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Bidirectional (DC-DC) Battery Charging Converter from PV System Review

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ABSTRACT

Applications for power systems based on renewable energy have lately drawn interest in energy storage. Batteries are one of the most widely used energy storage technologies in renewable energy sources, electric cars, and grid-connected devices. The bidirectional DC-DC (BDC) converter enables electricity to flow back and forth in battery applications by controlling the battery's charging and discharging stages. The BDC converter's duty cycle regulates battery current by accounting for both the direction of current and the battery's state of charge. The most significant investigations and research on a non-isolated BDC converter that operates on the buck-boost principle are covered in this paper utilizing diagrams and comparison tables, along with the contributions of researchers. This study will work on highlighting the latest and most recent research related to the topic of bidirectional converters, identifying the latest available technologies and proposals, evaluating their efficiency and advantages, and pinpointing their limitations and problems. Through this perspective, this review will enable researchers and those interested in the topic of bidirectional converters to identify gaps, formulate the research problem, and guide them in accurately selecting and building appropriate techniques while saving effort and time.

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1. INTRODUCTION

The BDC unit in the developed system controls the battery's and the DC link's bidirectional energy flow. In particular, the BDC unit utilizes a proportional-integral (PI) controller to control the battery current, while the DC link provides power to the battery in buck mode during the battery charging phase. Nevertheless, the battery provides DC current to the load during the DC link interruption in the battery draining phase in boost mode, and the BDC unit uses a PI controller to regulate the DC link voltage. To show how the BDC unit functions and is regulated in different scenarios, simulation results are shown. The significance of energy storage systems has increased as the ability of renewable energy sources to produce electricity increases and electric vehicles become more common in the transportation sector. Energy storage technologies like batteries and super-capacitors are commonly used to store energy from renewable sources and satisfy load needs. Batteries are regarded as the best energy storage technology because of their speed and accessibility. For consistent performance, battery charging and draining processes are therefore essential [1, 2]. The Bidirectional DC-DC Boost converter serves as a power stage that may move energy from the high-voltage source to the battery and vice versa while the battery is draining. The voltage distribution between the two terminals and the conversion rate (Duty Cycle) may be changed by adjusting the operating conditions using PWM signals. By enabling the use of the same set of turbines and connections between charging and discharging modes, the design offers flexible options for energy storage and load feedback. This configuration enables smooth state transitions without necessitating a whole structural change by merging the Buck and Boost functions into a single structure. In contrast, the conventional DC-DC Boost converter just increases the voltage supplied from the source to the load rather than allowing energy to return from the load to the source. However, depending on the power condition, the bidirectional inverter converter can operate in either way, raising or lowering the voltage. Additionally, it offers strong regulatory characteristics to assist regulate current and voltage in micro-grids and tiny power grids, and it makes it easier to manage the energy exchange between the PV and the battery. Furthermore, it often uses advanced control strategies like MPPT regulation and efficient load switching, which may work under a range of lighting conditions and demand variations. It should be mentioned that the needed parameters and the intended power range in the application continue to determine the exact circuit selection, the number of switches, the wiring layout, and the PWM signal timing arrangement [3, 4]. The bidirectional DC-DC converter (BDC) functions as an interface circuit between the battery and the power generation unit, controlling the battery's charging and discharging modes of operation. Bidirectional power flow, efficient performance, and transformer-less operation are some of the special features of BDC design. Because of its exceptional features, BDC is used in applications utilizing battery energy storage systems (BESS). In the corpus of current research, recent related works detailed the design and analysis of a solar photovoltaic (PV) system based on BDC. The bidirectional buck-boost operation with open loop control is presented based on simulation results. A typical BDC model's circuit design is shown in Fig. 1 [4, 5].

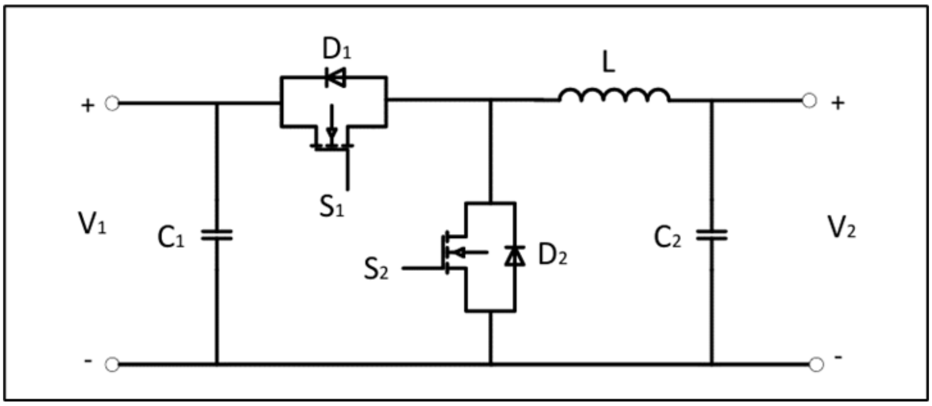

Fig. 1. Circuit diagram of a typical BDC model

The circuit representation for the non-isolated BDC design is shown in Fig. 1. Bidirectional power transmission, small size, and great efficiency are only a few advantages of this design. One inductor (L), two capacitors (C1 and C2), two diodes (D1 and D2), and two switching components (S1 and S2) make up the BDC, as illustrated in Fig. 1. An IGBT or a MOSFET can be used as the switching element to build this architecture. In order to transfer power in both directions, the BDC may basically operate in both boost and buck modes [3, 4].

2. RELATED EQUATION

The photovoltaic resulting energy is periodically computed and correlated to the last energy. If the achieved power is increased, an identical operation progresses else, the disruption is reversed. The resulting current, I, might be evaluated in the following formula [5, 6]:

$$I = I_{ph} - I_s\left[e^{\frac{V+I\cdot R_s}{A\cdot N_s V_T}} - 1\right] - \frac{V + I \cdot R_s}{R_{sh}} \tag{1}$$

In which I_L=I_ph, that denotes the photocurrent, V, is the obtained voltage, ID indicates the parallel diode current, R_sh represents the shunt resistance, I_sh is the shunt current, R_s denotes to the series load, also I, indicates the yield current. Moreover, the PV saturation current is obtained as [7-11]:

$$I_s = I_{rs}(\frac{T_{op}}{T_{ref}})^3 \left[e^{(\frac{q\epsilon_G}{Ak}\left(\frac{1}{T_{op}} - \frac{1}{T_{ref}}\right))}\right] \tag{2}$$

Whereas, the inverted saturation current is represented as:

$$I_{rs} = \frac{I_{sh}}{\left[e^{\frac{V_{dc}}{A\cdot N_s V_T}} - 1\right]} \tag{3}$$

Furthermore, the PV equivalent equation photon current might be presented such as [12, 13]:

$$I_{ph} = \left(\frac{G}{1000}\right) \cdot (I_{sc} + \alpha_{I_{sc}} \cdot \Delta T) \tag{4}$$

Where, G, denotes the PV cell irradiance (W/m2), ΔT=T_c-T_(c,ref) (Kelvin), T_c, indicates the driving cell heat (K), T_(c,ref) represents the cell heat at STC = 25 + 273 = 298 K, I_sc, describes the short circuit current (A) at STC, α_(I_sc), denote the heat coefficient of I_sc = 0.05% A/K) for suggested PV Module, I_rs, indicates the reverse saturation diode current (A), ϵ_G represents the physical band gap power (eV), (1.12 eV for Si). Also, k, represents the Boltzmann constant 1.38 × 10-23 J/K, q denotes the electron charge 1.602 × 10-19 C, and N_s, depicts the sum of cells attached in series. Applications requiring power supply and regenerative recovery, such as battery charging and discharging, require bidirectional boost converters, which are DC-DC power converters that let energy flow in both directions. In order to retain high efficiency and quick reaction, it works by switching components to step up voltage in one direction and step down in reverse. In order to power charging or discharging modes, energy is first stored in an inductor while the switch is ON and then transferred to the output when the switch is OFF. In continuous conduction mode, a boost converter's fundamental relationship is [12, 13]:

$$V_o = \frac{V_{in}}{1 - D} \tag{5}$$

Where, V_o denotes the output voltage, V_in indicates the input voltage, and D represents the duty cycle. In bidirectional processing, reversing current flow permits power to flow back along the battery or load. Thus Fig. 2 illustrates the control block diagram for buck mode operation [14, 15].

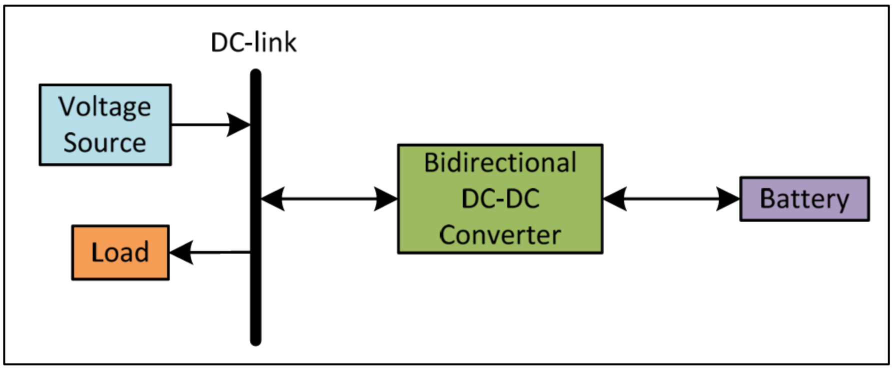

Fig 2. Demonstration of the control block diagram for buck mode operation

As displayed in Fig. 2, the battery is charged by controlling the battery current using a PI controller, and the voltage source is activated on the DC-link side. Over the past few decades, energy storage has grown in significance for electric electronics applications that depend on renewable energy sources. Batteries are a common choice for energy storage and are utilized by renewable energy sources, electric cars, and grid-connected gadgets. By regulating the battery charging and discharging phases, the bidirectional DC-DC converter (BDC) makes it possible to control energy flow in both directions in battery applications. Therefore, the battery current is controlled by varying the DC-DC converter's (BDC) duty cycle while accounting for the battery's charge level and current direction. The non-isolated bidirectional DC-DC converter that functions using the buck-boost converter principle is designed, analyzed, and used in this study.

3. RELATED STUDIES

By examining international publications and scientific research pertaining to bidirectional DC converters for battery charging in photovoltaic solar power system models connected to the grid with energy control, researchers have tried to offer suggestions and insights on various tactics and strategies. Reviews of the kinds of ideas and current research for this study will be carried out in order to obtain as many insights as possible on the most recent attainable improvements while retaining alterations linked with these technologies. The disadvantages and challenges of the suggested approaches are also covered, in addition to the advantages that are now accessible. Reviews of the most recent studies conducted during the previous four years on this subject are included in the following section.Alazrag and Sbita in 2023 [16], suggested bidirectional, non-isolated DC-DC (BDC) with MPPT. The study, provided comprehensive Simulink models with MPPT evaluation. The proposed technique suffers from the absence of real-time implementation information for PV-battery-grid. Christopher et al. in 2024 [17], proposed a bidirectional RES charging station DC/DC. The authors presented a bidirectional charging station architecture based on photovoltaics. The study's determinants may be summed up as follows: simulations that mostly rely on testing, and equipment defects. In 2022, Vamsi et al. [18], recommended a bidirectional converter for electric vehicles and DC loads. The suggested approach advanced a bidirectional converter designed for charging batteries with multiple loads. The study's inadequacies are summed up in the insufficient efficiency finding during solar energy variations. Singh et al. in 2022 [19], presented a bidirectional DC-DC for EV charging connected to PV. The study helps with two techniques of solar battery charging and draining. The suggested method is hampered by a dearth of studies on the dynamic fluctuations of solar energy. Mahesh et al. in 2025 [20], introduced a wireless charging from a battery or photovoltaic system using a three-port DC-DC converter with PV integration. The study contributes with novel multiport converter for wireless charging from PV/battery. The approach suffers from complexity of integration, also need for loss analysis. In 2025, Vijayan et al. [9], proposed a bidirectional DC-DC with many ports and high gain for micro-grids. The presented strategy provides better topology for DC micro-grid hybrid storage. The study ignores the variance in PV power quality. In 2023, Benlahbib et al. [7], proposed a validated bidirectional DC to DC buck-boost converter, designed to be implemented on the storage battery bank of a stand-alone PV system. The purpose of this work was to accommodate the intermittence and uncertainty of the PV source by incorporating a high-power bidirectional buck-boost converter capable of both charging and discharging operations.. Varma and Dhanamjayulu in 2025 [10], reviewed a bidirectional DC-DC hybrid EV/RES techniques. A thorough analysis of the functions and tactics of converters in HEVs that prioritizes HEVs above stationary PV. The limitations of the study that is focuses more on HEV than stationary PV cells. Al-Hysam and Raisz in 2025 [11], suggested an LVDC micro-grid using a hybrid bipolar converter. The proposed approach provides an improved control and voltage gain for battery/photovoltaic integration. The study requires more testing with changing solar input. In 2025, Mookkan et al. [8], recommended a multi-port high-gain converter for hybrid storage. A new multi-port topology for hybrid storage charging has been achieved with high efficiency. The proposed technology suffers from fundamental modeling problems, in addition to facing an experimental gap. Hence, a summary of the most recent articles related to the thesis topic is shown in Table 1.

Table 1. Summary of recent publications related to the thesis title

Reference	Employed technology	Contribution & advantages	Research limitations & gaps
Alazrag and Sbita in 2023 [16]	Non-isolated bidirectional DC-DC with MPPT	Detailed Simulink models for PV-battery-grid with MPPT review	Lacks real-time implementation details
Christopher et al. in 2024 [17]	Bidirectional DC/DC for RES charging stations	Proposes PV-based bidirectional charging station topology	Tests mostly in simulation; hardware gaps
Vamsi et al. in 2022 [18]	Bidirectional converter serving DC loads & EVs	Designed bidirectional converter for multi-load battery charge	Lacks efficiency analysis under PV fluctuation
Singh et al. in 2022 [19]	Bidirectional DC-DC for PV-tied EV charging	Two-mode operation for battery charge/discharge from PV	Limited investigation of dynamic PV changes
Mahesh et al. in 2025 [20]	Three-port DC–DC wireless charging with PV integration	Novel multiport converter for wireless charging from PV/battery	Integration complexity; loss analysis needed
Gaied et al. in 2024 [21]	ANN – Three-Phase Bidirectional DC-DC	Used ANN to control three-phase bidirectional converter for renewable energy sources, controlling bus voltage and reducing battery current ripple.	Three-phase topology only; no MPPT from real PV panel
Benlahbib et al. (2023) [7]	Non-isolated bidirectional DC-DC converter	Higher efficiency and reliability in PV-battery integration	No MPPT algorithm
Varma and Dhanamjayulu in 2025 [10]	Hybrid EV/RES bidirectional DC-DC review	Comprehensive review of converter roles/strategies in HEVs	Focuses more on HEV than stationary PV
Al-Hysam and Raisz in 2025 [11]	Hybrid bipolar converter for LVDC micro-grid	Enhanced voltage gain and control for battery/PV integration	Needs testing under variable solar input
Vijayan et al. in 2025 [9]	Multi-port high-gain converter for hybrid storage	Novel multi-port topology for efficient hybrid storage charging	Modeling primarily; experimental gap

Also, a statistical comparison summary of recent articles (2021–2025) has been provided in Table 2 (21-24)].

Table 2. A statistical comparison summary of recent articles (2021–2025)

Application	Number of articles	Example article (Title, Author et al, Year, Journal)
MPC based energy management	5	“Model Predictive Control based Energy Management System” - Ninad Gaikwad et al. in 2024 [22]
Battery charging	5	"Design of bidirectional DC-DC buck-boost converter for PV battery charger" - G. Venkata et al. in 2023 [24], IJPEDE
Photovoltaic cells	4	"Active X2G boost converter with HSTM-PI controller for PV based EV charging" - Chandrasekar et al. in 2025 [21], Nature Communications
Electric vehicles	6	"Control and Operation of Bidirectional Converter for Electric Vehicles" - Ghodake and Udaykumar in 2024 [25], Journal of Electrical Systems
Other Applications	8	"Modeling and control design for bidirectional DC-DC converter system" - Jessen et al. in 2023 [23], IEEE Transactions

Also, this statistical comparison summary of recent articles (2021–2025) has been displayed in Fig. 3.
Furthermore, Table 3 illustrates a statistical summary based on previous articles and scientific papers, arranged by year, control technique, and journal/source.

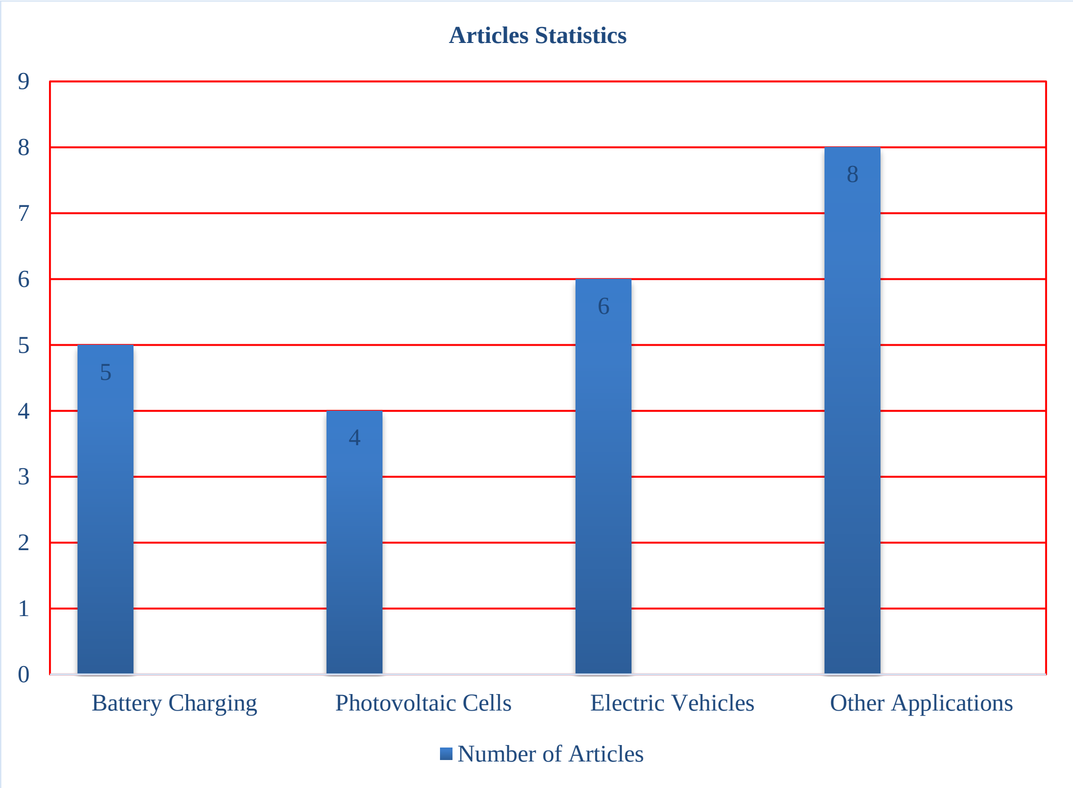

Fig. 3. A statistical comparison summary of recent articles (2021–2025)

Table 3. Statistical summary based on previous articles and scientific papers, arranged by year, control technique, and journal/source

Published year	**Article numbers**	**Main control technologies discussed**	**Journals / Publishers**
2022	1	PID + PWM	International Journal of Advanced Science & Technology / SSRN
2023	3	Sliding Mode Control (SMC), Extremum Seeking Control (ESC), Extended State Observer (ESO), CRM (Critical Conduction Mode), Digital Current Observer, Two-stage duty + resonant control	Sensors (MDPI), Frontiers in Energy Research, Energy (Elsevier)
2024	5	PID closed-loop, ANFIS (Neuro-Fuzzy), High-gain wide-range control, multi-strategy control reviews	IET Power Electronics, E3S Web of Conferences, Wiley/Hindawi journal, Elsevier (review), additional survey journal
2025	1	Machine-Learning-Based control	IET Power Electronics

Moreover, a summary review showing the latest control systems/technologies used to control bidirectional DC-DC converters (boost/buck-boost) has been presented in Table 4.

Table 4. A summary showing the latest control systems/technologies used to control bidirectional DC-DC converters (boost/buck-boost)

Year	Authors (short)	Control technique	Main application	Key limitations / issues
2023	Trinh et al. [26]	Sliding-mode + Extended State Observer + Extremum Seeking (robust adaptive)	Bidirectional boost converters under disturbances	Control complexity, ESO tuning, chattering reduction requirements
2023	Wan et al. [27]	Digital current-observer based CRM (Critical Conduction Mode)	Battery charging/discharging, ZVS operation	Mode transition complexity, observer accuracy for current
2023	Liu & Wu [28]	Two-stage closed-loop duty + resonant frequency control	More-electric aircraft DC power systems	Coordinating multi-stage control across wide voltage range
2022	Viswanatha [29]	PID & PWM with automatic bidirectional mode switching	Automotive BMS (12V ↔ 24V DC systems)	PID tuning challenges under abrupt load changes
2024	Kurtoğlu et al. [30]	Closed-loop controller (simulation-based)	DC microgrid bidirectional energy flow	Lacks experimental validation, hardware non-idealities not included
2024	Gholami et al. [31]	Control for wide-range high-gain buck-boost	Renewable/storage DC interfaces	Switch stress due to high voltage gain, nonlinear behavior
2024	Aeggegn et al. [32]	ANFIS (adaptive neuro-fuzzy)	DC microgrid converters under nonlinearities	Training complexity, ensuring stable fuzzy rule adaptation
2024	Alam et al. [33]	Survey: PI, SMC, CRM, MPC, etc.	Isolated BDCs (renewables, EV fast charging)	Selection trade-off between topology & control method
2024	Martínez-Vera & Banuelos-Sanchez [34]	Survey: EV-oriented bidirectional control	Energy management, V2G, regenerative braking	Long-term reliability + EV system integration issues
2025	Li et al. [35]	Machine-learning-based stable controller	Interleaved bidirectional EV battery converters	Training data needs & real-time safety verification

4. Classification Review

Next, this review was categorized to discuss and analyze various control techniques proposed by recent articles and published studies for bidirectional DC converters, according to the type, nature of operation, and methodology of the proposed controllers, which were classified based on their operational characteristics into the following types.

4.1 Classical controllers

In this type of controllers, 10 recent, foundational papers on bidirectional/DC–DC / MPPT / converter topologies & reviews are presented as shown in Table 5.

Table 5. Topologies & reviews of the classical controller types of the bidirectional/DC–DC / MPPT / converter

Year	Authors (short)	Technique used	Scientific contributions	Limitations & gaps
2024	Martínez-Vera & Banuelos-Sanchez [34]	Review — Bidi DC–DC topologies & control	Comprehensive survey of topologies & control trends for EV applications; classification by power levels.	Focus on EV; limited experimental cross-validation across topologies. (LatamT)
2024	Farajdadian et al. [36]	Review — Multiport DC–DC topologies	Comparative analysis of multi-port topologies & control strategies; identifies application niches.	Focused on taxonomy; few hardware validations. (ScienceDirect)
2024	Lencwe et al. [37]	Review — two-way converters for hybrid battery systems	Critical review and classification for hybrid BSESS development.	Needs unified performance metrics; limited experimental prototypes. (ScienceDirect)
2023	Sutikno et al. (review) [38]	Non-isolated BDC review	Focus on non-isolated buck–boost varieties for renewable systems and pros/cons.	Limited coverage of WBG (SiC/GaN) device impact. (OUP Academic)
2025	Tuluhong et al. [39]	Review — recent developments (survey)	Classifies converters and control strategies; updated topologies & performance discussion.	High-level; needs more comparative datasets. (MDPI)
2023	Algamluoli et al. [40]	Ultra-high gain interleaved converter (MTB+MSIC)	New triple-boost interleaved architecture for PV; high step-up gain demonstrated.	Complexity increases; EMI and component stress not fully addressed. (Frontiers)
2024	Hou et al. [41]	High-power TCM buck/boost design	15 kW prototype methodology for wide conversion ratios & high density.	Focused on high-power design — not directly optimized for low-power WSN/EV niches. (VTechWorks)
2024	Dodda et al. [42]	Model Predictive Current Control — three-level bidirectional	MPC current control for 3-level bidirectional buck–boost for battery BESS.	Controller complexity & computational cost for real-time. (Wiley Online Library)
2025	Reali et al. [43]	GaN-based bi-directional OBC (6.6 kW)	Automotive-grade GaN switches to achieve high switching frequency, compact OBC design.	Thermal management & long-term reliability concerns. (MDPI)
2024	Benlahbib et al. [44]	Experimental bidirectional buck-boost converter for PV charger	Experimental design and validation of non-isolated bidirectional buck-boost converter.	Limited to specific power range; need broader PV variation tests. (Nature)

4.2 Artificial intelligence controller models

In this controller types, another 10 modern studies that apply machine learning, deep reinforcement learning, and recurrent neural networks (ML/DRL/DNN) techniques have been employed in DC-to-DC converters, MPPT, and boost systems gave been reviewed in Table 6.

Table 6. Topologies & reviews of 10 modern studies that apply (ML/DRL/DNN) controller techniques employed in DC-to-DC converters, MPPT, and boost systems

Year	Authors	Technique used	Scientific contributions	Limitations & gaps
2024	Mazaheri et al. [45]	Deep RL (PPO) for DC-DC control	Shows model-free DRL (PPO) can control converters robustly across modes.	Practical hardware latency & safety constraints need more study. (MDPI)
2024	Saha et al. [46]	PPO RL for boost converter (PPO)	PPO-based controller achieves short settling times, robust to uncertainties.	Real-time implementation issues & reward shaping complexity. (PMC)
2025	Li et al. [35]	ML controller for interleaved bidirectional DC-DC	ML-based control with proven closed-loop stability for interleaved BDCs.	Early stage; training dataset & generalization need more detail. (IET Research)
2023	Banda et al. (47)]	DNN-based controller for bi-directional converters	DNN controller for V2V / V2G demonstrates high precision control.	Explainability & runtime determinism concerns. (MDPI)
2024	Zandi et al. [48]	DQN & DDPG for voltage control	Comparative RL agents for voltage regulation; DDPG effective in continuous action spaces.	Training stability and sample efficiency in hardware remain open. (ScienceDirect)
2025	Rajamallaiah et al. [49]	Deep Reinforcement Learning (DRL)	Comprehensive review of DRL applications in power converter control	Limited hardware Safety constraints & sample efficiency. (IEEE)
2025	Cheng et al. [50]	RL controller — DC-DC boost (novel RL variant)	Robust RL control for capacitor output regulation under disturbance.	Computational demands for embedded controllers. (ScienceDirect)
2023	Sharmin et al. [51]	PPO/DRL design methodology (arXiv)	Step-by-step DRL design for boost converters; benchmark results.	Sim-to-real gap not fully closed. (arXiv)
2023	Banda et al. [47]	A Deep Neural Network (DNN) based controller for non-isolated converters.	Developed a DNN-based controller for (V2V) and (V2G) applications. The controller achieves a very fast repone and reducing the overshoot duration.	Research is gradually (PINNs), to enhance control reliability and performance (MDPI)
2023	B. C. Phan, Y. C. Lai, C. E. Lin [52]	DRL – DQN + DDPG	Proposed DQN (discrete action space) and DDPG (continuous action space) for MPPT in PV systems under partial shading conditions (PSC), with comparison against P&O algorithm.	Simulation only (MATLAB/Simulink); no real hardware or battery charging validation. (Frontiers)

4.3 Insect controller models

In this controller kinds, further 10 advanced nature-inspired algorithms which represent insect behavior with their MPPT / converter applications are listed in Table 7.

Table 7. Summary of 10 advanced nature-inspired algorithms which represent insect behavior with their MPPT / converter applications

Year	Authors (short)	Technique used	Scientific contributions	Limitations & gaps
2024	Xia et al. [53]	Ant Colony Optimization (ACO) MPPT	Improved ACO for faster GMPP detection under shading.	Parameter tuning & convergence under fast irradiance change. (OUP Academic)
2024	Yilmaz and Akcan [54]	ACO + feature selection for PV	Uses ACO for feature ranking in concentrator PV performance modeling.	Specialized to LCPV; generalizability limited. (ScienceDirect)
2025	Abo-Khalil et al. [55]	Artificial Bee Colony (ABC) MPPT	ABC for MPPT; validated in co-simulation; robust to partial shading.	Long run times for large arrays. (Astrophysics Data System)
2024	Qi et al. [56]	Hybrid Cuckoo Search + ABC (CSA-ABC)	Hybrid metaheuristic for robust MPPT and global optimum convergence.	Hybrid complexity; hardware trials limited. (MDPI)
2024	Gong et al. [57]	ABC + heat transfer search hybrid MPPT	Two-stage hybrid (ABC + heat transfer search) for MPPT with improved robustness.	More computation; needs hardware verification. (ScienceDirect)
2024	Chen et al. [58]	Honey Bee Dancing (HBD) MPPT	New HBD method inspired by honeybee communication for GMPP tracking.	Early study; reproducibility across modules uncertain. (PMC)
2023	Zhao et al. [59]	Enhanced ACO with Cauchy-Gaussian fusion	Improves ACO global search & movement strategy; applied to image segmentation & optimization.	General optimizer — needs domain-specific tuning for MPPT. (Frontiers)
2024	Masmoudi et al. [60]	ACO + P&O hybrid	Hybrid ACO-P&O for faster convergence.	Tuning complexity; comparative hardware tests missing. (Studies Publicações)
2024	Senthilkumar et al. [61]	Survey (nature-inspired MPPT: DA, GOA, MFO, SSOA)	Summarizes nature-inspired algorithms applied to MPPT; comparative performance.	Survey; needs real-world experimental cross-checks. (SpringerLink)
2024	Lodhi et al. [62]	Dragonfly Optimization Algorithm (DA)	DA variant for GMPP under PSC; good global search.	Convergence vs PSO and ABC depends on landscape. (IDEAS/RePEc)

4.4 Animals controller models

Now, further 10 recent works describes DC to DC boost converters using animal-inspired meta-heuristics such as PSO, WOA, GWO, Cuckoo, Whale, Bat, etc. techniques which are summarized in Table 8.

Table 8. List of 10 recent works describes DC to DC boost converters using animal-inspired meta-heuristics — PSO, WOA, GWO, Cuckoo, Whale, Bat, etc. techniques

Year	Authors	Technique used	Scientific contributions	Limitations & gaps
2023	del Rio et al. [63]	PSO-based MPPT control (real system)	Real-time PSO control validations vs P&O; shows PSO viability.	Computational cost & parameter sensitivity in embedded controllers. (MDPI)
2024	Mariprasath et al. [64]	Cuckoo Search + MPPT (SSBC converter)	Stackable single-switch boost converter with CSA MPPT; good performance.	Focused topology; broader module tests missing. (Nature)
2024	Abdullah et al. [65]	Whale Optimization MPPT	WOA applied for GMPP tracking in single-stage grid-tied system.	Convergence speed under dynamic shading contested. (E3S Conferences)
2024	Tyagi et al. [66]	Beluga Whale Optimization (BWO)	New BWO for MPPT under dynamic shading, good tracking performance.	New algorithm — needs comparative benchmark across many datasets. (ScienceDirect)
2025	Abdelsattar et al. [67]	Enhanced PSO / Quantum PSO	Fast GMPP tracking in high dynamics; improved convergence.	Hardware tests limited. (ScienceDirect)
2025	Zemmit et al.[68]	Variable step-size MPPT based on (GWO) and (WOA) integrated with P&O	Validated using real data, developed unified fitness function minimizing ripple and overshoot.	Slightly longer response time compared to fixed-step PO (Nature)
2025	Jothi Swaroopan et al. [69]	PSO memetic algorithm (PSOMA)	PSO memetic for MPPT — improved search & fast convergence.	Newer method — needs real PV prototype validations. (Nature)
2025	Kothapalli and Sundar Rajan [70]	MISWOA (improved WOA)	Enhanced WOA for global search & convergence in optimization problems.	Benchmarking vs many alternatives required. (MDPI)
2024	Kothapalli et al. [71]	HBWO hybrid methods	Hybrid Beluga Whale for MPPT + OEWIM drive integration.	Complexity & computational load in embedded systems. (Nature)
2024	Percin et al. [72]	Whale optimization (WOA) MPPT for fuel cell	Comparative study showing WOA's effectiveness in PEMFC MPPT.	Domain-specific tuning for fuel cell dynamics required. (ScienceDirect)

4.5 Modern controlling technologies

Moreover, more 10 recent studies discussed the modern controlling strategies regarding DC-to-DC converters have been presented in Table 9.

Table 9. Modern controlling strategies review from recent studies

Year	Authors	Technique used	Scientific contributions	Limitations & gaps
2024	Farajdadian et al. [36]	Multiport DC-DC review	Survey of MPDC advances and control; identifies application trends for modern grid.	Needs hardware prototyping and standards mapping. (ScienceDirect)
2024	Waheed et al. [73]	Hybrid multimodule DC–DC with SiC/GaN	Shows multimodule benefits when using WBG devices for high switching freq & density.	Thermal/EMI and packaging for WBG at scale. (Nature)
2024	Reali et al. [43]	GaN-based 6.6 kW bidirectional OBC	Demonstrates automotive-grade GaN for compact OBC with high freq operation.	Long-term ruggedness & automotive qualification process. (MDPI)
2023	Gevorkov et al. [74]	Multiport converters for distribution review	Application-focused review for distribution and microgrid use cases.	Standards and grid code compliance discussion needed. (ScienceDirect)
2025	Ponnambalam et al. [75]	GaN converters for EV fast charging review	Survey of GaN benefits for EV fast-charging topologies & tradeoffs.	Rapidly evolving device ecosystem; supply chain & reliability open. (ScienceDirect)
2025	Ravindran et al. [76]	Wide & ultra-wide bandgap review	Technical analysis of SiC and GaN, pros/cons and reliability aspects.	UWBG (beyond SiC/GaN) manufacturing challenges. (ScienceDirect)
2024	Al-Dalawi et al. [77]	Multiport DC-DC review (MTU Journal)	Survey showing VR-BESS: multiport converter trends & benefits.	Few real-world long-duration studies. (Journal of Techniques)
2021	Mortazavizadeh et al. [78]	500 kHz GaN/SiC resonant bi-directional converter	Industry prototype for 800 V EV OBC with high frequency operation.	Proprietary design details; limited peer-reviewed validation. (Navitas Semiconductor)
2024	Energy Dept. (report) [79]	WBG strategy framework	Strategic guidance for WBG adoption and research priorities.	Policy & market adoption lagging technical potential. (The Department of Energy's Energy.gov)
2024	Sharma et al. [80]	Review of control strategies (PID, SMC, PSO-SMC, DEC, MPC, FLC, ANN, Digital Control, Boundary Control)	discusses advantages, applications, hybrid intelligent control (ANN-based) as promising approach	No experimental validation limited discussion on real-time implementation complexity (specialissue-ISET-2024/030)

Table 10 also presents summarized statistics for each category of controllers, showing the number of articles published for each category according to the year of publication.

Table 10. Article counts and publication year distribution

Controller class	Number of papers reviewed	2021	2022	2023	2024	2025
Classical	10	0	0	3	6	1
AI-Based	10	0	1	3	4	2
Insect-Based	10	1	1	2	5	1
Animal-Based	10	0	0	3	5	2
Modern techniques	10	0	0	1	6	3
Total	50	1	2	12	26	9

Through the analysis of Table 10, we can observe that research and published articles, especially in recent years, have focused on modern types of controllers, which either indicates researchers' inclination towards this category of control units or suggests their preference and suitability for modern practical applications.

Moreover, Table 11 below shows a summary of all the previous review tables, highlighting the most important applications, advantages, and limitations for each main control category.

Table 11. Summary of all the previous review tables, highlighting the most important applications, advantages, and limitations for each main control category

Control category	Key applications	Main advantages	Primary limitations
Classical Control (PID, PI, P&O, INC, deterministic linear control)	Well-controlled PV systems, DC–DC converter regulation, battery charging, steady-state energy flow	Very stable & predictable; low computational requirements; excellent maturity and reliability; easy implementation on embedded controllers	No learning or adaptively; weak performance under dynamic & nonlinear conditions; often converges to local maxima under PSC; limited flexibility
AI-Based Control (RL, DNN, LSTM, ML inference)	Intelligent converters, adaptive control under rapid irradiance/load changes, smart micro-grids, AI-augmented MPPT	Self-learning and adaptive; capable of global convergence; superior dynamic response; robust to non-linarites	Requires training data; computational complexity; potential safety issues; limited transparency/explainability; higher implementation cost
Insect-Inspired Metaheuristics (ACO, ABC, Bee-Dance, Hybrid ACO–P&O)	GMPP MPPT under partial shading (PSC), hybrid optimization in renewable systems, feature selection in energy prediction models	Strong resistance to false local peaks; good global search capability; robust to noisy conditions; flexible algorithmic structure	Algorithm parameters sensitive; slow convergence in real implementation; limited hardware validation; computational overhead in microcontrollers
Animal-Inspired Metaheuristics (PSO, WOA, BWO, MISWOA, hybrid swarm methods)	Rapid GMPP search, fuel-cell optimization, high-variability solar tracking, adaptive control in dynamic environments	Fast convergence; fewer iterations; good balance between exploration & exploitation; strong optimization outcomes in high dimension	Parameter tuning required; still computationally heavier than classical methods; stability not guaranteed; constrained by real-time system resources
Modern Technologies (GaN/SiC power electronics, high-frequency switching, multiport converters)	EV on-board charger systems, ultra-compact converters, multi-directional energy flow, high power-density systems, micro-grids	Highest operational efficiency; reduced size & weight; very high switching frequencies; industrial readiness; proven real-world deployments	Device cost; EMI/thermal management; long-term reliability still under study; integration demands advanced packaging and thermal engineering

A study of transverse control method types reveals a connection between contemporary flexibility and classic rigidity. Because of their simplicity and stability, classical controllers are perfect for low-dynamic, confined situations. Artificial intelligence algorithm-based methods and controllers, on the other hand, provide intelligent flexibility but need computational work and training. Additionally, when subjected to PSC limitations, algorithms that are modeled after the motions and behavior of insects and animals do very well at tracking GMPP states by effectively adjusting to transition between energy sources and looking for the largest peak. However, the practical implementation of embedded systems, particularly in real-time, presents a huge and fundamental barrier. Last but not least, contemporary technologies like GaN/SiC-based converters provide genuinely exceptional performance and operating efficiency, and they now represent the most viable approach for applications needing high power and variable frequency.

Thus, from the previous dense revision, we could summarize the controller’s classes and characteristics, Contributions, Limitations, and Suitability as displayed in Table 12.

Table 12. Summary of controller class characteristics, contributions, limitations, and suitability

Controller class	**Major novel contributions**	**Main limitations / gaps**	**Real-World suitability (low–high)**	**Best application area**
Classical	Stable & deterministic control; well-established converter designs; strong analytical grounding; validated hardware models	Lacks adaptivity; poor at unexpected transients; not self-learning; performance degradation under non-linear disturbances	High	Highly reliable, stable legacy systems where predictability is critical
AI-Based	Adaptive & predictive control; deep reinforcement learning; autonomously improves operation; handles complex nonlinearities	Requires training data; potential instability; heavy computational cost; embedded implementation challenges	Medium–High	Real-time optimization and fast dynamic response in smart energy systems
Insect-Inspired	Strong global search capability; robust under partial shading; high accuracy MPPT; hybrid algorithm success (e.g., ACO + P&O)	Slower convergence; parameter tuning required; limited hardware validation; inconsistent testing scenarios	Medium	PV systems under severe environmental variability & multi-peak GMPP
Animal-Inspired	Fast convergence; good global optima detection; swarm and herd intelligence; effective hybrid metaheuristics	Parameter sensitivity; computational overhead; risks of local minima; hardware scaling limitations	Medium	Fast real-time MPPT optimization in dynamic solar environments
Modern Technologies (GaN/SiC, MPDC)	Ultra-high efficiency; compact & lightweight; high-frequency switching; WBG integration; industrial adoption (EV & microgrids)	Thermal/EMI management issues; reliability testing needed; packaging challenges; cost	High	EV power electronics, grid storage, multiport converters, high-power DC infrastructure

It is evident from the examination of Table 11 that modern technology controllers (multi-port bidirectional GaN/SiC) are now the most feasible choice. This is because they have previously been included into distributed storage, high-frequency DC systems, micro-grids, and electric car chargers. In addition to generating compact designs of these technologies that are prepared for production, this kind delivers high power density, energy efficiency, and great thermal performance.

Additionally, we can observe and conclude that AI-based controllers (LSTM/RL/NN control engines) are the greatest developing and future alternative. This is because AI-based controllers outperform conventional controllers in dynamic environments and because these technologies offer real-time adaptive decision-making capabilities. Once the integrated safety and efficiency concerns and issues are resolved, AI controllers are anticipated to totally replace conventional control in the near future.

It can also be determined that using controllers based on insects and animals is the greatest option for enhancing partial wave (such as partial shading condition (PSC) and global Maximum Power Point (GMPP)). This is due to the fact that nature-inspired optimization is frequently quite effective, particularly when it comes to solving multi-peak MPPT problems in solar energy systems, particularly the difficulties posed by partial shade. In such particular circumstances, this kind of control technology works better than traditional control systems.

5. CONCLUSION

The Bidirectional DC Converter (BDC), which controls the battery charging and discharging phases to enable power flow back and forth in battery applications, is the subject of this article. The working cycle of the BDC converter regulates the battery current by considering the battery's state of charge as well as the direction of the current. Using charts, comparison tables, and researchers' contributions, this study highlights the most significant research and studies pertaining to the non-isolated BDC converter functioning in accordance with the Buck-Boost idea. This study's objectives are to give a summary of the most recent, trustworthy research on bidirectional converter control approaches, define their main uses, assess their effectiveness and advantages, and describe their disadvantages. According to this perspective, the study will assist researchers and other interested parties in bidirectional transformers in identifying gaps, characterizing the research issue, and offering recommendations for accurately selecting and creating suitable technologies while saving time and effort. The actual use of embedded systems poses a significant and fundamental challenge, especially in real-time. Finally, modern technologies such as GaN/SiC-based converters are the most practical solution for applications requiring high power and variable frequency since they provide truly remarkable performance and operational efficiency.

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