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Review

Survey of Optimization Techniques for Microgrids Using High-Efficiency Converters

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Abstract: Microgrids play a crucial role in modern energy systems by integrating diverse energy sources and enhancing grid resilience. This study addresses the optimization of microgrids through the deployment of high-efficiency converters, aiming to improve energy management and operational efficiency. This study explores the pivotal role of AC-DC and DC-DC bidirectional converters in facilitating energy conversion and management across various sources and storage systems within microgrids. Advanced control methodologies, including model-based predictive control and artificial intelligence, are analyzed for their ability to dynamically adapt to fluctuations in power generation and demand, thereby enhancing microgrid performance. The findings highlight that implementing high-efficiency converters not only enhances power stability and quality but also reduces operational costs and carbon emissions, thereby reinforcing microgrids as a sustainable and effective solution for contemporary energy management challenges. This research contributes to advancing the understanding and implementation of efficient energy systems in microgrids, promoting their widespread adoption in diverse applications.

Keywords: converters; MGs; optimization; efficiency

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1. Introduction

The integration of microgrids (MGs, see Table A1 in Appendix A) represents a pivotal advancement in modern energy systems, driven by the imperative to enhance energy efficiency, reliability, and sustainability [1,2]. While MGs have made significant strides in integrating renewable energy sources (RES) and improving grid resilience, there remains a critical gap in understanding the optimal utilization of high-efficiency converters within these systems. These converters play a crucial role in facilitating energy conversion and management across various sources such as batteries, supercapacitors, and fuel cells, yet their full potential in enhancing MG performance remains underexplored. Addressing this gap is essential as MGs continue to evolve in complexity and scale. Optimizing the deployment and operation of high-efficiency converters could significantly enhance voltage stability, frequency control, and overall grid performance, thereby maximizing energy utilization and minimizing environmental impact. By leveraging advanced converter technologies, MGs can not only bolster their resilience against fluctuating RES output but also contribute substantially to global efforts towards sustainable energy solutions. In light of these considerations, this study aims to explore the role and impact of high-efficiency converters in microgrid applications, shedding light on their potential benefits and addressing current research gaps. This research seeks to provide insights that will inform future advancements in MG technology, ultimately contributing to the broader goal of achieving efficient and sustainable energy systems.

Over time, the incorporation of advanced electronic components and smart meters has facilitated the evolution towards MGs [3]. These grids optimize system monitoring and regulation through advanced communication and automation technologies, necessary to manage the intermittency of RES. Figure 1 shows an energy system that combines renewable and non-RES with storage systems, representing an advanced MG transitioning to a sustainable system. Bidirectional AC-DC and DC-DC converters are essential for energy conversion and management between the different sources and storage systems, such as batteries, supercapacitors and fuel cells. In addition, advanced communication and automation technology is critical for monitoring and regulating the system, ensuring the stability and efficiency needed in an MG [4]. High-efficiency converters are essential in MGs, as they enable optimal energy conversion and management. They serve as electronic interfaces that enable the seamless integration of renewable and non-renewable RES. These converters are essential for tasks such as load sharing, voltage and frequency stabilization, and optimizing power flow [5]. Recent research has shown that advanced converters significantly improve voltage stability and frequency control, thus optimizing performance and reliability of MGs [6]. Among the innovations in converter technology, the modular multilevel converter stands out for its efficiency and modularity, making it ideal for applications in high-voltage transmission systems and hybrid MGs. The reduction in the number of circuit breakers reduces switching losses and improves operational efficiency [7]. In addition, the modular multilevel converter offers low harmonic distortion and improved power quality, presenting crucial benefits for MGs [6,8].

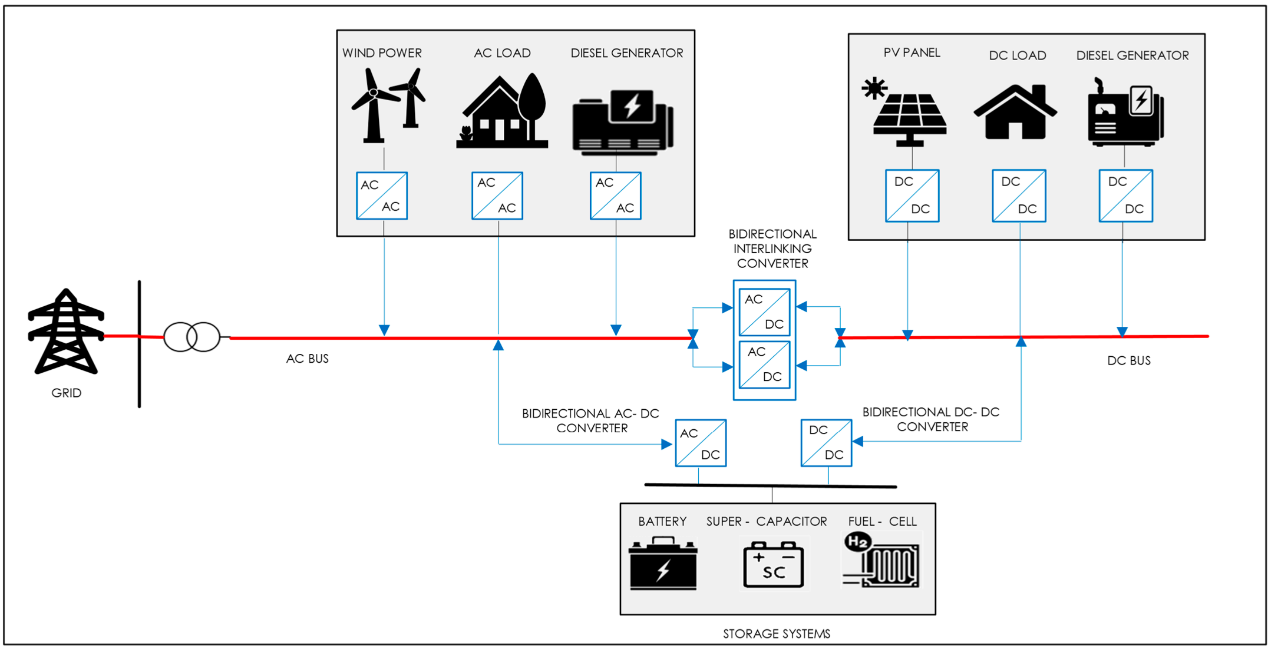

Figure 1. Hybrid MG schematic with bidirectional converters.

Predictive control has emerged as a promising technique for optimizing converter performance. This approach improves stability and efficiency in MGs and RES, outperforming traditional methods such as proportional-integral (PI) control and sliding-mode control (SMC) [9,10]. In DC-MGs, advanced predictive control strategies, such as long-horizon direct power predictive control, have been shown to reduce computational burden and improve feasibility in real-time applications [11,12]. The integration of smart converters not only facilitates the incorporation of RES, but also the active demand management and energy distribution [13]. These converters are essential for improving the efficiency and reliability of MGs, using advanced control algorithms to mitigate disturbances and ensure grid resiliency [14,15]. Accurate simulation models optimize operating parameters and evaluate the impact of converter characteristics on MG performance [16]. However, the integration of RES into the grid faces significant challenges that require appropriate regulatory frameworks for the effective adoption of advanced converters. The asynchronous connection of sources such as wind and photovoltaics presents challenges in providing essential power system services, which requires clear requirements for secure integration [17,18]. Furthermore, the commercialization of these technologies faces regulatory barriers that limit their diffusion [19]. To overcome these challenges, it is essential to establish regulatory frameworks that support the adoption of advanced converters, ensuring the efficient and safe operation of RES [20].

Real-time management of energy demand, as highlighted in several studies, underscores the importance of interlinking converters in optimizing RES and decreasing dependence on non-RES [21]. These converters improve power management and quality in hybrid AC/DC-MGs, allowing for more efficient and reliable integration of RES. In the field of energy storage systems (ESS), enhancing efficiency through advanced converters is critical and has proven effective in integrating and managing supercapacitors, significantly improving system efficiency [22]. Bidirectional DC-DC converters in hybrid battery–supercapacitor systems optimize energy management and respond quickly to fluctuating demands, essential for electric vehicles (EVs) and grids with high RES penetration [23–25]. Furthermore, future directions and challenges in the development of high-efficiency converters include improving bidirectional converter topologies and control strategies, addressing efficiency loss at light loads, and managing electromagnetic interference. The implementation of soft switching techniques, which aim to reduce losses and improve overall system efficiency, continues to be an active area of research [26].

This paper reviews in detail studies on high-efficiency converters, advanced control techniques and optimization methods applicable to MGs. It identifies the most efficient converters and the most promising control methods that improve the stability, efficiency and performance of these systems. By analyzing technological advances, this study provides a comprehensive view that guides future research and development. The relevance of this work lies in its ability to serve as a key reference in the energy field, providing a solid basis for evaluating and improving converters and control systems. This analysis is vital to further develop more efficient and sustainable energy systems, and to foster innovation in the design and implementation of converters and control techniques.

The key contributions of this study are detailed below:

- This paper compiles and analyzes the most recent and relevant studies on high-efficiency converters and advanced control techniques applicable to MGs. This analysis includes a critical evaluation of the existing literature, identifying trends and gaps in current knowledge.
- Presents and highlights converters that have demonstrated superior performance in terms of efficiency and stability. Includes a detailed comparison of different technologies and techniques, highlighting those with the greatest potential to improve MG performance.
- Advanced control techniques, such as model based predictive control and artificial intelligence, are highlighted. These technologies allow control systems to dynamically adapt to variations in energy generation and demand, improving the resilience and efficiency of MGs.
- It provides a comprehensive overview that guides the development of new research and applications in the energy field. Based on the findings of the review, specific recommendations are offered.

This paper is structured as follows: Section 2 reviews the development and advancements of high-efficiency converters in MGs, Section 3 discusses their impact on MGs, Section 4 explores the optimization of energy resources through advanced control techniques, Section 5 outlines the current challenges and future directions in this field, and finally, Section 6 presents the conclusions of the paper.

2. Development and Advances in High-Efficiency Converters for MG

The development of high-efficiency converters has been crucial for improving power conversion and management in MGs, reducing switching losses and increasing operational efficiency. The evolution of these converters has been driven by the increasing integration of distributed energy resources (DER) and the need to improve grid stability and efficiency. Initially, grid-following inverters were prevalent, but presented challenges, such as low grid inertia and the need for local voltage support, which led to the development of interconnection standards as mentioned in study [27]. Advanced converter innovation has been driven by the growth of sustainable energy sources, especially photovoltaic systems. A prominent example is the three-level converter with neutral-point locking, which improves efficiency and voltage gain [14,28]. To address stability issues due to the high penetration of power-electronics-based DERs, grid-forming control strategies have been introduced, which enable converters to provide voltage and frequency support [29]. The AC versus DC-MG debate has led to the development of versatile interconnect converters, capable of converting between DC and AC sources [30]. In addition to these advances, improved control methods for grid-connected converters have been proposed. For example, the combined control method improves the resilience of MGs and their performance [31]. Also, the adoption of digital proportional resonant current controllers based on infinite impulse response filters, together with advanced techniques such as adaptive neuro-fuzzy inference system (ANFIS) and particle swarm optimization (PSO), has optimized the inverter output and power quality in hybrid DC/AC-MGs [32].

According to the literature, the types of control detailed in Table 1, represent some of the most commonly used approaches in MG management. These approaches are crucial to ensure stability, efficiency and proper regulation. By adopting these techniques, MGs achieve superior adaptability to variations in demand and operating conditions, maintaining their performance in energy environments that demand high automation and dynamism.

Table 1. Types of control for MGs.

Ref	Control Type	Operating Principle	Advantages
[33]	Closed Loop Control with PI Controllers	Adjustment based on the difference between desired and actual states, using PI controllers for voltage and current stability.	Precise and stable adjustment, maintaining system stability.
[34]	Switching Mode Control	Control of power flow in both directions by switching switches.	High conversion gain, less stress on switches.
[35]	Linear Feedback Control	Linear feedback control to regulate voltage and currents, avoiding magnetic saturation.	Stability, robustness and prevention of damage due to magnetic saturation.
[36]	Centralized Control	Centralized algorithm to coordinate converters and manage power flow and voltage/frequency restoration.	Accuracy in power control and restoration of network parameters.
[37]	Hybrid Sliding Mode and PI control	Combination of ISM and PI controllers for voltage balancing in DC-DC converters.	Improved transient voltage balancing.
[38]	Decentralized Control	Specific techniques for handling zero sequence currents and active-reactive disturbances.	Suppression of unwanted currents and improvements in power quality.
[39]	Adaptive Admittance Control	Virtual admittance adjustment to improve voltage ripple suppression.	Improved ripple suppression and fine adjustment of the compensation current.
[40]	Distributed Cooperative Control	Cooperative control that facilitates power exchange and voltage regulation between MGs.	Allows power sharing, achieves precise voltage regulation.

These control methods, crucial to the operational efficiency of MGs, are significantly complemented by developments in power conversion technology. For example, high-gain DC-DC converters, such as the high-gain single-switch converter (HG-SIQBC), are crucial for improving voltage and efficiently integrating distributed power resources in the grid [41,42]. In addition, hybrid integration of switched capacitors and boost converters offers high voltage conversion ratios with minimum device voltage, reaching efficiencies of up to 96.1%, suitable for high power applications [43]. High-power multifunction converters facilitate power transfer between AC and DC grids, harmonizing their operation in MGs [44]. A specific example of these advances includes high-frequency isolated transformer integrated circuits, which are used in interconnecting converters to connect a three-phase AC grid to a DC-MG, improving efficiency by 3% compared to conventional circuits [45]. DC-DC converters are essential for the interconnection of photovoltaic systems and MGs, reaching efficiencies of up to 97% in the case of isolated converters [46]. Partial power processing based converters, which are modular and scalable, show maximum efficiencies of 99.36% and are particularly beneficial for all-electric marine applications [47].

The implementation of technologies such as highly efficient and reliable inverter concepts, which achieve a five-level output voltage with high efficiency and reduced leakage currents, significantly improves the power conversion efficiency in distributed generation systems [48]. In addition, the flying capacitor dual output converter in hybrid MGs allows interconnecting AC sources and loads at different amplitudes and frequencies, reducing power conversion stages and control loops [49,50]. The scientific literature provides a wide variety of high-efficiency converters, each with specific applications and benefits. For example, the Buck-Boost converter is widely used in MG applications due to its ability to operate under variable voltage conditions. This type of converter not only helps stabilize the grid, but also reduces gas emissions and improves energy efficiency in hybrid energy storage systems (HESS). The converter's features include bi-directional power flow management in HESS configurations, improving system stabilization and power quality in grid-connected environments [51]. The REDPRIME 40 kW vehicle-to-grid inverter is essential in advanced control systems. This inverter enables bi-directional energy transfer, optimizing the use of energy resources and improving grid stability. This is essential for optimal control systems that seek to reduce energy shortages. Its application is focused on MG control systems with vehicle-to-grid technology and optimization using advanced algorithms such as Support Vector Machine, Artificial Neural Network, Genetic Algorithm and Wavelet Transform [52].

The double active bridge (DAB) converter is another example of high efficiency, used primarily in DC-MG applications. This converter is crucial for voltage regulation and energy management in ESS, providing design and control guidelines that minimize harmonics and improve system stability. It is commonly used in solar photovoltaic systems interfacing with battery banks [53]. Dual active bridges with DC-DC converter are used in EV-MGs and solid-state power transmission systems. They regulate the output voltage and prevent component saturation to ensure continuous and efficient operation. These converters maintain stability in the DC-MG by regulating the output voltage and keeping the average current at zero [35]. The bidirectional DC-DC converter plays a crucial role in energy management in stand-alone MGs, enabling the efficient integration of RES and improving system resilience to load variations. This type of converter enables energy exchange between the battery and the supercapacitor, improving operational independence and maximizing the capabilities of energy storage devices [54]. High gain DC-DC converters are suitable for stand-alone photovoltaic (PV) system applications. These converters offer high voltage gain, which is beneficial for integration into distributed power generation systems. They improve conversion efficiency and power management in PV-MGs, with typical applications in stand-alone PV systems and DC applications [55].

The use of identification modules in converters improves the reliability of hybrid MGs, enabling the identification of faults and the implementation of effective protection schemes. This is essential for maintaining operational continuity and energy efficiency in hybrid MG systems. The faulty converter identification module helps to analyze and troubleshoot problems in the MG system [37]. Voltage controllers for DC-MGs are essential for the operation and stability of these systems. These controllers allow maintaining voltage and current balance, avoiding component saturation and ensuring stable and efficient operation. Intelligent switching modules control, for example, improves the

DC voltage balancing performance compared to conventional PI control [36]. On the other hand, active power filters handle reactive power without the need for a primary energy source. CUK, SEPIC and ZETA converters are used for power factor correction and discontinuous conduction, offering significant advantages in terms of efficiency and voltage regulation. These converters are essential for the stable and efficient operation of MGs with multiple power sources and are applied in RES such as solar PV, hydro and wind [56]. Three-port converters (TPCs) enable flexible power flow regulation in distributed PV power systems. These converters facilitate the integration of multiple power sources and improve conversion efficiency, which is crucial for the efficient operation of distributed PV-MGs. TPCs offer flexible power flow regulation between PV power, battery, and load/grid [57]. In distributed generation systems using grid-connected micro inverters, single-stage multimode converters are crucial. These converters significantly improve energy efficiency and reduce operating costs, facilitating more effective integration of RES into the power grid. Their design requires fewer components, allowing for a more compact size and higher efficiency [58]. According to the research [59], the partial power converter is used in battery energy storage applications in MGs. This converter regulates current to zero series voltage, which is essential for efficient and safe operation of ESS in MGs. This type of converter can achieve efficiencies up to 99.45% in experimental results. Figure 2 illustrates the efficiency of various types of converters, highlighting those with high efficiency performance, such as partial power converters.

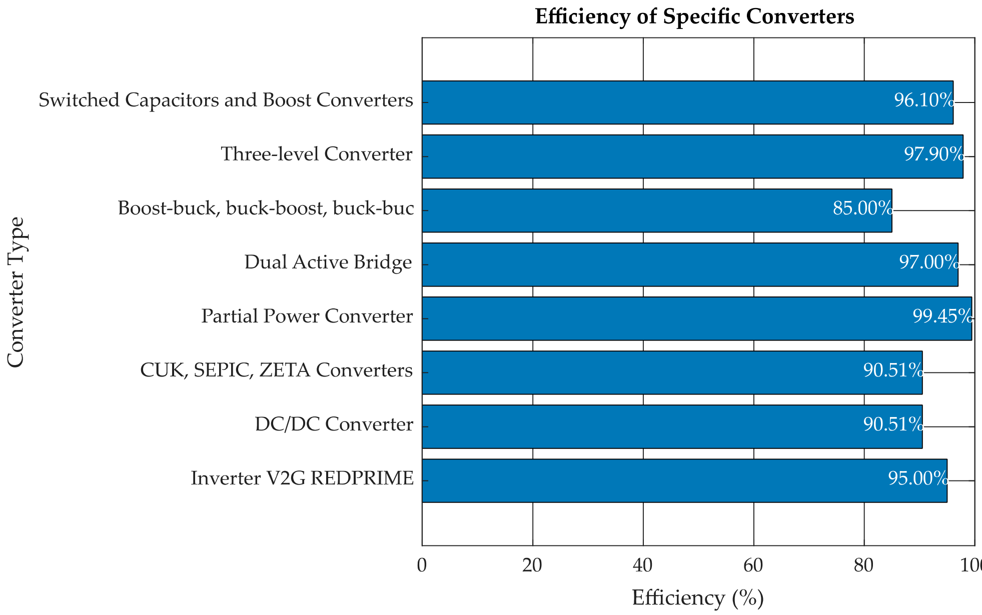

Figure 2. Efficiency of different types of converters in MGs.

On the other hand, the forward converter is used to integrate RES with ESS, enabling efficient and stable energy conversion. This type of converter is compact, cost-effective and high-powered, making it ideal for fast EV charging. It uses a high-frequency transformer for efficient energy transfer [60]. Bipolar converters are used in DC-MGs with automatic voltage balancing systems. These converters ensure high efficiency and operational stability, crucial for the integration of multiple power sources. They use full-range zero-voltage switching and automatic voltage balancing [61]. Three-port bi-directional converters are also essential for the integration of DER in MGs. They enable the efficient transfer of power between different ports, improving the flexibility and operational efficiency of MGs. These converters are particularly useful in DC-MGs with DER [62]. The hybrid converter with voltage gain is used in telecommunications, solar power and energy storage applications. This converter offers high efficiency and the ability to integrate multiple power sources, improving the operation and stability of hybrid MGs. It combines non-isolated converters for improved voltage gain and multiple outputs [63].

DC converters facilitate the integration of ESS and improve the operating efficiency of MGs. These converters ensure high efficiency and stability, which is crucial for the continuous and efficient operation of MGs with multiple power sources. Boost-buck, buck-boost and buck-boost (Vout) converters are common in these systems [64]. Multi-port converters then integrate several power sources and enable the efficient transfer of power between them. These converters are essential for residential applications and EV charging stations, improving the efficiency and operational flexibility of MGs. The authors in [65,66] analyze the control methods and topologies of DC-DC converter control in MGs. Below, Figure 3 shows a summary of the various application areas in which high-efficiency converters are used.

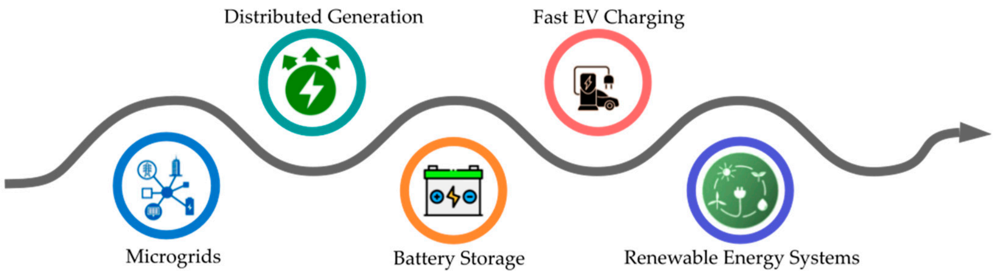

Figure 3. Use of high-efficiency converters.

3. Impact on MG Performance

The use of high-efficiency converters is vital to optimize the operation of these systems. These devices not only facilitate the integration of RES, but also improve voltage and frequency stability in MGs. The study conducted in [67] shows how advanced converters can improve control efficiency and integration into larger power systems. Similarly in [68] the authors analyze the application of advanced metering technologies and their impact on the efficiency and stability of MGs. In addition, bidirectional converters have proven to be particularly effective in managing energy storage and distribution of RES, and an improved design of these converters for MG applications, highlighting their ability to handle bidirectional power flows efficiently. This technology is essential for the integration of RES, such as solar and wind, which require flexible management of energy generation and storage [69]. The impact of advanced converters on system stability has also been the subject of study highlighting how these devices can significantly improve power quality in hybrid AC/DC-MGs, providing greater stability and reliability in system operation. These advances in converter technology not only improve energy efficiency, but also contribute to the sustainability and resilience of modern MGs [70,71].

3.1. Case Studies

The integration of advanced converters in MGs is crucial for improving RES utilization and overall system efficiency. Research papers highlight several innovative converter designs for this purpose, such as high-gain DC-DC converters for photovoltaic systems, highlighting their high efficiency of about 97.9% and their significant voltage gain of 42%, crucial for MG applications [72], high-voltage gain converters with the ability to eliminate current ripple [73] and non-isolated multiport converters for RES applications [74]. These converters play an important role in urban and rural MG environments, where RES such as photovoltaic systems and wind energy conversion systems are prevalent, as discussed in [75,76]. By employing advanced control algorithms such as fuzzy logic and artificial neural networks, these converters ensure stable DC-bus voltages, efficient power transfer, and optimal power management within MG systems, demonstrating the successful integration of RES with high-efficiency converters in various operational scenarios. In the study conducted in [68], advanced measurement and control technologies in MGs were investigated. The authors found that these technologies allow for greater accuracy in the operation of MGs, which improves both energy efficiency and system stability. This approach is particularly effective in urban environments where energy demand is high and fluctuations can be significant.

In study [70], power quality control in hybrid AC/DC-MGs was explored. Their study demonstrated that advanced converters can significantly improve power quality and system stability by addressing technical challenges such as voltage and frequency fluctuation. The methods used included literature reviews and experimental studies that provide a comprehensive understanding of the capabilities and limitations of these converters. Also in [69], investigated the design and implementation of bidirectional converters in MG applications. These converters are essential for the efficient management of RES storage and distribution. The results showed that bidirectional converters not only optimize the use of stored energy, but also facilitate the integration of RES into the grid, improving the resilience and sustainability of the system. Studies such as those presented in [5], offer a detailed review of converter control in MGs, highlighting advanced control techniques that improve system stability in various contexts. This study highlights the importance of tailoring converter technologies to the specific needs of each environment to maximize the benefits in terms of efficiency and stability. In study [77], a functional analysis of the MG concept applied to specific case studies was performed. This work focused on the practical implementation and evaluation of MGs in real environments, providing concrete examples of how MGs can improve energy efficiency and system stability in different geographic and socioeconomic contexts [78]. The use of smart inverters in MGs was analyzed in [79], demonstrating how these devices can reduce losses and improve system reliability. The study highlighted that smart inverters are crucial to maximize the efficiency of MGs by enabling more flexible and effective management of RES. The study on advanced control technologies for bidirectional converters in MGs, as discussed in [71], demonstrates that implementing these converters enhances the integration of RES by delivering improved stability and efficiency in energy management.

This approach is especially beneficial in MGs that rely on variable energy sources, such as solar and wind. In study [80], a review of distributed energy systems and MGs is conducted, identifying emerging trends and highlighting the importance of constant technology upgrades to maintain system efficiency and reliability. In addition, in [81] MG architectures were explored, describing topologies and system design that allow for greater flexibility and efficiency in energy management.

The implementation of cooperative control techniques for hybrid AC/DC converters in microgrids has proven to be an effective strategy for managing power flow and voltage regulation. These techniques, detailed in [82], where the authors use a hierarchical control system where primary and secondary controllers collaborate to maximize system performance. This methodology allows efficient integration of AC and DC sources, improving both system stability and cooperation. The effectiveness of these advanced strategies is not limited to theoretical studies but has also been validated in practical cases. A prominent example is the system implemented at the Florida Solar Energy Center (FSEC). This system, developed in collaboration with the University of Central Florida (UCF) and A.F. Mensah Inc. includes a 540 kVA three-phase two-way inverter and an energy storage system (BESS) with 1863.68 kWh lithium-ion batteries. Thanks to advanced control and integration strategies, the system was able to significantly reduce energy consumption and improve energy management. In addition, a total harmonic distortion (THD) level of only 0.07 was achieved when sending 200 kW of power to the grid [83].

In MG applications, the use of bidirectional DC-DC converters controlled by maximum power point tracking (MPPT) techniques has been shown to improve power quality and reliability, as demonstrated by Panda and Ghosh, who proposed a model predictive control (MPC) strategy to improve the performance of MG systems [83]. Moreover, the implementation of optimal power routing (OPR) schemes in hybrid AC-DC-MGs has minimized power imbalance, active power losses, and voltage deviations, as shown in the study where OPR was successfully applied in IEEE 13-bus and 34-bus test systems [84]. The use of modern optimization algorithms, such as Manta Ray Foraging Optimization (MRFO) and Marine Predators Algorithm (MPA), has further improved the performance of hybrid converters by minimizing the input current ripple and improving the power distribution, as demonstrated in [85].

In the context of MGs, the integration of RES and ESS has been optimized to achieve higher coverage factors and reduce losses. For example, a study on the power supply of an astronomical center in Chile explored the feasibility of combining solar and wind resources with a pumped hydroelectric ESS, achieving a 90% coverage factor with reduced losses [86]. In addition, optimization of bidirectional high voltage flyback DC-DC converters for capacitive actuators using an automatic winding design (AWL) technique has resulted in significant improvements in energy efficiency, as they show in study [87]. The application of the FMINCON optimization method in industrial power systems has also demonstrated the potential for minimizing generation costs and transmission losses, even when incorporating expensive RES such as wind generation [88]. In addition, the use of smart batteries and power converters at telecommunication sites has been shown to improve grid quality by compensating for harmonic and reactive currents [89]. The development of smart energy systems in urban areas, such as the district of Reininghaus in Austria, has optimized the use of local and external energy resources, resulting in financially viable and ecologically sustainable energy solutions [90]. The summary of some application cases of advanced converters in microgrids is presented below in Table 2.

Table 2. Summary of case studies of MG converters.

Ref.	Results	Methods and Applications	Challenges and Limitations	Contributions and Efficiency
[70]	Detail of advanced control techniques for bidirectional DC-DC converters in DC microgrids. Exploration of techniques such as MPC, SMC, PBC, backstepping and intelligent control.	Use of model predictive control, sliding mode control, backtracking, and more. Applications in DC-DC converters in DC microgrids, improving performance and stability.	Need for advanced technologies to improve converter performance.	Introduction of advanced strategies for converter stabilization in MGs. Significant efficiency improvement through advanced control technologies.
[71,77,81]	Power quality control in smart hybrid AC/DC microgrids. Primary and secondary control strategies for power quality compensation.	Real-time calculation methods and multi-frequency sampling. Improving cost-effectiveness and power quality in hybrid MGs.	Challenges such as low switching frequency and communication problems.	Focus on intelligent interface converters and their role in quality compensation. Improved efficiency through coordination of power converters.
[5,81]	Power electronics integrate distributed generation and MGs, improving efficiency, power quality and reducing costs.	Review of power electronics applications in systems such as wind turbines and photovoltaic systems. Functional analysis of MGs.	Problems such as harmonic injection and voltage drops. Limitations in microgrid protection systems.	Importance of static converters in improving the performance of distributed generation sources. Methodology for MG management. Significant improvements in efficiency and power quality.
[67,78,80]	Control methods for power converters in microgrids. Evaluation of control schemes such as concentrated and master–slave.	Concentrated control analysis, virtual synchronous generators, and others. Need for intelligent converters to improve power quality and stability.	Challenges due to the rapid growth of distributed energy resources.	Focus on advanced control methods to optimize energy efficiency in microgrids. Improved efficiency through advanced and predictive control schemes.

Table 2. *Cont.*

Ref.	Results	Methods and Applications	Challenges and Limitations	Contributions and Efficiency
[67,68,83]	Analysis of the functionalities of microgrids in energy management. MG functions for efficient energy management.	Functional analysis of MGs. Improvement in the efficiency of MG management.	Limitations in MG protection systems.	Methodology for microgrid management. Efficiency in MG management.

3.2. Improvements in Stability and Control

The integration of advanced control methods for voltage and frequency regulation in MGs has significantly improved system stability. These methods, which include sensorless combined control, virtual synchronous machine control, and dispatchable virtual oscillator control, address various challenges, such as unbalanced grid conditions, abrupt load changes, and short-circuit faults [91,92]. Modern feedback control methods for DC/DC converters, such as the disturbance and uncertainty estimation and attenuation framework, have shown promise in improving robustness against disturbances [93]. In addition, the stability of power-electronics-based converters, which can replace synchronous generation, has been studied using alternative configurations and linearized state space models to provide deeper insights into the network tracking control behavior in weak networks [93]. The concept of fast interacting converter driven stability was introduced to address the interactions between fast control loops and passive network elements, further improving the stability in various MG topologies [94]. Research has also highlighted the importance of taking into account the feedback between AC and DC states in network-forming converters to avoid problems such as DC-side voltage collapse during large load disturbances [92].

The implementation of high-efficiency converters has significantly improved energy efficiency and system reliability in several applications. For example, a 3 kW partial power converter prototype demonstrated a maximum efficiency of 99.36%, demonstrating its potential in all-electric marine applications [47]. Similarly, a high-speed switch-mode Z-source DC-DC converter achieved high-voltage gain and efficiency, making it suitable for grid-connected inverters [95]. In ESS, three-phase two-way DC-AC converters reduced power losses and system volume, and a 10 kW prototype validated its high efficiency and reliability [96]. The use of wide bandgap devices in power converters has also been instrumental, with a SiC-based soft-switching converter achieving a maximum efficiency of 97.3% [69]. The six-phase interleaved boost converter demonstrated an efficiency of 93.82% and 95.74% at input voltages of 20 V and 200 V, respectively, highlighting its superior performance over the existing models [97]. The integration of advanced control algorithms, such as direct nominal voltage compensation control, further improved the grid power quality and system reliability [98]. In addition, a novel arrangement of buffer circuits in a three-level converter minimized the effects of output capacitance, achieving an estimated efficiency of 99.3% [69]. Comparative analysis of multilevel OBD converters for solar applications revealed that the 2L-DAB converter, which required less chip area, achieved higher full-load efficiency compared to the machine learning (ML)-DAB. In study [72], a high power factor single-stage AC/DC single-stage converter integrating a Buck-Boost and Flyback converter achieved high power factor and efficiency with a smaller number of components. Finally, a multiport power electronic converter for hybrid renewable power generation demonstrated a system efficiency of 96.2%, with significant reductions in static level error and total harmonic distortion [69,72,75,94–96].

3.3. Energy Efficiency and System Stability

Energy efficiency and system stability in MGs are critical areas of focus due to the increasing integration of RES and power electronic devices. The stability of MGs is compromised by the interactions between fast control loops and passive grid elements, which gave rise to the concept of fast interacting converter-based stability [94]. The high penetration of RES and power electronic converters requires modeling and validation at the system level, where clustering methods and real-time simulations can be employed to ensure stability [98]. Stability limits in inverter-based MGs can be determined using generalized eigenvalues of the Laplacian matrix, which depend on the R/X ratio of the grid rather than the grid topology, allowing optimization of tilt gains to maximize stability regions [99]. Voltage and frequency deviations in isolated MGs require robust control schemes, where dynamic decouplers can significantly widen the operating window under variable frequency conditions, ensuring stability [100]. Stability issues arising from converters are due to several root causes, such as converter controls and grid robustness, so understanding these mechanisms is necessary to address the future challenges of power electronics-based grids [101]. High-order filters, essential for attenuating current harmonics in grid-connected inverters, can introduce resonances that complicate stability analyses, but the theory of sampled data control can achieve rigorous input-output stability and robust performance through sampled data control theory [102]. Critical inverter groups, identified through the weighted network admittance matrix spectrum, play an important role in system stability, as the eigenvalues indicate proximity to stability limits and guide necessary adjustments in inverter configuration [103]. Virtual synchronous generators, such as synchronverters, mimic traditional synchronous generators to maintain stability in MGs with high RES penetration, with stability mechanisms characterized by internal voltage dynamics and enhanced by auxiliary correction control loops [104]. Figure 4 illustrates how different types of advanced converters contribute to improved efficiency and stability in microgrid systems.

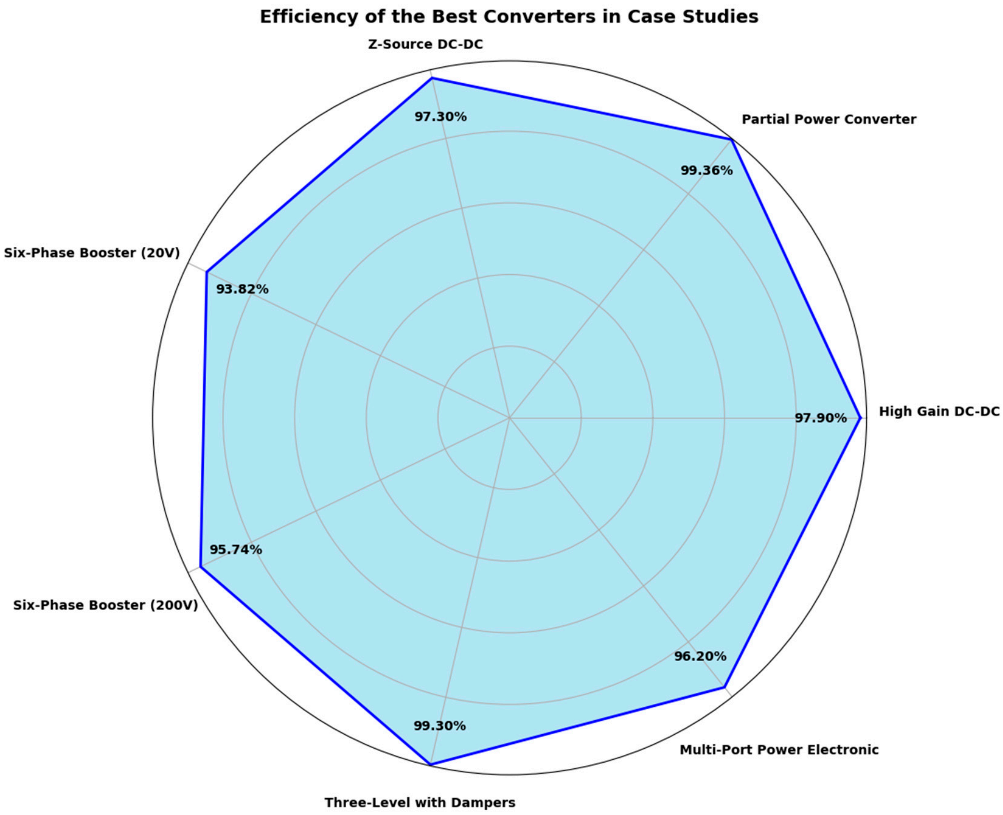

Figure 4. Efficiency of converters applied in case studies.

4. Optimization of Energy Resources

The most advanced methods for optimization include economic dispatch, stochastic programming and predictive control techniques, which allow efficient management of power generation and consumption, minimizing costs and maximizing system stability [105]. High-efficiency converters, such as bidirectional power converters, are essential in the integration of RES and in the stability of MGs. These devices improve power quality and enable precise coordination of energy resources by managing power flows in a bidirectional manner, which is crucial for the operability of MGs [106]. In addition, advanced control algorithms and techniques, such as model-based predictive control (MPC) and decentralized control, are essential for energy optimization in distributed systems. These algorithms make it possible to predict and adapt to variations in energy generation and demand, improving efficiency and reducing losses [107]. User-side demand management within a MG optimizes electricity consumption, improving efficiency, reducing costs and improving the performance of the grid [108,109]. It can therefore be said that, the integration of advanced control techniques and high-efficiency converters is essential for the optimization of energy resources in MGs, thus achieving a more sustainable and efficient electricity system.

The implementation of high-efficiency converters plays a key role in improving the overall energy efficiency of systems, particularly in MGs. These advanced converters, such as partial power processing-based converters and wide bandgap semiconductor devices, significantly optimize energy resources, resulting in significant economic and environmental benefits. For example, partial power processing-based converters, which are modular and scalable, have demonstrated peak efficiencies of up to 99.36% in offshore applications, demonstrating their potential to drastically reduce energy losses and improve system reliability [47]. The economic benefits of these high-efficiency converters are manifold. By reducing energy losses, they lower operating costs and increase the return on investment of energy systems. For example, in the iron and steel industry, incorporating productivity benefits into the economic evaluation of energy efficiency improvements can double the cost-effective potential of such investments, highlighting the significant economic advantages of adopting advanced energy efficiency technologies [110]. In addition, energy-efficient snubber circuits, which recycle switching energy instead of dissipating it as heat, further improve the overall efficiency of power converters, which contributes to reduced energy consumption and operating costs [111]. From an environmental perspective, high-efficiency converters contribute to reducing greenhouse gas emissions and other pollutants by optimizing the use of energy resources. The integration of energy-efficient technologies in buildings, for example, not only reduces energy consumption, but also plays a key role in combating energy poverty and improving living standards without compromising environmental sustainability [112]. Moreover, the adoption of energy-efficient technologies in various sectors, including health care and traditional architecture, underscores the broad applicability and environmental benefits of these advances.

Case studies from different industries and applications consistently demonstrate significant improvements in energy efficiency achieved through the use of advanced converters. For example, dynamic voltage optimization in high-temperature superconductors under varying electromagnetic conditions has yielded promising results in improving the energy efficiency of superconducting applications [112,113]. The deployment of high-efficiency converters in MGs and other energy systems offers significant economic and environmental benefits. By optimizing energy resources, these advanced technologies not only reduce operating costs and improve system reliability, but also contribute to global efforts to mitigate climate change and promote sustainable development. Consistent results from several case studies underscore the transformative potential of high-efficiency converters to improve overall energy efficiency across diverse applications [47,114].

Optimization Models

The optimization of energy systems, especially photovoltaic MGs and hybrid renewable energy systems, is crucial to improve efficiency, reduce costs and meet technical and sustainability challenges. This field has been enriched by the development of various algorithms and techno-economic models that enable more effective management of energy resources. The optimal configuration of PV-MGs has been extensively investigated. For example, the use of dynamic programming and the improved ant colony optimization algorithm (IACODP) has been shown to be highly effective in improving operational efficiency and reducing costs, achieving an increase in efficiency of 15% over traditional methods [115]. Other studies have implemented the particle swarm algorithm for optimal sizing of hybrid RES, highlighting its ability to improve both efficiency and economic viability by 20% [116]. Minimizing operating costs in MGs is also a key area. The modified frog hopping algorithm (MFLA) has been used to significantly reduce operating costs in MGs with hybrid energy resources, obtaining a 25% reduction in operating cost [117]. This method optimizes the use of energy resources, achieving a more efficient and economical management. Additionally, the use of genetic algorithms and particle swarm optimization has been effective in reducing operating costs by 18% and improving energy efficiency by 22% [118,119].

Microgrid control and management have been topics of interest, using strategies such as droop control to improve system stability and reliability, resulting in a 30% stability improvement [120]. Optimization techniques, including predictive control and robust control, have been employed to effectively manage fluctuations in power generation and demand, ensuring system stability and reducing fluctuations by 28% [106,121]. An innovative approach is the scaled arithmetic optimization algorithm with sine augmentation (SASAOA), applied in the optimization of energy systems. This method has demonstrated remarkable efficiency in solving complex optimization problems, improving the convergence and accuracy of the results by 35% [122]. Moreover, the integration of artificial intelligence and machine learning algorithms in energy management systems has improved demand prediction and optimization of system operation, increasing the accuracy of predictions by 40% [123,124]. Optimization of hybrid renewable energy systems involves the use of advanced techniques such as the particle swarm algorithm and other heuristic methods. These methods have enabled optimal sizing and efficient management of energy resources, improving both the efficiency and economic viability of the systems by 25% [125,126]. The integration of different renewable energy sources, such as solar and wind, has been optimized using stochastic programming and robust optimization techniques, increasing the reliability and flexibility in system operation by 30% [127,128].

Techno-economic models play a crucial role in the optimization of energy systems. These models allow evaluating the performance and economic viability of different system configurations, facilitating informed decision making and reducing operating costs by 15% [129]. The economic evaluation of renewable energy projects has been improved by using life cycle analysis and multiobjective optimization methods, increasing efficiency by 20% [130,131]. Energy efficiency and cost reduction are key objectives in the optimization of energy systems. Several studies have shown that the use of advanced algorithms can significantly improve operational efficiency and reduce associated costs. For example, the use of optimization techniques based on genetic algorithms and particle swarm optimization has allowed optimizing the operation of MGs, reducing energy costs by 18% and improving sustainability by 22% [132,133]. In addition, the implementation of energy storage systems has been optimized to maximize efficiency and minimize costs, using optimization algorithms and predictive models that have achieved a 20% cost reduction [134,135].

In another approach, the energy management strategy using the Bald Eagle Search (BES) optimizer for MGs with renewable energy sources and plug-in hybrid electric vehicles has been shown to be effective in reducing operating costs by 20% and mitigating pollutant emissions by 25% [136]. In addition, the application of a super-retorted sliding mode controller based on particle swarm optimization has shown promising results in energy balancing in smart MGs using dynamic pricing, achieving an operating cost reduction by 18% and improving system stability by 22% [137]. Optimization methods and techniques in the context of microgrids and renewable energy systems are diverse and advanced. The use of algorithms such as IACODP, MFLA, and SASAOA, together with control strategies and techno-economic models, has enabled significant improvements in efficiency, cost reduction and energy resource management. The integration of artificial intelligence and machine learning techniques has revolutionized energy management, providing more accurate and efficient tools for the optimization of complex systems. A summary of optimization methods and their main characteristics is presented in Figure 5.

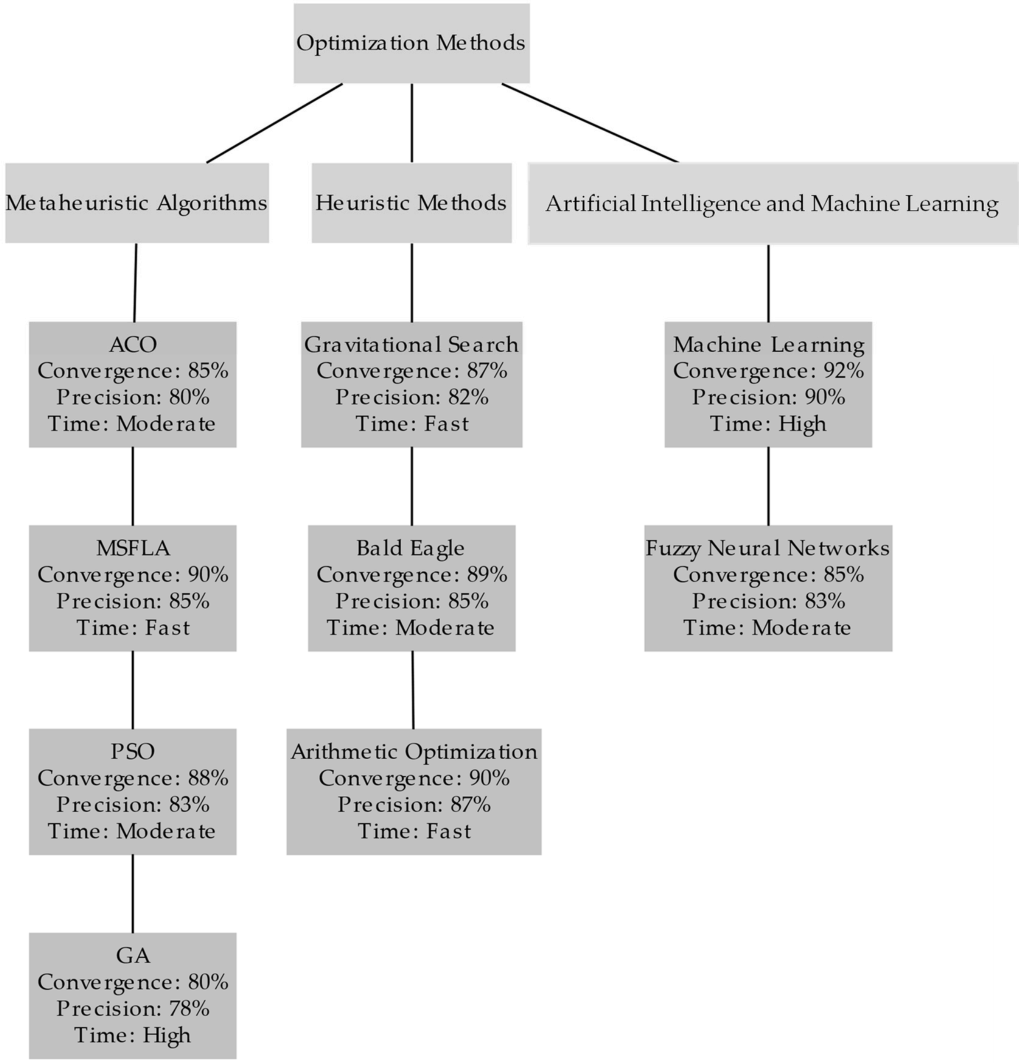

Figure 5. Optimization methods and their characteristics.

In addition, several studies have investigated the optimization of MGs to minimize electricity costs. Table 3 shows how various methods have been used to optimize generation and storage capacity, load balancing, and energy management. These approaches have achieved efficient configurations that significantly reduce operating costs and improve system performance and stability.

Table 3. Electricity cost optimization in MGs.

Ref.	Optimization Model	Function Objective	Key Variables	Restrictions	Results
			Metaheuristic		
[138]	Genetic Algorithm (GA)	Minimize Total Net Present Cost (TNP)	Sizing of solar panels, wind turbines, batteries, etc.	Generation capacity, demand, resource availability	Optimal hybrid system configuration
[139]	PSO (Particle Swarm Optimization), Cuckoo Search	Minimizes total costs	Capacity of solar panels, wind turbines, batteries, etc.	Budget, storage capacity, available resources	Optimal configurations, reduced costs and improved efficiency

Table 3. *Cont.*

Ref.	Optimization Model	Function Objective	Key Variables	Restrictions	Results
[140]	Mixing and Exploring Algorithm (MEXA)	Weighted combination of objectives (cost and efficiency)	Costs, efficiency, storage	Minimization of costs, maximization of efficiency factors	Improved efficiency and effectiveness
[141]	Optimized Beluga Whale Algorithm (Boosted WOA)	Minimize total operating costs	Battery charging/discharging operations, power management	Charging/discharging operations, energy management	Significant reduction in operating costs
			Heuristic		
[142]	Firefly Algorithm	Minimize total cost of microgrids	Storage capacity, generation costs	Load balancing, storage, network limits	Reduced costs, improved load balancing
[117]	Grasshopper Optimization Algorithm (GOA)	Minimize Total Net Present Cost	Components, demand, renewable generation	Component capacity, budget, demand	Optimal configuration, economic and environmental feasibility
[143]	Promoted Remora (PRO) Algorithm	Minimize costs of cargo operations	Generation, load, network capacity	Generation capacity, power balance	Efficiency and profitability in cargo operations
			Hybrid		
[126]	Hybrid gravitational search and pattern search algorithm (GSA-PS).	Minimize total costs	Energy management, storage, renewable generation	Optimal management of RESs, plug-in hybrid electric vehicles (PHEVs), storage, generation	Considerable reduction in generation costs
[133]	Fuzzy neural networks + Modified PSO	Minimizing the value of a multi-functional target	Generation, storage, demand	Time-dependent, adaptability, generation	Superior energy savings
[144]	Particle Swarm, Search for Harmony	Minimize total operating costs	Energy demand, renewable generation, grid capacity, etc.	Generation capacity, demand, network limits	Cost reduction, energy distribution optimization
			Analytical		
[145]	Integer Linear Programming (ILP)	Minimize total operating costs	Costs, generation, demand	Energy balance, asset operations, network capacity, etc.	Optimal asset selection, efficient dispatch
			Deep learning reinforcement		
[146]	Deep Q-Learning	Minimize electricity costs	Load capacity, quality of service requirements	Discharge capacity, waiting times, accuracy	Improved costs and response times

5. Future Perspectives

High-efficiency MG converters face several major challenges, mainly due to the complex and dynamic nature of MG systems. One of the main issues is the integration of RES, which are inherently variable and can impact the reliability of power supply. This requires robust and intelligent control systems, as well as effective energy storage solutions to maintain stable and efficient power supply [147]. The operation of hybrid AC/DC-MGs (HM) is particularly challenging due to non-convex system models, which require advanced data-driven convex models to linearize the efficiency behavior of bidirectional converters and ensure high computational efficiency [53]. Future prospects for high-efficiency converters include the design of a PI controller optimized for fast reference tracking, the implementation of a SEPIC converter, and the future extension of the project work with a type-3 controller and a P&O-based MPPT algorithm [148]. These converters are incorporated into a DC-MG, showing different modes of operation of the MG. High-efficiency converters, such as those mentioned above, play a crucial role in improving the power permanence and efficiency in MGs.

Reactive power compensation, key devices include the static synchronous compensator (STATCOM), the distribution static compensator (DSTATCOM), the custom power devices (CPD), the unified power quality conditioner (UPQC) and the unified power flow controller (UPFC). These devices provide or absorb reactive power to maintain the stability of the power system and improve power quality [149]. The CPDs are especially useful for addressing specific power quality problems, while the UPQC combines active and reactive power correction functions. Optimization of MGs is crucial for improving energy efficiency and energy management. Hybridization of optimization algorithms presents a promising avenue for future research. As MGs involve multiple power sources, loads, and storage systems with different operational constraints, hybridization of multiple algorithms can provide more efficient solutions. In addition, the development of distributed optimization algorithms can increase the flexibility and resilience of MG systems, reducing the risk of failures [150].

Future prospects also include evaluating the effects of different operating parameters on fuel cell performance and the recovery and utilization of the heat generated by these cells. The exergoeconomic analysis and multiobjective algorithms are essential to determine the most efficient and cost-effective system with lower emissions [151]. With respect to protection, the development of adaptive and robust schemes is essential to address the unique characteristics of DCMGs, such as bidirectional current flow and the absence of phasor parameters. Further, ML-based predictive maintenance techniques are crucial to improve the accuracy of equipment monitoring, real-time fault detection and diagnosis, and to contribute to the efficiency and reliability of MGs [152]. In addition, the development of adaptive and robust schemes is crucial to address the unique characteristics of DCMGs, such as bidirectional current flow and the absence of phasor parameters [153]. Implementing ML can increase reliability and reduce operating costs of MGs, consolidating their role as a sustainable and efficient solution for energy management. Table 4 provides an overview of future perspectives and challenges in advancing high-efficiency converters for MGs, highlighting the evolving landscape and critical areas for improvement.

Table 4. Future perspectives in high-efficiency converters for MGs.

Ref.	Future Perspectives	Experimental Prototypes and Challenges
[116]	Future extension with type-3 controller and P&O-based MPPT algorithm in DC MGs.	High-efficiency converters in DC MG operations.
[117]	Reactive power compensation using STATCOM, DSTATCOM, CPD, UPQC, and UPFC devices for power system stability and quality.	Application CPDs in power quality improvements.
[118]	Optimization of MGs through hybridization of optimization algorithms and development of distributed algorithms.	Hybridization of multiple optimization algorithms for efficient MG operation.
[119]	Evaluation of fuel cell performance and utilization of generated heat through exergoeconomic analysis and multiobjective algorithms.	Exergoeconomic analysis for efficient and cost-effective MG systems.
[120]	Implementation of ML for predictive maintenance and fault detection in MGs.	ML-based predictive maintenance techniques for improved reliability and efficiency.

6. Conclusions

This review study underscores the critical importance of high-efficiency converters in MGs, essential for the optimal integration of renewable sources such as solar panels and wind turbines. Leveraging advanced semiconductors like GaN, these converters not only effectively manage variable power flows but also enhance system reliability by significantly reducing energy losses. Significant advancements include the application of advanced control strategies such as MPC and SMC, which improve power quality and stability in MGs. Devices like STATCOM and UPQC play a crucial role in reactive power compensation, ensuring grid stability amidst dynamic fluctuations. Hybridization of optimization algorithms and exergoeconomic analysis in fuel cell systems are pivotal for maximizing energy efficiency and minimizing emissions in MGs. These advanced approaches, supported by AI-based predictive maintenance techniques, enhance operational reliability and optimize costs associated with MG maintenance and operation. In summary, this review highlights how technological advancements in high-efficiency converters and energy management systems are paving the way for more efficient, sustainable, and resilient MGs. These developments are crucial in addressing dynamic challenges associated with RES integration and continuous optimization of energy resources in MG environments.

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Appendix A

Table A1. Abbreviations and Their Meanings.

Abbreviation	Meaning	Abbreviation	Meaning
AC	Alternating Current	ILC	Interlinking Converters
Ant Colony Algorithm	Ant Colony Algorithm	IoT	Internet of Things
APF	Active Power Filter	ISM	Sliding Mode Control
AWL	Automatic Winding Layout	KVA	Kilovolt-Ampere
BDC	Bidirectional Converter	MEXA	Mixing and Exploring Algorithm
BESS	Battery Energy Storage System	MFLA	Modified Frog Leaping Algorithm
Boosted WOA	Boosted Whale Optimization Algorithm	ML	Machine Learning
Search for Harmony	Harmony Search	MMC	Modular Multilevel Converter
CPD	Custom Power Devices	MPC	Model Predictive Control
Cuckoo Search	Cuckoo Search	MPIBC	Multiphasic Interleaved Boost Converter
DC	Direct Current	MPA	Marine Predators Algorithm

Table A1. *Cont.*

Abbreviation	Meaning	Abbreviation	Meaning
DER	Distributed Energy Resources	MRFO	Manta Ray Foraging Optimization
DPMPC	Direct Power Model Predictive Control	OPR	Optimal Power Routing
DSTATCOM	Distribution Static Compensator	P&O	Perturb and Observe
DUEA	Disturbance and Uncertainty Estimation and Attenuation	PI	Proportional-Integral
EV	Electric Vehicle	PRO	Promoted Remora Algorithm
ESS	Energy Storage System	PR	Proportional Resonant Controllers
FCDO	Flying Capacitor Dual Output	PSO	Particle Swarm Optimization
FICDS	Fast Interaction Converter-Driven Stability	PV	Photovoltaic
Firefly Algorithm	Firefly Algorithm	SASAOA	Scaled Arithmetic Optimization Algorithm with Sine Augmentation
FSEC	Florida Solar Energy Center	SEPIC	Single-Ended Primary Inductor Converter
Fuzzy Neural Networks + Modified PSO	Fuzzy Neural Networks + Modified PSO	SiC	Silicon Carbide
GA	Genetic Algorithm	SMC	Sliding Mode Control
GaN	Gallium Nitride	SPV	Solar Photovoltaic Systems
GFM	Grid-Forming	SST	Solid-State Transformers
GFL	Grid-Following	STATCOM	Static Synchronous Compensator
GOA	Grasshopper Optimization Algorithm	THD	Total Harmonic Distortion
GSA-PS	Gravitational Search Algorithm and Pattern Search Hybrid Algorithm	TPC	Three-Port Converters
HESS	Hybrid Energy Storage System	UCF	University of Central Florida
HG-SIQBC	High Gain Single-Inductor Quadratic Boost Converter	UPFC	Unified Power Flow Controller
HM	Hybrid Micrograds	UPQC	Unified Power Quality Conditioner
HVDC	High Voltage Direct Current	V2G	Vehicle to Grid
IACODP	Improved Ant Colony Optimization with Dynamic Programming	VSG	Virtual Synchronous Generators
IIR	Infinite Impulse Response	WBG	Wide Bandgap Devices
ILP	Integer Linear Programming	WT	Wavelet Transform

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