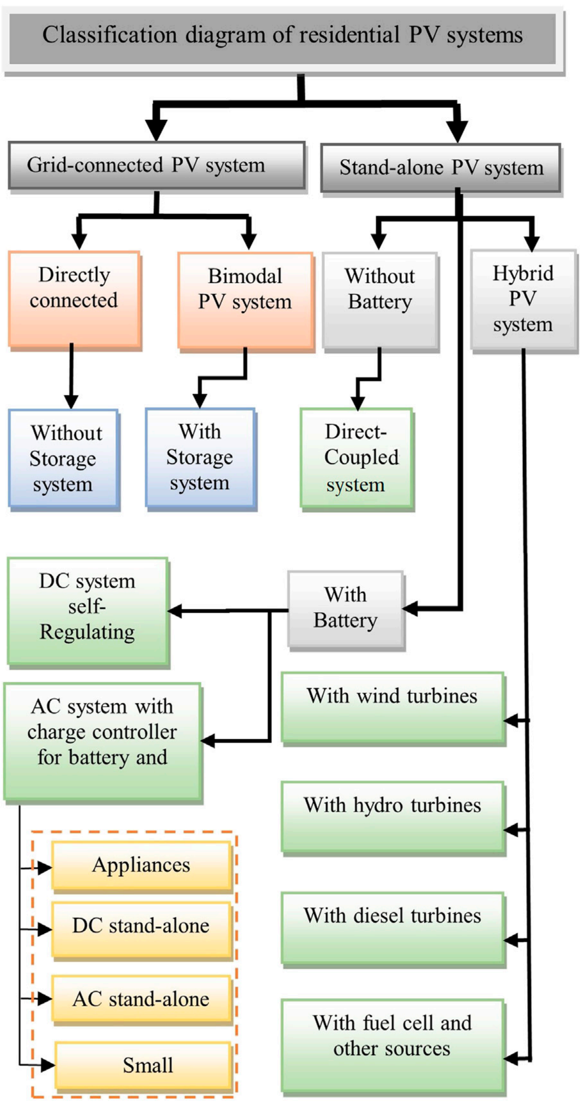

FIGURE 2
Classification of residential solar PV systems (Pennstate, 2022).

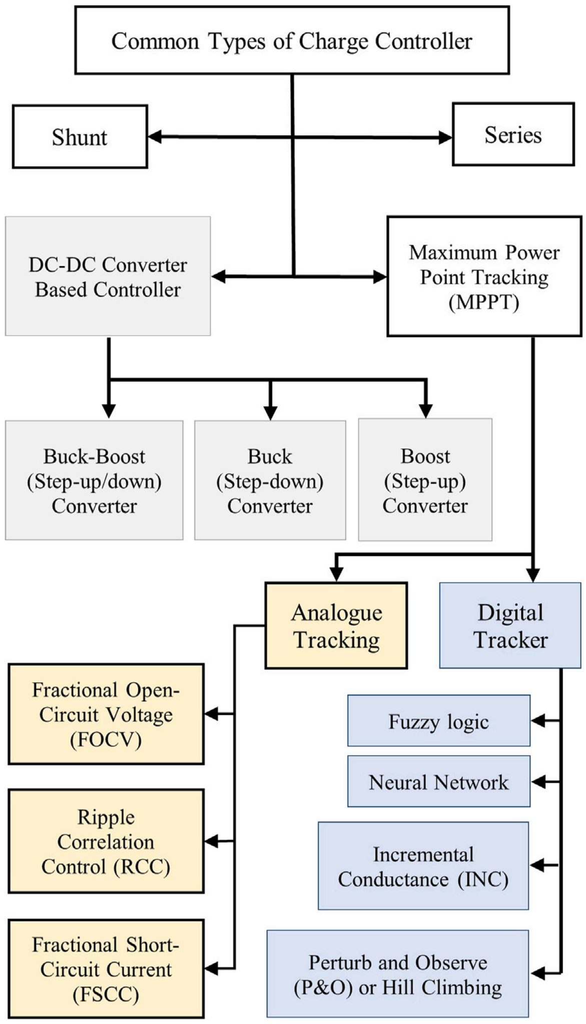

FIGURE 3
Common types of solar charge controllers.

examined and thoroughly analyzed by a group of subject matter specialists. A summary of the PV-integrated BESS is presented in the flowchart in Figure 1.

As stated in the above methodology flowchart and review process, the selection criteria for publications are based on keywords, publication type, and content from high-quality database publishers. A particular recent period was specified, depending on the number of extracted publications subject to content duplication. Publications were also subjected to another filter on their compatibility with review goals. Finally, publications were classified into major PV-Storage systems, research gaps, and modeling.

As stated above, different types of publications were reviewed, and a summary is presented in (Table 1). Considering the number of studies shown here, journal articles covered the majority of the reviewed research, while only 44 conference papers were considered informative.

This study includes documents published online between 2005 and 2022. It should be noted that the topic of the papers was limited, and we focused on reviewing the major PV-integrated BESS. Furthermore, the research aims to provide insight into Solar PV integrated BESS and topologies. During the research, it was found that there is a lot of interest in the prospects of PV-integrated BESS.

TABLE 2 Compilation study of PV system classifications in the literature.

PV system types	References
Without Storage system	Elkholy *et al.* (2016); Hammoud *et al.* (2016); Halabi and Mekhilef, (2018); Regis et al. (2019); Singh *et al.* (2019); Karuniawan et al. (2020); Abobakr *et al.* (2021)
With Storage system	Chen and Wu, (2008); Bortolini et al. (2014); Khoury *et al.* (2015); Khoury et al. (2016a), Khoury et al. (2016b); Jacob *et al.* (2017); Khamis *et al.* (2018); Modi and Singh, (2020); Najafi Ashtiani *et al.* (2020)
Direct-Coupled system	(Merino et al. (2008); Almaktoof *et al.* (2015); Tsuanyo *et al.* (2015); Janghorban Esfahani and Yoo, (2016); Townsend, (2016); Chahartaghi and Hedayatpour Jaloodar, (2019); Mohamed, (2020)
DC system self-Regulating	Gibson and Kelly, (2010); Elgammal and Sharaf, (2012); Xu et al. (2015)
AC system with charge controller for battery and load	Fahmi *et al.* (2014); Mohanty and Muneer, (2014); Soh and Tiew, (2015); Ghafoor and Munir, (2015); Sharma et al. (2016); Ameur *et al.* (2017); Aziz *et al.* (2018); Premkumar et al. (2018); Bello *et al.* (2021); Chtita *et al.* (2021); Dash and Sarojini, (2021)
With wind turbines	Ngan and Tan, (2012); Baneshi and Hadianfard, (2016); Hosseinalizadeh *et al.* (2016); Jahangir et al. (2020); Kartite and Cherkaoui, (2020); Khan and Javaid, (2020)
With hydro turbines	Mahmoudimehr and Shabani (2018), Ming *et al.* (2018), Shabani and Mahmoudimehr (2018), 2019; Elgammal and Boodoo (2021)
With diesel turbines	Nfah et al. (2007), Lau *et al.* (2010), Khatib *et al.* (2011), Girma (2013), Ismail et al. (2013), Jeyaprabha and Selvakumar (2015), Ghenai *et al.* (2017), Halabi *et al.* (2017), Ibrahim and Ghandour (2018), Mahmoudi et al. (2018), Shezan (2019), Wichert and Lawrance (2020)
With fuel cell and other sources	Alam and Gao (2007), Thounthong *et al.* (2013), Saravanan and Thangavel (2014), Fathabadi, 2017b (2017a), Dursun and Aykut (2019), Padmanaban *et al.* (2019), Benlahbib *et al.* (2020), Ghenai et al. (2020), Singh *et al.* (2020)

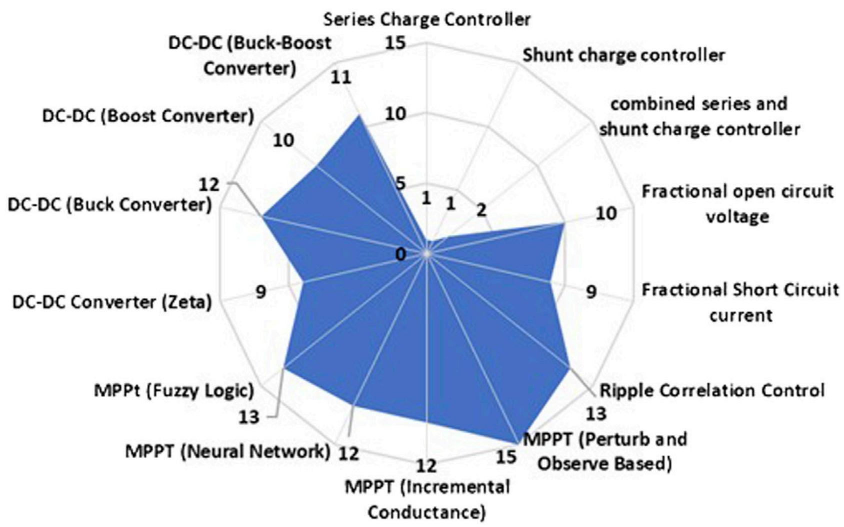

FIGURE 4
The core fields focused on by different research groups.

3 Contributions

This paper's major contributions can be summarized as follows.

- A general overview of the principles for solar PV-integrated BESS and its characteristics, as well as knowledge of extreme weather occurrences and their devastating consequences.
- Discussion of the differences in the efficiency calculation of solar PV-integrated BESS.
- A PV-integrated battery energy-storage framework provides a general understanding of such systems.
- An important contribution is to present a comprehensive assessment of current research on proactive solar PV integrated battery energy storage enhancement measures. The use of the voltage-balancing concept for strengthening the solar PV-integrated BESS is one of these solutions, which has been fully discussed in this study.
- A brief discussion on failure probability statistics for the system components of solar PV-integrated BESS

TABLE 3 The reference table according to the classification of PV-battery charge controller systems.

Charge controller	Number of references
series shunt	Lokeshreddy *et al.* (2017) Lokeshreddy *et al.* (2017)
series and shunt	Lokeshreddy *et al.* (2017); Maithili and Kanakaraj, (2019))
DC-DC converters (zeta)	Andrade *et al.*, 2015a; Andrade et al. (2015b); Mahendran and Ramabadran, (2016); Venmathi and Ramaprabha, (2016); Ananda-Rao *et al.* (2020b); Ananda-Rao et al. (2020a); Chandran et al., 2021; Chaudhary et al. (2021)
Fractional short circuit current	(Sher *et al.*, 2015a; Sher *et al.*, 2015b; Shebani et al. (2016); Keerthana et al. (2018); Owusu-Nyarko et al. (2019); Albatran and Assad, (2020); Claude Bertin Nzoundja Fapi *et al.* (2021); Nadeem *et al.* (2021); Nzoundja Fapi et al. (2021)
Fractional open circuit voltage	(Jafer et al. (2016); Shebani and Iqbal, (2017); Bandyopadhyay and Parui, (2018); Rajendran *et al.* (2019); Atri et al. (2020); Atri et al. (2021); Benlahbib et al., 2020; Abdul-Razzaq, Fahim Sakr and Rashid, (2021); Olzhabay et al. (2021a); Olzhabay et al. (2021b)
Ripple correlation control	Ferdous *et al.* (2018); Hammami *et al.* (2019); Shim *et al.* (2019); Al Kader Hammoud and Bazzi, (2020); Ricco *et al.* (2020); Sahu and Dey, (2021); Sahu et al. (2021)
MPPT (perturb and observe based)	Zaouche *et al.* (2017); Rezkallah *et al.* (2018); Chtouki *et al.* (2019); Situmorang et al. (2019); Padmagirisan and Sankaranarayanan, (2019); Rokonuzzaman *et al.* (2020); Tan et al. (2020); Almutairi *et al.* (2021); Dey, (2021); Gil-Velasco and Aguilar-Castillo, (2021); İnci, (2021); Mallal *et al.* (2021); Mohammadinodoushan *et al.* (2021); Mukhi, (2021); Mandourarakis *et al.* (2022)
MPPT (Fuzzy logic)	Zaouche *et al.* (2017); Kiswantono et al. (2019); Pathak and Yadav, (2019); Tripathi *et al.* (2020); Zerouali *et al.* (2020); Marhraoui et al. (2020c); Nagaiah and Sekhar, (2020); Pan *et al.* (2020); Baramadeh et al. (2021); Lagudu et al. (2021); Rkik *et al.* (2021); Seguel and Seleme, (2021); Sudiharto et al. (2021)
DC-DC (buck converter)	López *et al.* (2016); Chakraborty *et al.* (2018); Premkumar et al. (2018); Venkatramanan and John, (2019); Sharma et al. (2019); Marhraoui et al. (2020a); Obukhov *et al.* (2020); Chtita *et al.* (2021); YAYLACI, (2021); Messaoud and Haddi, (2021); Nazar Ali *et al.* (2021); Shufian et al. (2021)
MPPT (incremental conductance (INC))	Zakzouk *et al.* (2016); Ammar *et al.* (2019); Anowar and Roy, (2019); Necaibia *et al.* (2019); Sener *et al.* (2020); Mirza *et al.* (2020); Pilakkat and Kanthalakshmi, (2020); Gupta *et al.* (2021); Kawde and Muley, (2021); Ahmad et al. (2022a); Ahmed et al. (2022b); Isknan *et al.* (2022)
MPPT (Neural network)	Messalti et al. (2017); Hidayat *et al.* (2019); Yonis Buswig *et al.* (2020); Kapoor and Sharma, (2020); Masoumi *et al.* (2020); Qays *et al.* (2020); Ezzitouni *et al.* (2021); Villegas-Mier *et al.* (2021); Roy *et al.* (2021); Saeed *et al.* (2021); Saidi *et al.* (2021); Syed and Khalid, (2021)
DC-DC (Buck-Boost converter)	Triki *et al.* (2018); Zulkifli *et al.* (2019); Chen *et al.* (2019); Goud and Gupta, (2019); Goud and Gupta, (2020); Mohapatra *et al.* (2019); Bagherwal and Badoni, (2020); Chandrasekar *et al.* (2020); Veeramallu et al. (2020); Mustafa *et al.* (2022); Viswanatha and Venkata Siva, 2018
DC-DC (Boost converter)	(Sansare et al. (2018); Bjaoui *et al.* (2019); El-Shahat and Sumaiya, (2019); Bagherwal and Badoni, (2020); Marhraoui et al. (2020b); Al-Quraan and Al-Qaisi, (2021); Rajanna and Kumar, (2021); Sabzehgar and Ghali, (2021); Sabzehgar et al. (2022); Zizoui *et al.* (2022)

including failure rates per unit hour of the PV-battery systems.

4 Review structure

4.1 Classification of residential solar pv system

A good classification study is shown in (Figure 2)for residential solar PV systems, as conducted by (Pennstate, 2022), which is the most cited article related to this concept. In this regards (Table 2), in the present study is a compilation of PV system classifications discussed in previous literature on the topic. Grid-connected and stand-alone PV systems are two types of PV systems used. Grid-connected PV Systems and Stand-alone PV Systems are the two subcategories of PV systems. Those grid-connected PV systems that are Directly Connected to the Utility and those that are Categorized as Bimodal PV Systems can be further divided into two groups. Systems that are classed as Bimodal PV Systems do have storage systems, but systems that are Directly Connected to the Utility do not. Without battery, with battery, and hybrid PV systems are the three subcategories of stand-alone PV systems. Direct-coupled systems are systems without batteries, while self-regulating DC systems or AC systems with a charge controller for the battery and load can be systems with batteries. Systems featuring wind turbines, hydroelectric turbines, and solar panels can all be included in hybrid PV systems.

Grid-connected PV systems are further divided into two types: direct utility connections and bidirectional PV systems (Melath et al., 2020). Directly connected to utility networks do not have storage; however, bimodal PV systems do. With or without a battery, hybrid PV systems are the three types of standalone PV system. Direct-coupled systems do not have batteries, whereas self-regulating DC or AC systems with a charge controller for the battery and load contain batteries. Wind turbines, hydro turbines, diesel generators, fuel cells, and other sources can all be included in hybrid photovoltaic (PV) systems. Most studies presented in the classification study are explained in detail in the following section.

TABLE 4 Comparison table of the previously conducted studies in literature.

Ref.	Method	Applications	Significant results	Research gap
Ahsan *et al.* (2020)	Optimization model as a mixed integer linear programming problem with optimization studio and CPLEX solver	Residential	43% annual profits	Only simulation
				No details on: memory, system components, and controlling the PV-Battery charging system
Liu *et al.* (2020)	Both single-criterion and multi-criterion optimizations based on decision-making strategies	low-energy buildings	Can achieve increasing of 15.0% and 48.6% with standard deviation of net grid power, battery cycling aging, and CO2 emission is reduced by 3.4%, 78.5% and 34.7% respectively	Just a framework of optimization
				No details on: the hardware, memory, and system components
Mariaud *et al.* (2017)	A Technology Selection and Operation (TSO) optimization model of decentralized PV and battery energy systems	Commercial buildings	30% of energy used on-site can be supplied by PVs while achieving a carbon reduction of 26%	Just as a framework for assessing technology investments
				No details on: integrating PV system with battery storage
				Memory, and system components
Slama *et al.* (2021)	A management scheme based on a system behavioral approach with a power flow management strategy	grid-PV system	Absolute control of power electric path, and precise adaptation without compromising consumer's comfort	Only simulation model
				No details on: system cost
				PV-Battery charging system
Kapoor and Sharma (2020)	Using a data obtained from short-term load, weather, solar forecasting, and time of-use tariff using random forest (RF) technique	Residential	The optimal battery scheduling algorithm can increase the net saving in the electricity bill	Only simulation model No details on; electronic hardware components/proposed implementation cost and memory
Schmid and Behrendt (2021)	Numerical power flow simulation and multi-objective optimization with the objective functions Power-Cut-Offs, and Levelized Cost of Electricity	Solar Home Systems	Costs saving for MPPT reduced PV peak power (by 31.2%–38.6%) and battery capacity (by 2.8%–8.8%)	Only simulation model
				Comparing and analyzing only the off-grid case
				No details on; memory and system components
Yi et al. (2018)	A control and power management system for PV-battery systems	hybrid microgrids (both grid-connected and islanded modes)	Successful in regulating the voltage on both DC and buses, transferring between grid-connected and islanded operating modes smoothly	No daily energy transfer efficiency
				No details on memory and system components
				Although it stimulates both grid-connected and islanded modes, it provides just island experimental verifications
Lv *et al.* (2021)	A control strategy based on the SOC of the BESS.	Distributed power generation	The fluctuation range of the DC bus voltage is controlled by 4.5%	No dependency on daily energy transfer
				Only a simulation model
				No details on memory and system components
				Deal with only the case of Isolated DC Microgrid

4.2 Classification of battery charge controllers

Maximum power point tracking (MPPT) is a common approach in both PV controllers (battery charger and inverter) to maintain the adjustment of the impedance faced by the PV and maintain a system operating very close to the peak power value of the PV array under varying conditions. The conditions are represented mainly by the solar irradiance (Irr), cell temperature (T), and load. Applications of predictable, continuous, and small-sized loads can be configured to operate without using a battery charge controller (Harrington, 1992; Abu Eldahab et al., 2016). The classification of common charge controller methods is shown in (Figure 3).

The evolution of a handful of PV-Battery charge controller systems has been studied in the literature, particularly in recent years. The focus of this topic is inspired by the ever-increasing demand for trusted charge controller techniques (Othman, 2020; Tan et al., 2020; Chtita et al., 2021). As a result of that, the performance of all contemporary charge controller technologies proposed in the literature is observantly evaluated in this section.

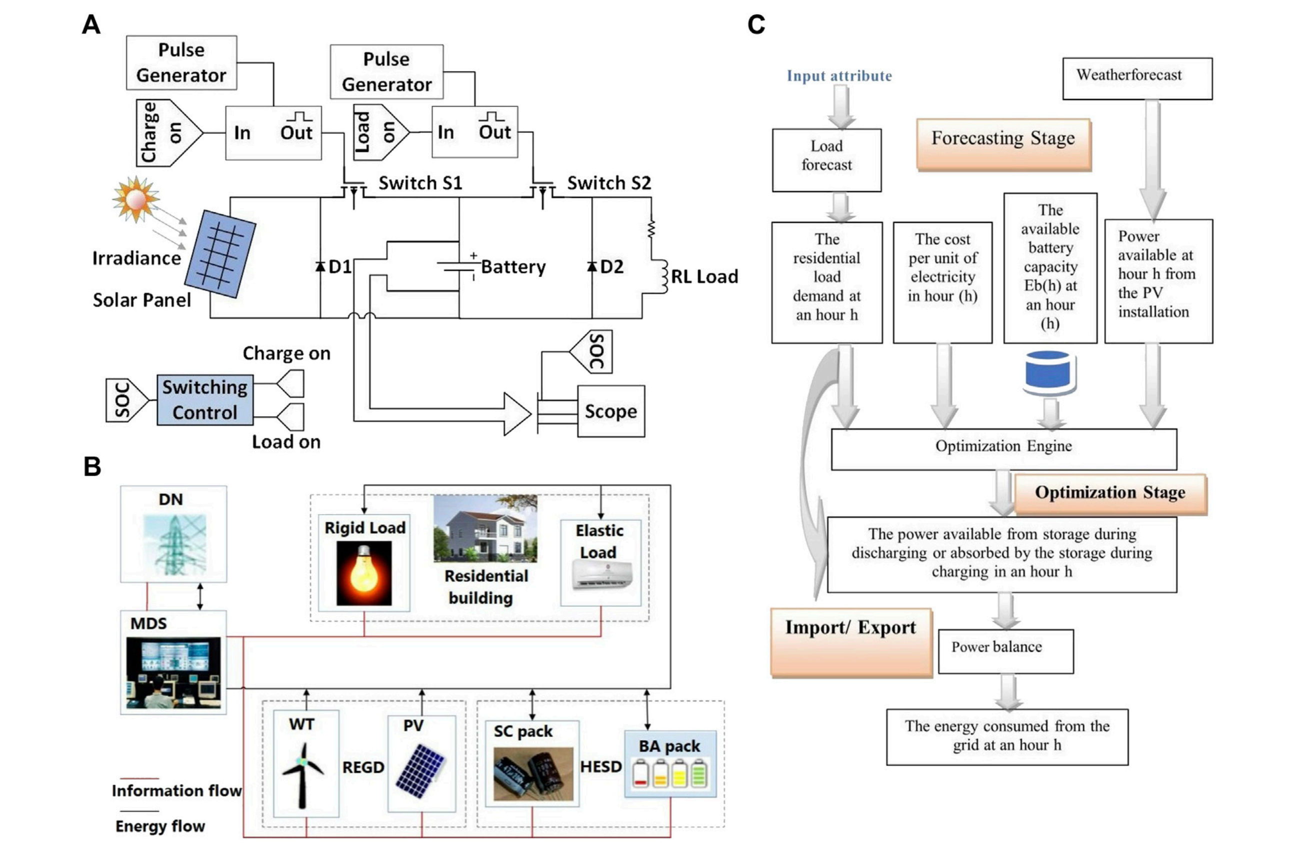

FIGURE 5
General-topology diagram for **(A)** buck-boost converter-based charge controller.**(B)** Energy dispatch scheduling of grid-connected solar PV system with battery storage (Jing et al., 2022). **(C)** Ideal charging and discharging schedule for a hybrid PV-battery system (Kapoor and Sharma, 2020).

Specifically, this study divided advanced battery charge controller approaches into 14 groups. Based on this methodology, each technique controls the power flow from the PV to the battery(Table 3).and the wheel chart illustrated in (Figure 4) depict the full region of inquiry in terms of PV battery methodologies.

It is observed in this figure that the charge controller technology with Perturb and Observe technique was the most common MPPT algorithm considered in the past studies as a battery charge controller, which is followed by Incremental Conductance based and the Ripple correlation control. In contrast, the series-based, shunt-based, and the combination between them are the methods that are less used in the previous presented topologies. This result was not surprisingly due to the advances in digital electronics and the corresponding efficiencies of these technologies. However, the digital controllers are less sensitive and lower reliability due to their complexity.

Each technique is thoroughly examined in the following subsections, which also include a summary of several research papers in each category. The wheel chart summarizes the limited number of studies that have mainly considered shunts, series, and their combinations to transfer solar PV energy to batteries. A comparison of the significant results and research gaps is presented in (Table 4).

It can be seen that the control problems of energy transfer for the PV microgrid and the mismatching sags of the DC grid voltage are rarely highlighted. All published studies compete on the fast tracking of MPPs rather than evaluating systems by the efficiency factor of the energy conversion/transfer over an entire day. The difficulty lies in using a high sampling frequency to obtain the MPP values. This issue is crucial for MPPT in grid-tied PV systems without batteries that require high-speed processors and memory. These high switching frequencies can increase the stress on power modules and reduce their operating lifetimes (Jia et al., 2018). Therefore, switching with a relatively lower frequency and DC voltage balance plays a crucial role in power quality and reliability.

4.3 Battery charger topologies

A general topology diagram for a buck-boost converter-based charge controller is shown in (Figure 5A) (Lokeshreddy et al., 2017; Maithili and Kanakaraj, 2019).

Owing to its characteristics, the lead acid battery was chosen for charging and discharging the series and shunt charge controllers. The authors employed MOSFETs for switching to reduce switching losses. The proposed charge controller was created in MATLAB and the charging and discharging processes of the constructed charge controller were tested (Lokeshreddy et al., 2017).

An energy management system (EMS) algorithm for a PV grid-linked system integrated with a storage system was presented in

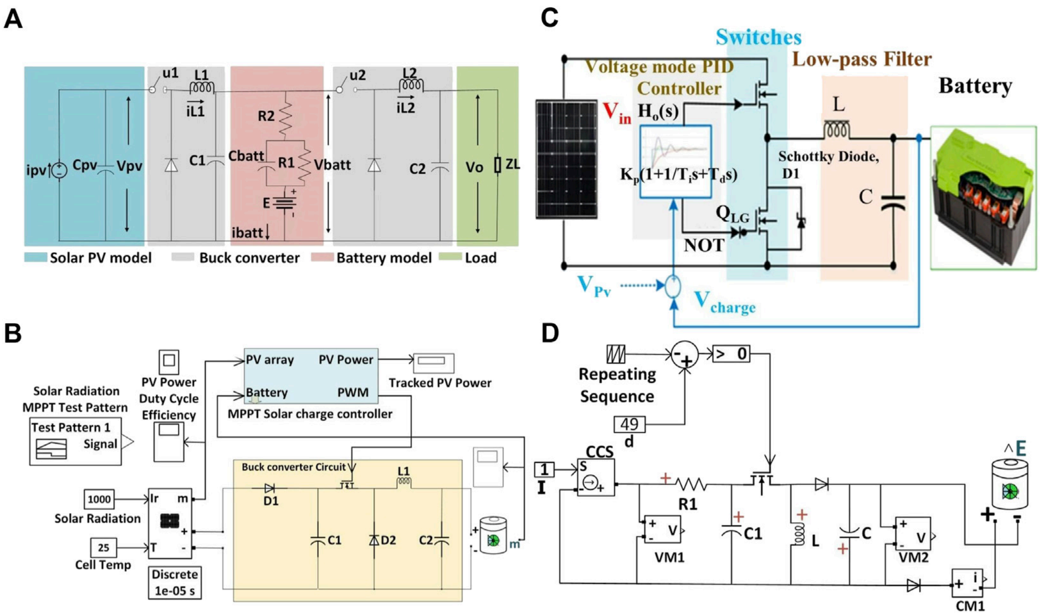

FIGURE 6
PV-Battery charge controller for **(A)** Hybrid electric and powertrain controller (Padmagirisan and Sankaranarayanan, 2019). **(B)** DC-DC buck topology and Perturb and Observe MPPT circuitry modeling for the standalone scheme (Tan et al., 2020). **(C)** PID controller with DC-DC buck converter (Chakraborty et al., 2018). **(D)** IoT-based P&O-based, MPPT, and buck-boost converter (Rokonuzzaman et al., 2020).

(Slama et al., 2021) to reduce PV component redundancy, which affects grid stability. The PV and energy storage systems were connected to the same DC bus in the simulation model, and the EMS provided control over the power flow from the PV generator to the grid, based on a predetermined PV power level. When the PV power falls below a predetermined threshold, energy is saved in the batteries, which can be used during peak energy demand (PED) periods. Otherwise, it continued to supply the main grid. The system topology is shown in (Figure 5B).

An ideal charging and discharging schedule for a hybrid PV-battery system installed on a residential customer's premises was proposed in (Kapoor and Sharma, 2020). The scheduling method was designed to reduce customers' electricity bills. Short-term load, weather, and solar forecasting data were used in the proposed approach. This utility is expected to establish a time-of-use rate plan. This method was applied to a test with a real-world household load and solar-generation situation. The topology used in this study is illustrated in (Figure 5C).

A hybrid electric car with a solar PV battery and powertrain controller (HEV) was considered in (Padmagirisan and Sankaranarayanan, 2019), as shown in (Figure 6A). The major goal of the proposed controller is to improve battery management, load regulation, and maximum power extraction from the PV panels whenever possible. A powertrain controller can be divided into two levels: lower-level controllers and high-level control algorithms. Individual tasks such as MPPT, battery charging, and load regulation are performed using lower-level controllers.

Reference (Tan et al., 2020) presented a buck topology and Perturb and Observe (P&O) MPPT circuitry modeling for a solar PV integrated lead acid battery charge controller for the standalone scheme in a MATLAB environment. The charge controller charges the batteries using a 3-stage charging approach, including MPPT bulk charge with a float charge stage and constant voltage absorption charge. The results showed that the MPPT can track the PV panel maximum point within 0.5 s with an overall average efficiency of 98.3%. The topology is illustrated in (Figure 6B). A PID controller with a DC-DC buck converter battery charge controller was presented in (Chakraborty et al., 2018) to charge lead-acid batteries in a solar PV array, as shown in (Figure 6C).

The experimental and simulation results confirmed that the dynamic response of this circuit was improved by considering a higher charging current and the capability to charge the battery at low irradiance, high stability, and low cost. However, the efficiency of the system was not calculated in this study.

In (Rokonuzzaman et al., 2020), an Internet of Things (IoT)-based P&O-based, MPPT, and buck-boost converter PV-battery charge controller sent vital data to the cloud for remote control and monitoring functions. The results showed that the attained efficiency approached 99.74% during 1 month of performance testing duration. The circuit diagram is shown in (Figure 6D).

Because of temperature and irradiance variations, there are difficulties with non-linearity and power fluctuations in the PV panel coupled storage system and grid. To overcome this problem, three aspects of control were combined in (Marhraoui et al., 2020a), as illustrated in (Figure 7A). The first section is devoted to devising an algorithm to minimize non-linearity to achieve MPPT by controlling the duty cycle of the DC/DC boost converter. Next, two algorithms were combined: Fuzzy Logic and Integral Backstepping (Fuzzy Logic-Integral Backstepping Controller). Then, the Integral Backstepping approach to construct the law control based on the Lyapunov theory to improve the PV-

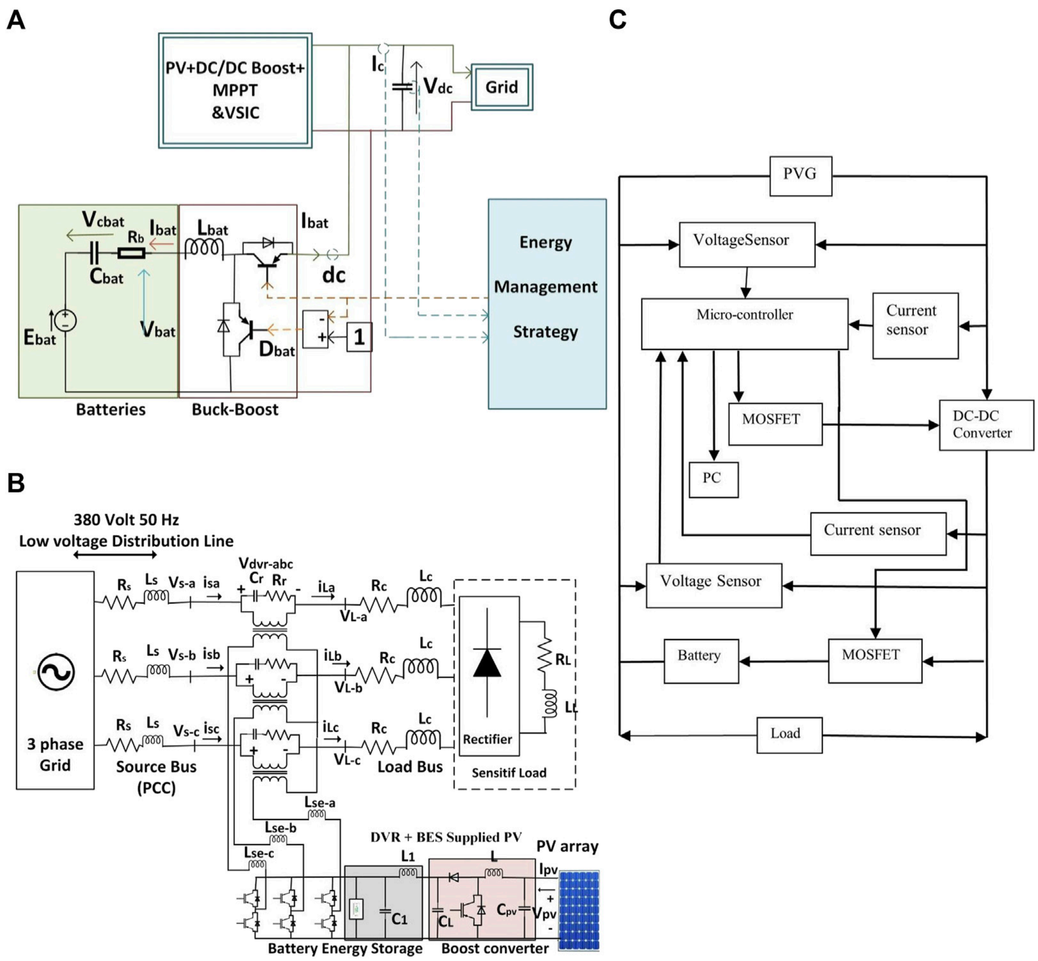

FIGURE 7
PV-Battertopology diagram for **(A)** a control management algorithm on the DC/DC side using VSIC as a charge controller for the stability of the grid parameter (Marhraoui et al., 2020b). **(B)** MPPT-based FS and MPPT-FM methods connected to 3-phase three-wire distribution network (Kiswantono et al., 2019).**(C)** P&O-based MPPT triggered by PWM system (Situmorang et al., 2019).

connected storage system and the grid's robustness and stability were considered.

The cited paper (Kiswantono et al., 2019) presented a comparative performance between the MPPT-based Fuzzy Sugeno (FS) and MPPT-fuzzy Mamdani (MPPT-FM) methods on a PV battery system connected to 3-phase three-wire distribution network. This study stated that MPPT-FM can provide better performance in terms of the percentage of load voltage than MPPT-FS. The battery storage system is illustrated in (Figure 7B).

A P&O-based MPPT triggered by Pulse Width Modulation (PWM) with an Arduino board ATMega 328 microcontroller and MOSFET was used (Situmorang et al., 2019). Although the input voltage fluctuated slightly, the tracking output voltage was higher than the input voltage value and practically constant. The use of MPPT in the battery charging process resulted in a charging time of 8 h without MPPT, and 3 h and 20 min after utilizing MPPT. The battery storage system is illustrated in (Figure 7C).

A three-stage (bulk, absorption, and float) MPPT Buck Converter PV-Battery charge controller for improving charging/discharging was proposed in (Abdul Rahman et al., 2020). The results demonstrate that the time required to fully charge the battery decreases with the application of MPPT in the bulk stage. The circuit diagram used in this study is shown in (Figure 8A).

A P&O-based MPPT-based Zeta converter was used in (Ananda-Rao et al., 2020a) to drive a lead-acid battery as a load, as shown in (Figure 8B).

In (Seguel and Seleme, 2021), a buck converter and two fuzzy logic controller (FLCs) MPPT PV-Battery charge controllers were proposed. The proposed control strategy has the advantage of obtaining the most energy from the PV panel while avoiding battery damage caused by fluctuating MPPT voltages, thereby extending the battery lifetime. It also eliminates the disadvantages of traditional solar chargers, which become slow or inaccurate when weather conditions suddenly change. This technique was implemented using a low-cost Arduino AT91SAM3X8E microcontroller, as shown in (Figure 8C).

In (Shufian et al., 2021), a smart irrigation system was introduced to improve the production efficiency of an automatic irrigation control system with sensors, solar panels, fast chargers,

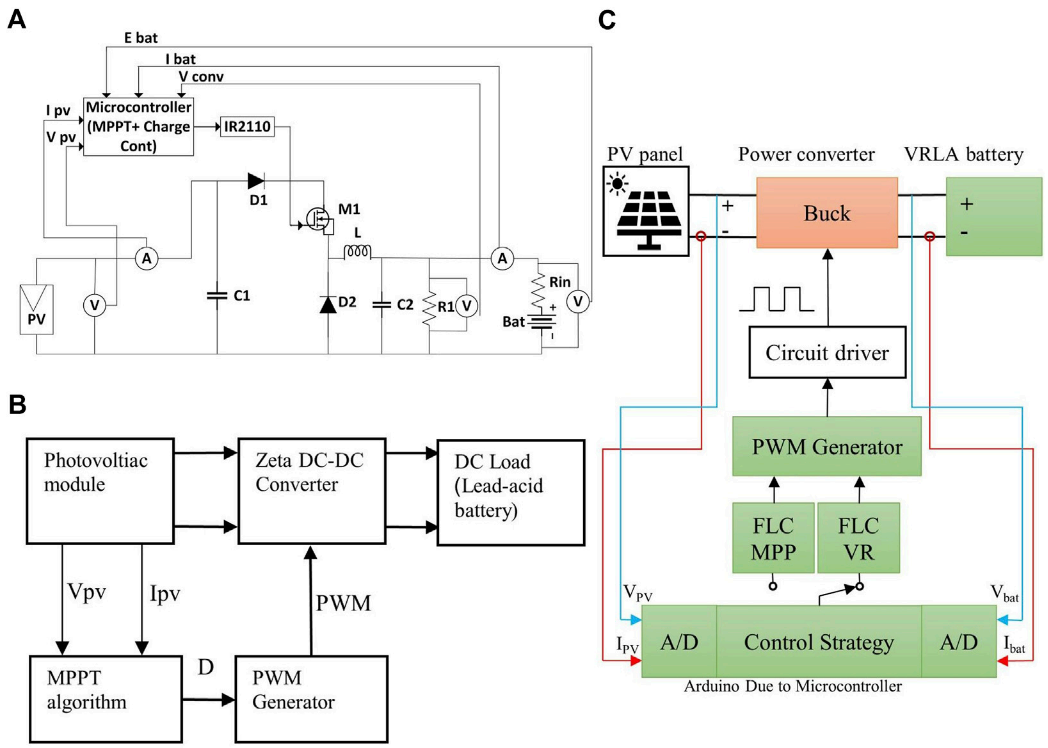

FIGURE 8
Schematic diagram for pv-battery charge controller based on **(A)** A three stages (bulk, absorption, and float) mppt buck converter (Abdul Rahman et al., 2020). **(B)** P&O-based MPPT-based Zeta converter (Ananda-Rao et al., 2020b). **(C)** Buck converter, two FLCs MPPT (Seguel and Seleme, 2021).

and batteries. These sensors detect moving water, both above and below the ground. An Arduino microcontroller was used for this setup. The ESP8266 online Wi-Fi module was used to control the automated online monitoring and receive sensor responses. A fast charger was used as backup. The entire circuit is more efficient, and can be operated both automatically and manually. The block diagram of the system is shown in (Figure 9A).

In (Chtita et al., 2021), an improved power balance control strategy based solely on two proportional and integral (PI) compensators was proposed, which can effectively balance the PV power flow delivered to the DC load and battery, allowing the PV power to be effectively utilized and the battery to be properly charged. To simplify the design of the PI compensators, the complete system was modeled using a linear PV array model as the starting point. In addition, four operating modes were developed to address the aforementioned concerns regarding the weather and load demand variations. The results showed that the proposed control approach performed well in power balancing and MPPT control under a variety of atmospheric conditions, particularly in terms of efficiency (99.79%). A block diagram of the system is shown in (Figure 9B).

Using a PWM-based voltage-controlled boost converter and MATLAB, an example of this work in reference (Sansare et al., 2018) offered a design arrangement with the fewest components to produce an efficient standalone solar energy battery charger for a 40Ah, 48 V lead acid battery system. To create the boost topology in a PWM power converter, we employ a power MOSFET as a switching device, which is controlled in a switching-on and switching-off manner to manage the duty cycle of the power MOSFET. With an increased converter switching frequency, PWM power converters solve the low-efficiency issue of traditionally used linear power converters. A block diagram of the system is shown in (Figure 9C).

The design and implementation of an MPPT-based boost converter for a stand-alone PV-Battery system are presented in (Bjaoui et al., 2019). The control scheme was a combination of the adaptive P&O fuzzy logic controller (P&O-FLC) MPPT and backstepping sliding mode control (BS-SMC) technique. The results showed that this system provides near-perfect tracking in terms of dynamic response, steady-state error, and overshoot and offers greater stability and robustness than a traditional PI controller. A block diagram of the proposed scheme is shown in (Figure 9D).

In (Nagaiah and Sekhar, 2020), a topology for fuzzy-based battery energy management in a hybrid solar and wind renewable system was presented. The system includes a unidirectional boost converter and battery storage with a bidirectional DC-DC converter. The system topology is shown in (Figure 10A).

A previous study (Sudiharto et al., 2021) presented a PV-Battery charge controller topology using Pulse Width Modulation (PWM) for fast battery charging. The duty cycle value was modified using fuzzy control to ensure that the converter output matched the setpoint. Based on the simulation results, the study's control

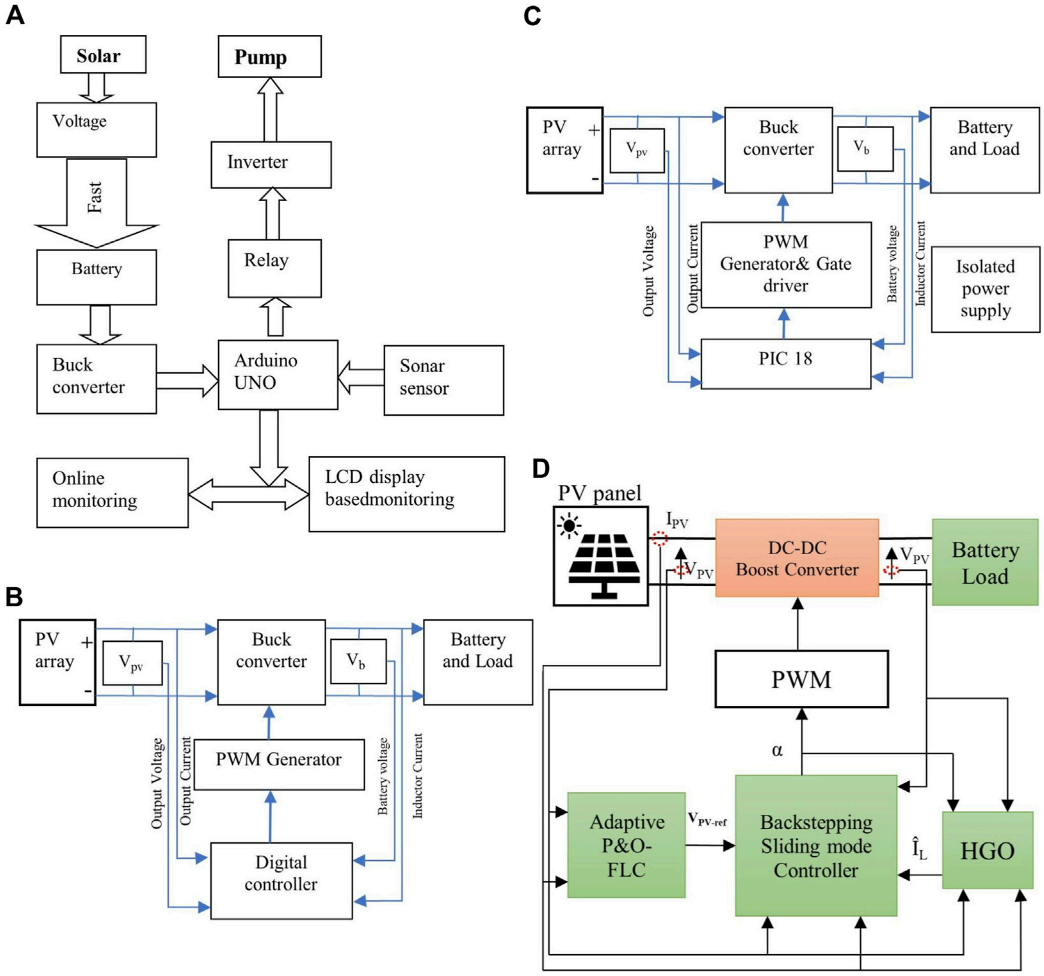

FIGURE 9
A PV-Battery charging system as **(A)** introduced within a smart irrigation system to improve production efficiency (Shufian et al., 2021). **(B)** based on PI controller (Chtita et al., 2021). **(C)** Implemented by a DC-DC boost converter in a PWM signal (Sansare et al., 2018). **(D)** MPPT-based boost converter with a combination of the adaptive P&O fuzzy logic controller MPPT and (BS-SMC) technique (Sansare et al., 2018).

obtained an output current of 12 A with an erroneous ripple current of 8.3%. After 45 min, the battery's SOC climbed by 75.74%. The system diagram is shown in (Figure 10B).

The modeling of an intelligent combined MPPT and lead acid battery charger controller for freestanding solar PV systems was presented by the study cited in (Rkik et al., 2021). It entails controlling a DC/DC buck converter *via* a control unit that incorporates two cascaded FLC that modify the converter's required duty cycle based on the SOC and the three-stage lead acid battery charging system. The first FLC (FLC1) is an MPPT controller that extracts the maximum power from the PV array, whereas the second FLC (FLC2) is responsible for controlling the voltage across the battery to ensure the three-stage charging technique. A diagram of the system is shown in (Figure 10C).

A multiport DC-DC power converter was proposed to deal with the intermittent nature and delayed reaction of renewable energy applications (Almutairi et al., 2021). In addition to the energy storage unit, the proposed converter incorporates a DC-DC converter and a DC-AC inverter, and the proposed circuit incorporates several renewable energy sources. The impact of intermittency can be significantly reduced by combining renewable energy sources with a statistical tendency to offset each other. This combination improved the overall dependability and usability of system. A diagram of the system is shown in (Figure 10D).

5 Solar-battery charge controller

Generally, PV systems have two main problems: energy conversion efficiency when the generated power is low, and the effects of weather conditions on the generated power. Furthermore, the non-linear characteristics of the I-V and P-V relationships of a PV system cause its output power to change continuously with surrounding conditions. To overcome this issue, MPPT and alternative techniques are required. The reason for this is to ensure that the optimal employment of PV cells is achieved. The major obstacle to the inability of optimal employment is the

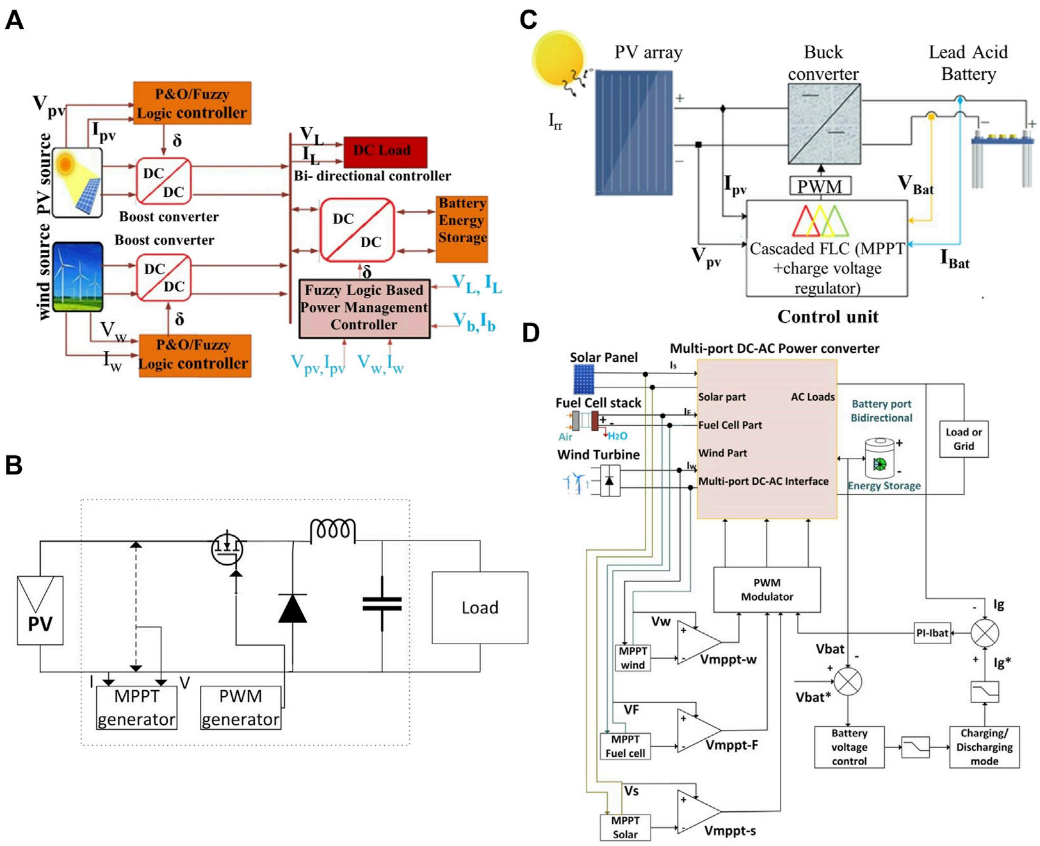

FIGURE 10
PV-Battery charge controller topology using **(A)** Fuzzy-based battery energy management in a hybrid solar and wind renewable system (Nagaiah and Sekhar, 2020). **(B)** A PWM for fast battery charging (Mehmood et al., 2016). **(C)** incorporates two cascaded FLC (Rkik et al., 2021). **(D)** A multi-port DC-DC power converter (Almutairi et al., 2021).

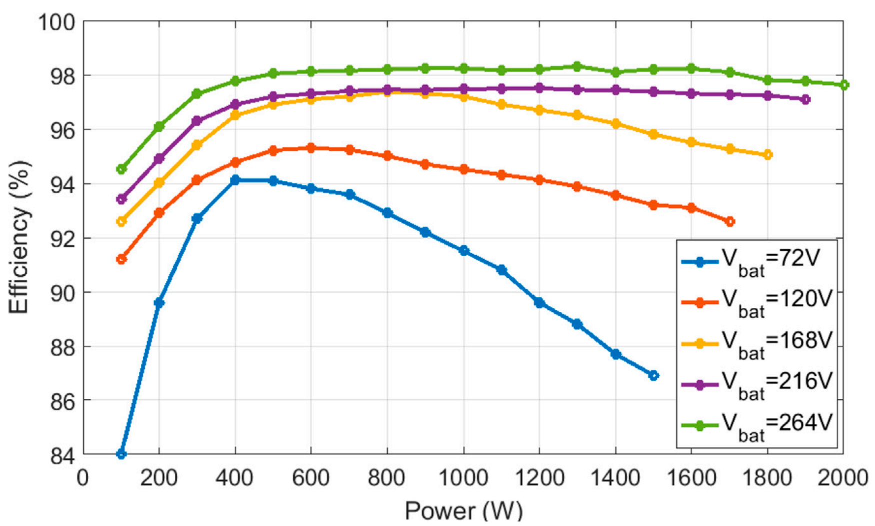

FIGURE 11
Efficiency vs. power at different V_{bat} for a Conventional Shunt charger topology.

TABLE 5 Failure rate per unit hour of PV-Battery systems (Abdon *et al.*, 2020).

Component sub-component	F.R. (failure/unit-h)*10^{-6}	References
PV array		
Mounting Struct. (per string)	0.845	Gallardo-Saavedra et al. (2019)
Mounting Structure	0.101	Oozeki *et al.* (2007)
PV Module	0.065	(Gallardo-Saavedra et al. (2019))
PV Module	0.0152	Oozeki *et al.* (2007)
PV Module	0.025	Baschel *et al.* (2018)
PV Module	0.035	Baschel *et al.* (2018)
PV Module	0.04	Baschel *et al.* (2018)
PV Module Connector	0.0056	Baschel *et al.* (2018)
PV String cabling	0.845	Gallardo-Saavedra et al. (2019))
PV String cabling	0.002	Baschel *et al.* (2018)
Fuses	2.28	Gallardo-Saavedra et al. (2019))
Fuses	0.063	Baschel *et al.* (2018)
Breaker	6.075	Baschel *et al.* (2018)
Inverter		
Generic – 3 kW	16.3	Gallardo-Saavedra et al. (2019)
Generic – 30 kW	65.1	(Gallardo-Saavedra et al. (2019))
Generic – 100 kW	217	(Gallardo-Saavedra et al. (2019))
Generic – 26 kW	11.2	Oozeki *et al.* (2007)
Generic – Central Type	74	Baschel *et al.* (2018)
Generic – Central Type	130	Baschel *et al.* (2018)
Generic – String Type	15.1	Baschel *et al.* (2018)
Capacitor	17.8	Baschel *et al.* (2018)
Capacitor	41.5	Baschel *et al.* (2018)
Capacitor	8.31	(Gallardo-Saavedra et al. (2019))
Ctrl & Communication board	26.7	Baschel *et al.* (2018)
Ctrl & Communication board	63.7	(Gallardo-Saavedra et al. (2019))
Cooling fan	26.7	Baschel *et al.* (2018)
IGBT module	16.6	(Gallardo-Saavedra et al. (2019))
IGBT module	8.9	Baschel *et al.* (2018)
Relays	2.77	(Gallardo-Saavedra et al. (2019))
Transformer	17.8	Baschel *et al.* (2018)

possibility of a mismatch between the load characteristics and MPPs of the PV system. In this study, techniques such as the incremental (INC) Algorithm, P&O, and FOCV were assessed for comparison with the proposed approach (Rezk and Eltamaly, 2015). The characteristic equations of a PV array (Saadeh et al., 2018) can be demonstrated as follows: the short-circuit point, slope at the short-circuit point, slope at the open-circuit point, PV current at the MPP, and $\frac{I_{mp}}{V_{mp}}$ relation derived at $\frac{\partial P}{\partial V} = 0$ are given sequentially by

$$I_{sc} = I_{ph} - I_0\left(e^{\left(\frac{(I_{sc}R_s)}{nV_t}\right)} - 1\right) - \left(\frac{I_{sc}R_s}{R_{sh}}\right) \tag{1}$$

$$\frac{1}{R_{sh}} - \frac{1}{R_{sh} - R_s} + \frac{I_0}{nV_t}e^{\left(\frac{(I_{sc}R_s)}{nV_t}\right)} = 0 \tag{2}$$

$$I_{ph} - I_0\left(e^{\left(\frac{(V_{oc})}{nV_t}\right)} - 1\right) - \left(\frac{V_{oc}}{R_{sh}}\right) = 0 \tag{3}$$

$$I_{mp} = I_{ph} - I_0\left(e^{\left(\frac{V_{mp}+\left(I_{mp}R_s\right)}{nV_t}\right)} - 1\right) - \left(\frac{V_{mp} + I_{mp}R_s}{R_{sh}}\right) \tag{4}$$

$$\frac{I_{mp}}{V_{mp}} = \frac{I_0}{nV_t}\left(1 - \frac{I_{mp}}{V_{mp}}R_s\right)\left(e^{\left(\frac{V_{mp}+\left(I_{mp}R_s\right)}{nV_t}\right)}\right) + \frac{1}{R_{sh}}\left(1 - \frac{I_{mp}}{V_{mp}}R_s\right) \tag{5}$$

For any point (I_i, V_i), the following relations can be written:

$$I_i = I_{ph} - I_0\left(e^{\left(\frac{V_{PV}+(I_{PV}R_s)}{nV_t}\right)} - 1\right) - \left(\frac{V_{PV} + IR_s}{R_{sh}}\right) \tag{6}$$

$$\begin{aligned}\left.\frac{\partial I}{\partial V}\right|_{V=V_i} &= -\frac{I_0}{nV_t}\left(1 + \left.\frac{\partial I}{\partial V}\right|_{V=V_i}R_s\right)\left(e^{\left(\frac{V_i+(I_iR_s)}{nV_t}\right)}\right) - \frac{1}{R_{sh}}\left(1 + \left.\frac{\partial I}{\partial V}\right|_{V=V_i}R_s\right) \\ &= \frac{1}{R_i}\end{aligned} \tag{7}$$

where I_i, I_{ph}, I_0, and I denote the current in each output, PV, reverse saturation current, and the load, respectively. V_{PV}, and V_t denote the PV and thermal voltage, respectively. P_{PV} denotes PV power. R_{sh}, and R_s are the series and shunt resistance, respectively. n is the diode factor. I_{rr}, I_{sc} denote the light irradiance and short-circuit current of the PV array, respectively.

The theoretical MPP values used to evaluate the simulation and experimental results are obtained from (4) and (5), where the MPP points are obtained from the relation $P_{mp} = I_{mp}{}^{*}V_{mp}$. The relation between the battery charging power and that delivered from the PV array represents the converter efficiency (η_{conv}) and is given by

$$\eta_{conv} = \frac{P_{bat}}{P_{PV}} \quad (8)$$

Referring to most PV-battery topologies, this work conducted an experiment showing the effect of source-load voltage balancing to reduce the conversion losses is evaluated by measuring the efficiency *versus* output power at different battery voltages ranging from 72 V to 264V, which represents 6–22 units of the 12 V battery. This result is shown in (Figure 11).

The result shows that the circuit performs a lower efficiency at a lower level of battery voltages, which is agreed with the findings of (Siraj and Khan, 2020). Therefore, higher potential difference, between the source and battery, lower energy transfer that enhances the proposed voltage-matching concept.

6 Failure probability statistics of PV-battery systems

In this paper, we briefly discuss the failure probability statistics of a solar PV-integrated BESS, which is essential for the design and implementation of solar PV systems. Although advances in power electronics and commercially widespread devices with lowered prices play a significant role in the design and PV system applications, the failure probability and lifespan of these components remain major unsolved problems. It is worth mentioning that power conversion devices from DC to AC, represented by inverters, are more complicated and have more electronics in their design than AC-DC rectifier circuits. In the same context, the DC-DC converters of the PV-Battery charge controllers are more complex than linear DC-DC converters. In addition, the various techniques of using MPPT algorithms also contribute to adding complexity and, therefore, increasing the failure probability of PV systems.

Several studies have discussed the issue of failure probabilities in solar PV system components (Abed and Mhalla, 2021; Ghaedi and Gorginpour, 2021; Ostovar et al., 2021; Shashavali and Sankar, 2021; Firouzi et al., 2022). (Table 5) lists the failure rates per unit hour of the PV-battery systems (Abdon et al., 2020). The results show that the DC-AC power inverters had the highest failure rate per unit hour of the PV-Batter systems, as expected.

7 Conclusion

To reduce the number of power conversion stages and the cost of power modules, and to meet the maximum energy transfer efficiency, it is necessary to enhance the flexibility and efficiency of energy transfer. Moreover, research efforts are required to eliminate losses owing to high-frequency switching devices and the complexity of using multiple hardware. In addition, the presented work validates the effectiveness of the proposed concept by evaluating the energy transfer efficiency through simulations and experimental measurements over the entire day. The functionality of a PV-battery controller topology can provide the following benefits: 1) cost-effectiveness and high reliability owing to fewer electronic components, 2) resilience improvement of renewable-powered systems, and 3) lower barriers toward more deployments of PV-powered microgrid systems. Future developments in this field may be suitable for standalone and grid-tied PV systems with battery storage. The topological characteristics of a future charge controller are summarized as follows.

1) Maintaining PV-battery voltage matching will provide features for more control flexibility and enhanced reliability. Batteries with different SOC and capacity conditions can be connected to different solar PVs based on balancing the DC bus voltage, and the MPP is maintained further by controlling the temperature of the PV modules. Compared with a conventional charger that requires power-switching modules with a high operating frequency, only a low-frequency switching power module is required to drive cooling fans.
2) Compared with the conventional charge controller, the DC-DC conversion stage can be removed not only from the stage between the PV and battery but also from the battery-load stage. This configuration leads to a reduction in hardware costs and improvements in system efficiency.
3) This review presented a brief discussion on failure probability statistics for the system components of solar PV-integrated BESS including failure rates per unit hour of the PV-battery systems. The statistical results demonstrated that the DC-AC power inverters had the highest failure rate per unit hour of the PV-Batter systems.
4) As a future solar PV integrated battery energy storage system, to reduce the number of power conversion stages and obtain maximum energy transfer efficiency, a fundamentals-based algorithm and topology, without the integration of DC-DC converter, is proposed. Moreover, the voltage control issue in the DC microgrid is treated as an optimization problem to minimize the hardware complexity and the losses of high-frequency switching devices. The presented work validates the effectiveness of the proposed concept *via* the evaluation of the energy transfer efficiency in simulations and experimental measurements over a full daytime. The functionality of the proposed topology can provide benefits such as 1) cost-effective and high reliability due to lower electronic components, 2) resilience improvement of renewable-powered systems and 3) lower barriers toward more deployments of PV-powered microgrid systems.

Author contributions

MH: performed the research, Data Analysis, Writing–Reviewing and Editing. SA: review, editing, and supervision. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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