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Review

Nanogrids in Modern Power Systems: A Comprehensive Review

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Highlights:

What are the main findings?

- Recent advancements in nanogrid architecture, control, energy management, and applications.
- The advantages and disadvantages of the existing and proposed nanogrid realizations.

What is the implication of the main finding?

- There is room for improving the efficiency and reliability of the energy supply, reducing the cost of energy for prosumers, and prolonging the lifetime of assets through advancing architecture and the management of individual nanogrids and coordinated operation of clusters of nanogrids.

Abstract: Nanogrids are becoming an essential part of modern home power systems, offering sustainable solutions for residential areas. These medium-to-low voltage, small-scale grids, operating at medium-to-low voltage, enable the integration of distributed energy resources such as wind turbines, solar photovoltaics, and battery energy storage systems. However, ensuring power quality, stability, and effective energy management remains a challenge due to the variability of renewable energy sources and evolving customer demands, including the increasing charging load of electric vehicles. This paper reviews the current research on nanogrid architecture, functionality in low-voltage distribution systems, energy management, and control systems. It also explores power-sharing strategies among nanogrids within a microgrid framework, focusing on their potential for supplying off-grid areas. Additionally, the application of blockchain technology in providing secure and decentralized energy trading transactions is explored. Potential challenges in future developments of nanogrids are also discussed.

Keywords: nanogrids; microgrids; peer-to-peer power sharing; energy management system; power electronic converters; blockchain

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1. Introduction

The global shift towards sustainable energy is becoming increasingly prominent, as renewable energy sources (RESs) such as wind, solar, and hydro continue to play a growing role in the energy mix. This transition is critical for reaching the net-zero emissions (NZE) target, mitigating climate change, and fostering a more sustainable and resilient power grid. In 2023, renewable energy sources accounted for over 30% of global electricity generation, and this share is expected to grow due to supportive policies and declining technology costs [1]. For instance, Canada's achievement of a 31% reduction in greenhouse gas (GHG) emissions from electricity generation since 2010 is largely attributed to the adoption of RESs like wind and solar [2]. Prosumers have played a key role in the development and widespread adoption of these cost-effective renewable sources. Nevertheless, fossil fuel-based electricity generation, a significant contributor to GHG emissions, accounted for about 58.5% of the world's electricity production in 2023 [1], and the continual depletion of fossil fuel reserves continues to increase non-renewable energy costs. Moreover, government initiatives, such as the NZE target by 2050, and investments in electric vehicle (EV) charging infrastructure, reported at 18.6 million CAD in Canada in 2024 [3], highlight the need for advanced grid systems.

The rising integration of RESs, coupled with advancements in energy storage systems (ESSs), has introduced new challenges to the conventional grid. RESs are intermittent, weather-dependent, and distributed, which causes fluctuations in power production, complicating voltage regulation, and demand-response management [4]. Additionally, the replacement of conventional power stations with RESs reduces synchronous inertia in the grid. Synchronous inertia, inherently provided by conventional generators, acts as a natural buffer against sudden frequency changes. The absence of this inertia in inverter-based RESs makes the grid more susceptible to rapid frequency deviations, increasing the risk of instability and requiring advanced control strategies or synthetic inertia solutions to maintain system stability during disturbances [5].

These challenges are further exacerbated by the growing adoption of EVs, representing over 8% of all vehicles in Canada in 2022. The stochastic charging load of EVs adds uncertainty to the grid operation. Integrating ESSs mitigates part of these issues by charging/discharging the storage devices during periods of excess/deficit in power. Integrating RESs and ESSs into smart distribution grids like microgrids (MGs), nanogrids (NGs), and virtual power plants (VPPs) helps mitigate the impact of intermittency and variability of RESs and protect the grid while enhancing its flexibility and resilience [6]. These smart grid technologies are essential in maintaining grid stability, reducing dependence on fossil fuels, and transitioning to a more sustainable energy future.

VPPs bring together a variety of energy assets, such as solar panels, wind turbines, batteries, and demand response systems into a unified, cloud-based network across multiple locations to optimize power generation, storage, and consumption. MGs and NGs, which are smaller-scale power grids, operate in both islanded and grid-connected modes, integrating distributed generators (DGs) and ESSs to ensure reliable local power supply. While MGs are designed for larger-scale DGs in medium voltage (MV) and low voltage (LV) networks, NGs are more compact, with capacities up to 20 kW, making them well-suited for individual homes or small clusters of buildings [4,6].

NGs have a modular design and easier control structures, which make them especially useful for residential applications. The residential sector accounted for 25% of the world's electricity demand in 2024, making it the second-largest user after the industrial sector [1]. Additionally, trends like the construction of new buildings, renovation of existing ones, and growing popularity of EV charging at home, all contribute to this demand emphasizing how vital it is for the residential sector to be self-sufficient by employing NGs. Even though MGs and NGs have similarities in terms of structure and control and a rich literature exists for MGs [7–9], dedicated studies on NGs are necessary because of their adaptability for smaller-scale applications, the rising energy demands in households, and their potential benefit for development in remote communities [4]. Recent studies on NGs cover a wide range of aspects including control and communications [7,10,11], interfacing converters [12,13], and NG structure [14]. This paper focuses on residential-scale NGs, explores the features that make them a suitable option for LV distribution systems, details their specifications, and examines their applications in distribution-level scenarios.

NGs can be either AC or DC, with DC nanogrids (DCNGs) making an ideal option for integrating renewable sources with DC interfaces. Due to their high reliability and efficiency, DCNGs are expected to play a significant role in future smart homes [15]. However, the current dependence on the AC grid makes a rapid transition to DCNGs challenging [16]. This shift involves regulatory requirements, financial costs, and safety concerns. Hybrid NGs offer a preferred solution by combining AC and DC NGs, accommodating sources and loads with both AC and DC interfaces within homes. Still, challenges related to control, metering, energy management, communication, and protection must be addressed to make hybrid NGs practical.

NGs employ power electronic converters to integrate local loads, RESs and ESSs within the NG, and link NGs to a higher-level grid (e.g., an MG). Within an AC nanogrid (ACNG), distributed energy resources (DERs) featuring a DC interface, such as PV panels and batteries, connect to the AC bus through single-stage or two-stage DC/AC converters, whereas AC/DC/AC converters are used to connect DERs with AC interfaces to the AC bus. Within a DCNG, DC/DC converters connect DERs with DC interfaces to the DC bus, while single-stage or two-stage AC/DC converters are used to connect DERs with AC interfaces to the DC bus. Converters connecting RESs and loads are unidirectional, whereas those interfacing ESSs are bidirectional. Converters interfacing the DC and AC buses of DC and AC nanogrids to the higher-level grid may be bidirectional as well. With advancements in EV charger technology, electric vehicles' battery packs can participate in bidirectional power exchange, i.e., delivering power to the grid or house (vehicle to grid (V2G) or vehicle to house (V2H), generally known as V2X), and absorbing power from the grid (G2V). To enable these transactions, EVs must be connected to the NG's bus via bidirectional converters.

A hierarchical control strategy is commonly employed in both MGs and NGs. This strategy is composed of three layers: primary, secondary, and tertiary. The primary layer is responsible for real-time power management and local control of converters. This layer operates at the shortest timescale (milliseconds-seconds) reacting to changes in load demand and generation, ensuring balance by local control of the power processed by the converters [17]. The secondary layer is tasked with system-wide voltage and frequency regulation. It works over a longer timescale (seconds-minutes), taking care of imbalances within NG and setpoints for local controllers. The tertiary layer oversees the power exchanges between the NG and the higher-level grid, with the goal of minimizing energy costs and improving overall system efficiency. It enables power-sharing among NGs and helps NGs function as self-sustained units within a larger grid infrastructure [17–20]. In conjunction with hierarchical control, energy management systems (EMSs) are essential for coordinating the operation of RESs, ESSs, and controllable loads within NGs. EMSs employ real-time monitoring, rule-based decision-making, and optimization methods to ensure efficient power flow, reduce energy costs, and improve the lifespan of energy storage devices [20]. DC bus signaling (DBS), implemented at the secondary control layer, facilitates efficient voltage regulation and power dispatch. DBS ensures seamless integration of units with both DC and AC interfaces within the NG, optimizing the operation of components [19]. Moreover, power line communication (PLC) serves as a vital communication method within NGs. PLC ensures reliable data exchange and coordinates control strategies between various NG components, enhancing the overall connectivity and management of power and energy flow in real time [17].

As more PV systems are installed in NGs, the power imbalance between consumption and local generation will affect higher-level grid stability. As a solution, policies developed by the governments allow local distribution companies to purchase excess energy from prosumers and provide compensation [21]. As another solution, peer-to-peer (P2P) energy trading in a microgrid of NGs, supports localized transactions, balancing local generation with demand [22,23], reducing transmission losses, offering premiums for excess energy [22–24], and facilitating the provision of energy access to remote and off-grid communities [14]. Advances in blockchain technology and the Internet of Things (IoT) further facilitate P2P energy trading by enabling direct transactions without intermediaries, simplifying processes, and reducing administrative costs [25]. Energy trading can occur behind the meter (BTM), enabling direct transactions and exchanges among participants without involving third parties, thereby maximizing the localization of power generation within a specific geographical area [26]. Engaging in a P2P power-sharing system enables NGs to bolster their sustainability. However, power sharing among peers may encompass losses originating from power electronic converters. Additionally, distribution losses, influenced by factors such as the distance between peers and the voltage range, contribute to higher overall power dissipation. Furthermore, node voltage escalation emerges as another constraint associated with power sharing [27].

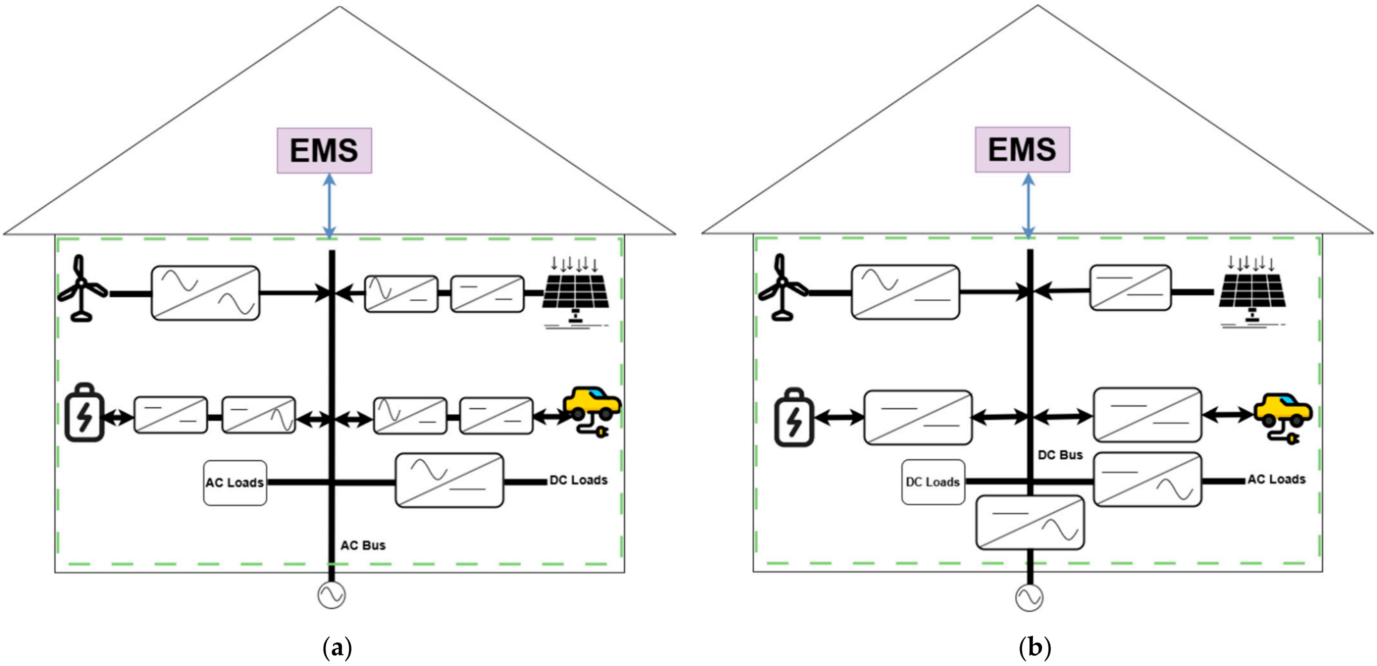
The rest of this paper is organized as follows. Section 2 offers a comprehensive review of NGs and their impacts on the LV distribution system, emphasizing the distinctions between DC and AC nanogrids, and exploring recent progress in NG research. In Section 3, various types of power electronic converters employed in NGs to link RESs and ESSs to the loads and connect NGs to the higher-level grid, are reviewed. Section 4 is dedicated to elucidating common control methods employed in NGs and delving into energy management strategies to efficiently dispatch power. In Section 5, the features of power sharing among NGs, common communication techniques, and some relevant projects are reviewed. Section 6 discusses potential challenges caused by developing NGs in the power grid. Finally, Section 7 provides a summary and draws some conclusions.

2. Nanogrids

Developing a modern power system, that incorporates ESSs and stochastic RESs and loads into the grid, with enhanced reliability and efficiency, necessitates a hierarchical power distribution structure. This is achieved through the introduction of MGs and NGs as subsystems of the smart grid [6]. NGs are typically assigned to single houses and buildings, and the grouping of NGs forms an MG. NGs are connected bi-directionally to a higher-level power system, which could be an MG, other NGs, or the main grid. While MGs cater to broader geographical areas, NGs are smaller in scale (10–20 kW) and serve localized communities and loads [14]. Operating in grid-connected or islanded mode, they offer a decentralized solution for enhanced energy management. The applications of NGs span from residential neighborhoods to industrial complexes, where their nimble structure facilitates optimized energy consumption, load balancing, and integration of renewable energy resources, leading towards both net-zero emissions and minimum electricity cost. Structurally, a typical NG encompasses a limited number of energy sources (such as RESs), local loads, battery energy storage systems (BESSs), and, in recent applications, the stochastic load of EVs.

2.1. Nanogrid Configurations

From a structural point of view, MGs and NGs can be of AC (Figure 1a), DC (Figure 1b), or hybrid type. Within a DCNG, one stage of the DC-DC or AC-DC converter connects DERs and loads to the DC bus. On the contrary, in ACNGs, each source/ load, with a DC interface, is connected through a DC-DC converter and a DC-AC converter to the AC bus, resulting in more conversion stages compared to the case where the connection was made to the DC bus of a DCNG [28–30].



(**a**) (**b**)

Figure 1. Typical structures of household nanogrids: (**a**) AC nanogrid, (**b**) DC nanogrid.

From a protection viewpoint, the main protection in an ACNG is overcurrent protection that is implemented by a central circuit breaker for all connected loads, with a current rating of five times that of the electrical wiring [15]. In contrast, in DCNGs, overcurrent protection can be carried out by power converters through current limiting. However, relying solely on converters for protection is insufficient, particularly in cases of short circuits within the converter itself. To address such scenarios, additional measures like fast-acting fuses, fault diagnosis algorithms based on switch control signals and inductor current slope, and fault-tolerant techniques based on bypassing the faulty module and incorporating redundancy in the converter structure are employed. These strategies ensure robust and reliable protection in DCNGs [31].

All in all, due to the lower number of conversion stages, DCNGs have higher overall efficiency and lower cost. Importantly, the control and energy management of a DC system is easier, and the connection of all sources, loads, and batteries to a common DC bus through power electronic converters gives the NG under decentralized control a simpler plug-and-play feature [28,29]. Also, DCNGs do not need frequency or phase synchronization and are simpler and more secure, gaining lower electricity costs for the system [29,32]. Hybrid NGs combine the features of DCNGs and ACNGs, allowing for the connection of DC loads and renewable sources with the DC interface to the DC bus, as well as AC loads and sources with the AC interface to the AC bus. As a result, the system's complexity and cost will decrease, and the number of conversion stages will be kept to a minimum, improving efficiency and allowing for optimal sizing of RESs and ESSs [29].

2.2. Nanogrid Projects Overview

NGs can operate in stand-alone mode, making them appropriate for off-grid areas, black-out periods, and regions with high electricity prices. By incorporating RESs and ESSs at the residential level, NGs can supply the demand, and store excess energy for later use. This capability allows NGs to adopt a bottom-up approach [6], supporting local energy needs independently. A bottom-up structure proposed in [6] showcases how isolated networks of NGs can form an open-energy system (OES). Within this setup, DCNGs equipped with PV and battery can not only supply their own loads but also share surplus energy with other NGs through a DC bus. This design enhances system resilience, ensures energy autonomy, and enables scalability to larger communities without relying on the main grid. The energy management for such NGs employs a multi-layer control strategy, where each NG independently manages its power balance while simultaneously interacting with a higher-level EMS to facilitate energy exchanges with other NGs in the community. This ensures optimal energy distribution, improved resilience, and adaptability to changing energy demands.

In Bangladesh, a group of islanded DCNGs based on centralized PV systems support both residential electricity consumption for about 10 houses and irrigation pumping [33]. The findings indicate that with a high rate of solar irradiation during the dry season, the PV system alone, and without requiring battery storage, can adequately meet both household energy needs and irrigation demands in the daytime, while the system allows for powering other devices, such as computers and phones. The surplus energy from the PV system will be used to charge the battery, which can then be used to meet household demand at night. Moreover, the NG setup solution has proved to be more cost-effective than the traditional diesel-based systems, with a cost reduction of 46% for the irrigation energy.

Implementing NGs involves a high initial cost; however, the investment can be recovered over time through local energy generation, leading to a reduction in overall energy cost. The Millvale Moose NG project in a flood-prone community [34], with an initial cost of 195,000 CAD for the entire MG, demonstrates the potential for solar-powered nanogrids to achieve energy independence while significantly reducing carbon footprints. The project study results show that 95.2% of the building's electricity demand is met by local renewable sources, with an average cost of 11 cents/kWh over the 25-year lifetime of the DCNG, effectively offsetting the initial investment. Additionally, the system achieves net annual carbon emissions of approximately −11,382 kg by reducing fossil-fuel-based energy usage and selling solar energy, outperforming net-zero carbon emissions and showcasing the environmental benefits of NG implementations. Still, in some areas that are heavily dependent on the main grid, it is not feasible to quickly update the current infrastructure to match the evolving DCNG developments.

As a new development in DC microgrids (DCMGs), applicable in NGs as well, and a viable solution for DC community grids, the low-voltage bipolar DCMGs [35,36] can provide the desired AC or DC voltages through three lines, allowing connection to a wider variety of loads, enhancing the reliability of the system in case of blackouts or faults. However, in DC bipolar structures, maintaining the balance of voltage between the positive and negative poles is a significant challenge. Voltage imbalance arises when loads with varying power levels are unevenly distributed across the poles. This issue is further exacerbated when DGs, such as solar panels and wind turbines, are connected to only one pole, causing unequal power distribution. The resulting imbalance can lead to deviations in pole voltage levels, which increases the stress on system components, reduces their lifespan, and degrades power quality. Sensitive loads may experience adverse effects due to voltage fluctuations, and overall system losses may increase. Additionally, unbalanced loading can destabilize the DC bus voltage. To address these challenges, power electronic converters designed for voltage balancing are commonly employed to effectively mitigate the issue and ensure stable system operation.

The energy control center (ECC), a two-stage NG configuration proposed in [37], is designed to limit short circuit currents on the DC side and manage power flow and balance within the system. Reducing the size of the DC-link capacitor decreases the amount of energy that can be discharged during a fault, protecting power electronic components from excessive fault currents and allowing a faster dynamic response to changes in load or generation. However, reducing the capacitor size also diminishes its energy-buffering capability, which increases voltage ripple across the DC link and causes significant voltage oscillations. These fluctuations result in higher switching and thermal losses in power electronic converters, ultimately reducing the overall efficiency and stability of the configuration [37]. Additionally, a DC-DC converter stage is required to ensure a safe voltage level when connecting loads with various voltage levels, such as computers and TVs with a 48V requirement.

A hybrid AC-DC nanogrid, with a three-port structure, to link the grid, PV, and ultracapacitor inside an NG is proposed in [38]. The model equipped with a three-layer hierarchical controller can function well in both islanded and grid-tied modes. The high-voltage DC bus is connected to the low-voltage ultracapacitor via a bidirectional interleaved boost converter with coupled inductors, which creates galvanic isolation between the two sides. However, this topology leads to higher cost and complexity when compared with its capable counterpart, the dual active bridge (DAB) converter. Additionally, since the PV is linked to the high-voltage DC side without isolation, its parasitic capacitor's effect on the DC bus leads to an impact on the voltage, power regulation, and stability of the DC bus and AC power quality.

A proposed NG with smart critical load (SCL) coupled to the AC bus supplied by a solid-state transformer (SST) in the home is introduced in [39]. NGs are low inertia systems; therefore, in the events of sudden load shift, islanding, or PV power fluctuation, NGs are more likely to see variations in voltage and power. These occurrences could affect not just the building but also the NG-based MG's power quality and stability. While SST controls the LVAC bus and decouples the MV and LV networks, the SCL is connected to an electrical damper via an inverter. Nevertheless, by managing the real-time load power and voltage variations and providing acceptable AC bus power quality, the battery lifespan is extended. Since the SST used has an AC-AC structure, the AC bus that enters the house from the SST needs an additional power electronic converter to provide DC voltage levels. Moreover, adding additional loads, like batteries and electric vehicles, increases the system's size and control complexity.

Table 1 gives an overview of selected existing NG projects deployed worldwide.

Table 1. Overview of selected nanogrid projects.

Project Location	Project Features
Aalborg University, Denmark [22]	• countryside-scale islanded MGs, including a cluster of NGs • scalable configuration • decentralized control • capable of power sharing among NGs
Indonesia [40]	• integrating AC and DC sources • providing power by NGs during blackout • smart switching between power sources
Kyushu, Japan [6]	• multi-level open energy system • modular/expandable, bottom-up approach • no central control • loss management towards an efficient and robust system • power sharing among NGs
Nigeria (case study) [41]	• off-grid area • solar-based NGs, with battery bank • capacity enhancement financially feasible • power-sharing possibility

Table 1. *Cont.*

Project Location	Project Features
Perris, California [42]	• targeting 37 households as NGs • backup power provided by community center ESS • large scale battery-based ESS • 5 kW solar panel and 40kWh battery for each house • cost-effective; revenue generation by energy management
Hawaii [42]	• increases utilization of solar panels • replacing the current smart meter, electricity panel, and load panel with a new controller • intelligent system triggered by failures and price changes
California [42]	• combines PV-powered NGs with fuel cell • net-zero carbon system • enhanced robustness due to fuel cell–solar energy combination
Virginia Tech's Centre for Power Electronics Systems (CPES), USA [43]	• DCNG testbed of residential scale (380V, 10kW) • includes solar panel, wind turbine, and battery • addresses challenges in the design of DCNGs • distributed droop control technique • electricity bill reduction through energy management
Keating NG, Illinois institute of technology, USA [44]	• hybrid AC/DC NG • AC MG as a higher-level network • discrete PV installations linked to the AC and DC subsystems (48V, DC, and 120V, AC) • power sharing among NGs and MG • isolated NG operation in emergencies/MG faults

3. Power Electronics Converters

Power electronic converters, as crucial components in NGs, are responsible for power conversion and voltage step-up/step-down, to accommodate the connection of sources, loads, and grids. These converters can contribute significantly to bidirectional energy management within households, facilitate fault detection and isolation, and offer advantages such as enhanced system efficiency, reduced energy costs, and improved communications [30,45]. This section presents an overview of the power electronic converters employed in NGs. Advances in semiconductor device technology in the last decade, particularly the development of 10kV SiC MOSFETs, have created opportunities for the connection of the MV utility grid to the LV system through power electronic converters [46,47].

The connection of the utility grid to the DCNGs or hybrid NGs takes place through a rectifier, which can be an active rectifier. Active rectifiers can maintain a high power factor through the generation of sinusoidal AC-side currents. They enhance system efficiency, aid in DC voltage regulation, and enable bidirectional power flow.

In [48], a two-level Voltage source converter (VSC) with a grounding inductor is proposed as a rectifier for bipolar DC microgrids. This approach is claimed to effectively mitigate voltage imbalances within bipolar DC systems by introducing a DC current to the neutral point on the DC side. In comparison to similar topologies designed for bipolar DC distribution systems, the VSC proposed in [48] offers the advantage of a streamlined configuration with fewer power electronic components. However, it is essential to note that the use of a magnetic core, adopted to address saturation concerns, may contribute to increased magnetic losses [48,49]. Figure 2a illustrates this VSC converter.

Another prevalent type of rectifier, shown in Figure 2b, is the neutral point clamped (NPC) converter. The NPC, characterized by clamping diodes, is a multi-level converter that proves to be a suitable choice for MV and LV applications [17,49,50].

A dual buck-boost AC/DC converter, introduced in [51], offers bidirectional power flow with a bipolar output voltage. The incorporation of united grounding for the DCNG, coupled with the introduced converter as depicted in Figure 2c, enhances safety, and enables the connection of NG to various common low-voltage AC systems, thereby providing flexibility in DCNG connectivity. Illustrated in Figure 2d, the single-phase power factor correction (PFC) AC/DC converter proposed in [46] is characterized as a full-bridge converter with an additional LC circuit operating under integrated triangular current mode (iTCM) control. Key attributes of this converter include mitigation of switching losses through implementation of zero voltage switching (ZVS), capability of bidirectional power flow, and improved efficiency achieved by segregating paths for high-frequency (HF) and low-frequency (LF) triangular current mode (TCM) currents. While these features make the mentioned converter a suitable candidate for MV applications, such as SSTs, its applicability in LV DCNGs may be constrained by the high number of switches and associated costs [47].

In addressing this limitation, multi-cell series-parallel (MCSP) converters have been introduced, eliminating the need for heavy transformers to connect to the MVAC grid [47]. MCSPs shown in Figure 2e, comprised of multiple switching cells controlled using pulse width modulation (PWM) techniques and arranged in series following a simple diode rectifier, present a viable AC/DC converter option for DCNGs. However, it is important to note that a significant limitation of this converter is its unidirectional power flow capability, limiting its application to scenarios where NGs do not engage in energy exchange with the utility. The capacitor voltage balancing issue in the MCSP converter can be resolved by using a phase-shifted multi-carrier PWM technique implementing selected switching modes [47,52].

In [37,45], a single-phase, two-stage, bidirectional full-bridge converter, shown in Figure 2f, is presented as an ECC converter, serving to interface residential DCNGs with the grid. The proposed ECC converter controller effectively mitigates voltage ripple within the DC system, utilizing a compact DC link capacitor. This converter regulates a high DC-bus voltage (380V), rendering it well-suited for EV charging applications. Despite offering bidirectional control and mode transition capabilities, it is important to note that the controller design complexity and sensitivity of ripple power decoupling to controller parameters pose challenges.

The conversion stage after the rectifier involves DC-DC converters supplying power to an inverter to feed AC loads. Also, RESs such as PV, as well as ESSs with DC interfaces, are connected to the DC bus through DC-DC converters. Two main categories of DC-DC converters, namely, isolated and non-isolated, can be utilized. Non-isolated converters are favored for their higher efficiency, smaller size, and cost-effectiveness, while isolated converters offer electrical isolation, enhancing safety at an additional cost. In NGs, incorporating a solar PV system necessitates stepping up the voltage to extract maximum power from the PV panels [53]. The most common type of step-up converters interlinking solar panels to the DC bus is the boost converter. However, its efficiency is low at low input voltages, and it might struggle with maintaining maximum power point tracking (MPPT) during rapid changes [54].

The tri-switching double-duty ratio boost converter (TSDDC), depicted in Figure 2g, proposed in [53] operates with three switches, along with some diodes and inductors, and facilitates achieving a high voltage gain to harvest solar energy in DCNGs by controlling the converter based on two duty ratios. In contrast to similar topologies [12,54], TSDDC demonstrates superior efficiency at high power levels. However, it is important to highlight that it employs a higher number of switches and diodes. To increase the voltage gain, addressing a common issue in boost converters, particularly in applications involving solar PV systems, a configuration of boost converter featuring a coupled inductor and the switched capacitor technique is proposed in [55]. Compared to similar configurations, the cost is reduced due to the lower number of devices and reasonable efficiency; however, the voltage gain is dependent on the duty cycle.

The DAB converter in Figure 2h, serving as a bidirectional isolated DC/DC converter, is a prevalent choice for DCNGs/DCMGs. This converter is favored in DCNG applications due to its ability to provide a wide range of voltage gain and galvanic isolation, support multiple output voltage levels, maintain inherent soft switching, and exhibit a fast dynamic response during power flow direction changes [36,44,45]. It employs two full bridges for the primary and secondary stages, along with an inductor and a high-frequency transformer, effectively reducing the converter's size and weight [44,45]. Various control techniques, including singlehase modulation and double-phase modulation, have been proposed in the literature [36,45]. An isolated bidirectional AC/DC converter using DAB integrated with a half-bridge boost rectifier is proposed for EV chargers, featuring low current stress on devices [46]. The controller for this converter works under a single-phase shift technique, based on voltage regulation, allowing power flow control in both directions.

The diversity of existing DC sources and loads within NGs/MGs emphasizes the importance of considering the system's capability to connect various types of sources and loads while ensuring safety and reliability simultaneously. Multi-port converters in DCNGs offer the capability of connecting several energy sources with various voltage levels [56,57]. In [56], a three-port bidirectional DC/DC converter designed for DCNGs is proposed. This converter, shown in Figure 2i, utilizes two shared switches to integrate PV systems and battery-based energy storage systems within the DC grid, resulting in a reduction in the number of switching components and overall cost. Control of the PV power flow is achieved through adjustment of the switching frequency, while the power flow for the battery can be regulated by adjusting the duty cycle. The incorporation of discontinuous current mode (DCM) and a multivariable controller enables bidirectional power flow capabilities, soft switching conditions, and increased efficiency for the converter [56]. However, extracting high power from solar PV systems at higher frequencies can be a challenge.

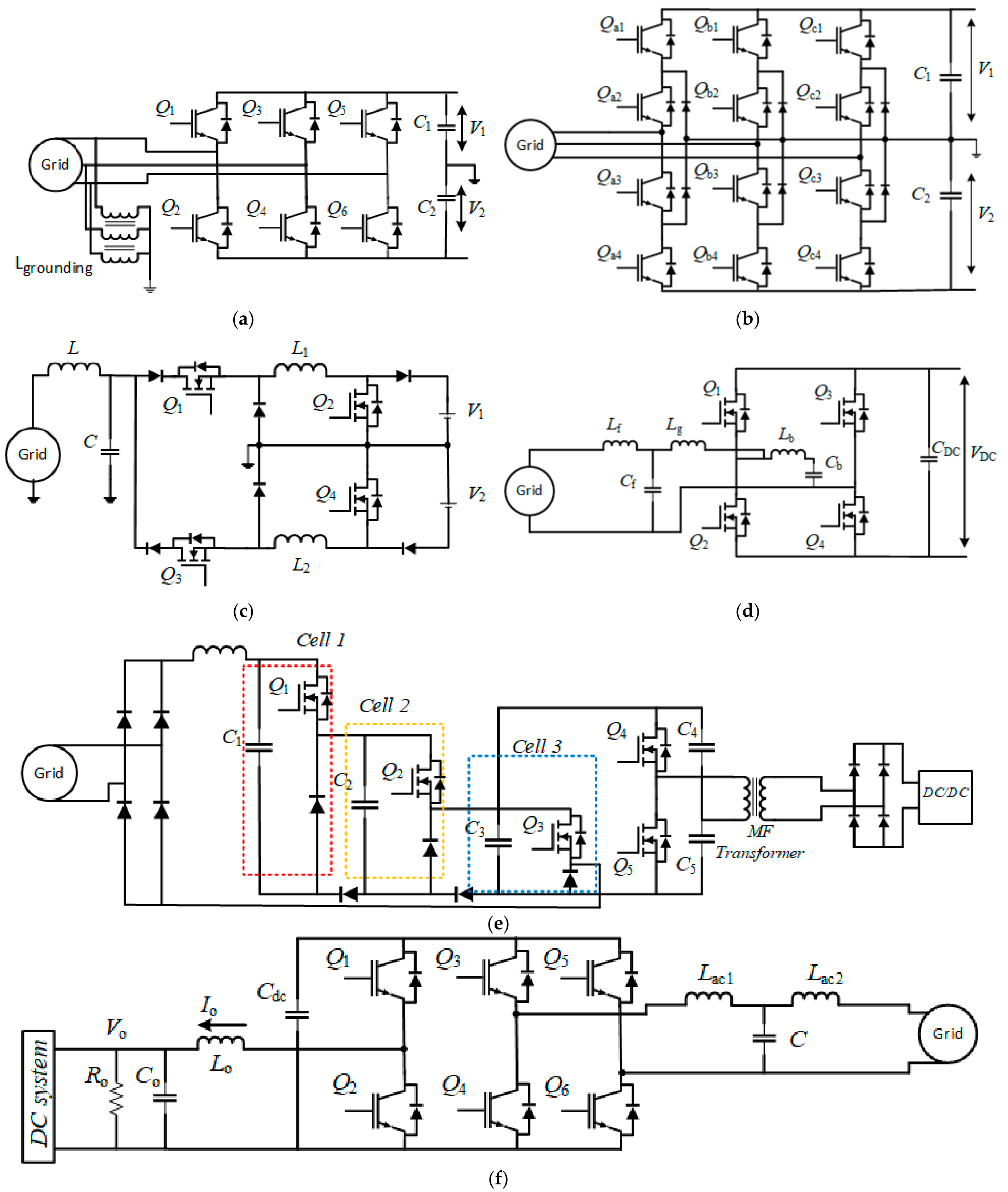
A multi-port bipolar DC-DC converter is introduced in [58]. This converter, depicted in Figure 2j, contains a DAB converter with multiple ports designed for renewable sources, allowing efficient load power sharing by the input sources. By incorporating an NPC converter at the secondary side and implementing phase shift control, bipolar voltage regulation is achieved, which is important when connecting loads at different voltage levels. However, the high number of switches introduces a complex switching state combination, necessitating control with four phase shift angles to balance the output voltages, and resulting in lower efficiency at high switching frequencies.

Voltage balancers serve as power electronic converters, offering a solution to the issue of voltage imbalances in bipolar nanogrids. The conventional voltage balancer, a variant of the buck-boost converter, employs two switches and connects the zero terminal through an inductor to the capacitor's common point, as shown in Figure 2k [36]. This configuration allows the adjustment of the zero point's voltage, particularly when the inductor current contains high ripples; however, it has high turn-off switching losses [36,48]. For a more in-depth exploration of voltage balancer converters implemented in bipolar DCMGs, a comprehensive review is available in [36]. Table 2 gives a comparison of some other proposed converters in literature suitable for NG application.

SSTs, also known as power electronic transformers, were initially used in traction systems to replace bulky line-frequency transformers, offering reduced size, weight, and long-term costs, and increased efficiency. Recently, SSTs have emerged as an alternative to traditional distribution transformers, serving as energy gateways for integrating renewable energy sources into MGs and NGs. Their ability to operate in both MV and LV distribution systems, as well as bidirectional power flow capability, make them particularly valuable, given the increasing demand for renewable energy and the expansion of MGs and NGs in modern power grids. Their versatility enables applications in AC, DC, and hybrid systems, including renewable energy plants, data centers, EV charging stations, and military infrastructure. SSTs enhance power quality by mitigating harmonics and voltage sags and swells, while their modular design supports scalability, allowing NGs with SSTs to evolve into interconnected NGs or MGs. SSTs are presented in three configurations, namely, single-stage, two-stage, and three-stage, as shown in Figure 3.

The single-stage design, shown in Figure 3a, is the most basic configuration for an SST. It consists of a direct AC-AC power conversion that reduces MV to LV. Because this configuration has only one conversion stage, it is lighter and more efficient than the two-stage and three-stage configurations. But, the absence of a DC link makes connecting DC sources, ESS, or loads more difficult and expensive. Furthermore, unidirectional power flow is a feature of this topology [59,60]. Two-stage topology is split into two configurations, one with an MV DC link and the other with an LV DC link, as illustrated in Figure 3b,c. Both reactive power compensation and bidirectional power flow are possible with this arrangement. They do, however, consist of more switching devices and require more complicated control systems compared with single-stage SST. Furthermore, because the MV DC link structure is not grid-isolated, it is not appropriate for integration of renewable energy sources [60,61]. A three-stage SST structure is shown in Figure 3d. Improved features like support for different loads and devices in both MV and LV distribution systems and higher power quality are made possible by this arrangement, which offers two DC links. Because of its extensive potential, it is regarded as the most appealing topology. The voltage regulation performed by the three-stage SST is favorable.

The DAB converter is the most suggested DC-DC converter topology for managing power flow between the stages. Using a phase shift controller, this converter actively regulates the transferred power while offering soft-switching and high efficiency [60]. The converters that are most frequently used in the MV side are modular multi-level converter (MMC), cascaded H-bridge (CHB), and NPC. Among these, the CHB converter is notable for having a simplified control structure and lower total harmonic distortion (THD) because of its large inductance. Nevertheless, it is less appropriate for high-power applications due to its huge inductance. On the other hand, the NPC converter has a more complex control circuit but is still very appropriate for industrial applications. Furthermore, to manage high power, many converter modules must be cascaded due to the limiting operating voltage of current IGBT technology. However, because of requiring a big filter on the DC side, MMC is more expensive than other options for establishing a DC link for MV DC sources and loads [61]. One of the most widely used converters to convert LV DC to LV AC on the LV side is the half-bridge topology. This straightforward design can be used as a three-level converter by incorporating flying capacitor or neutral point connection (NPC arrangement) [61].



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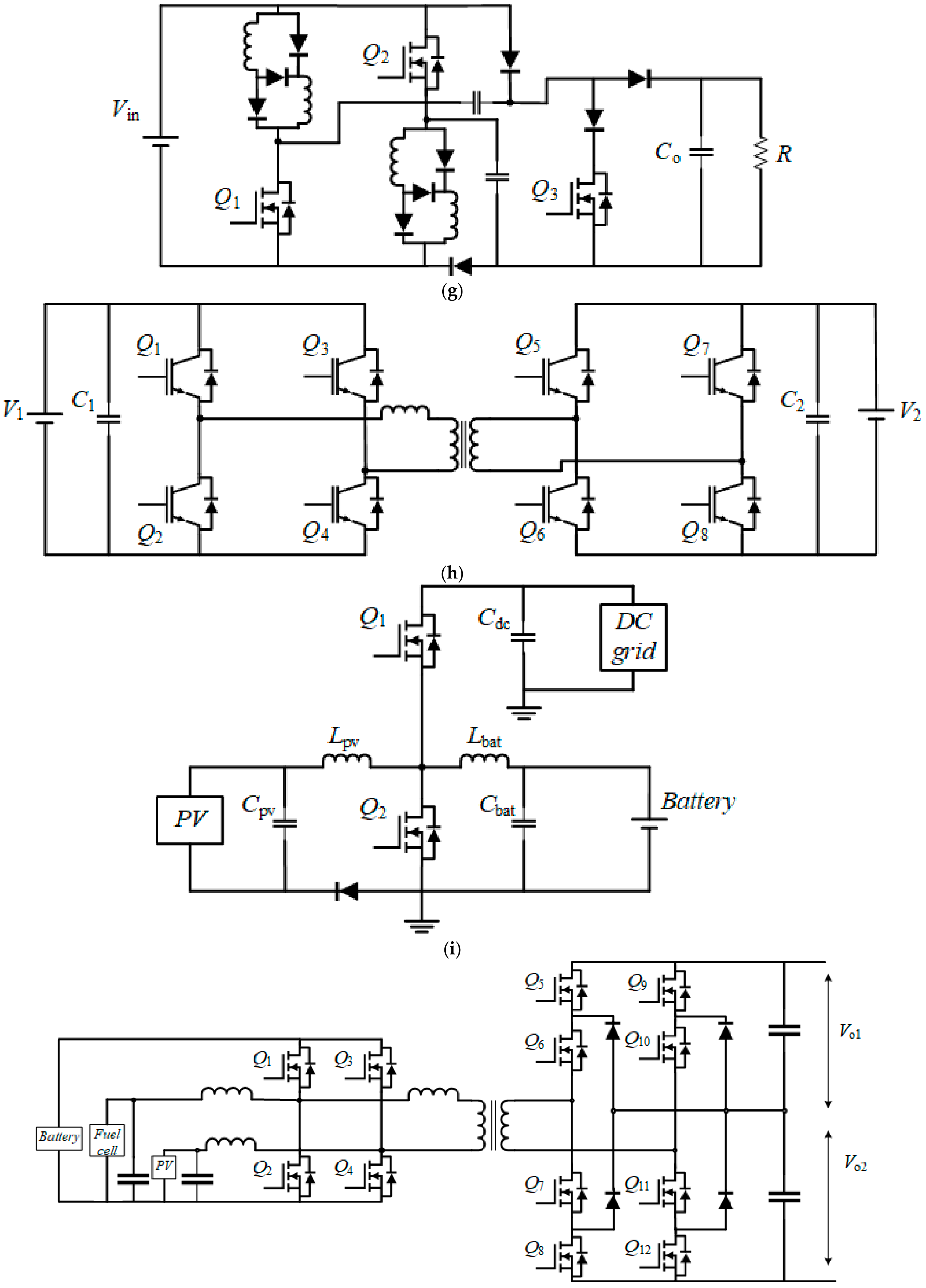

(**g**)

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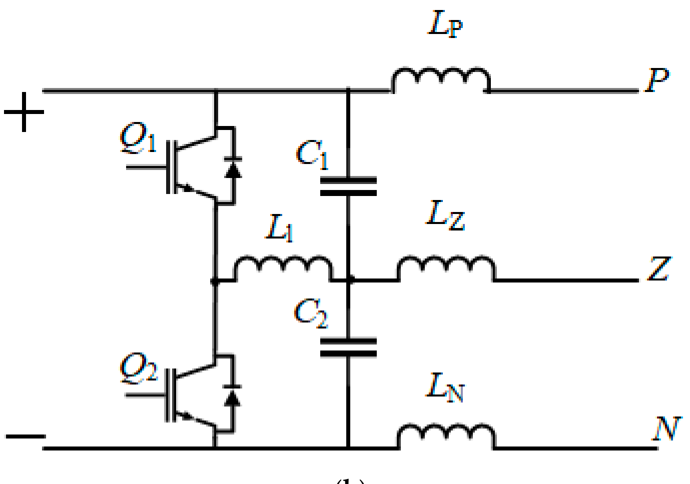
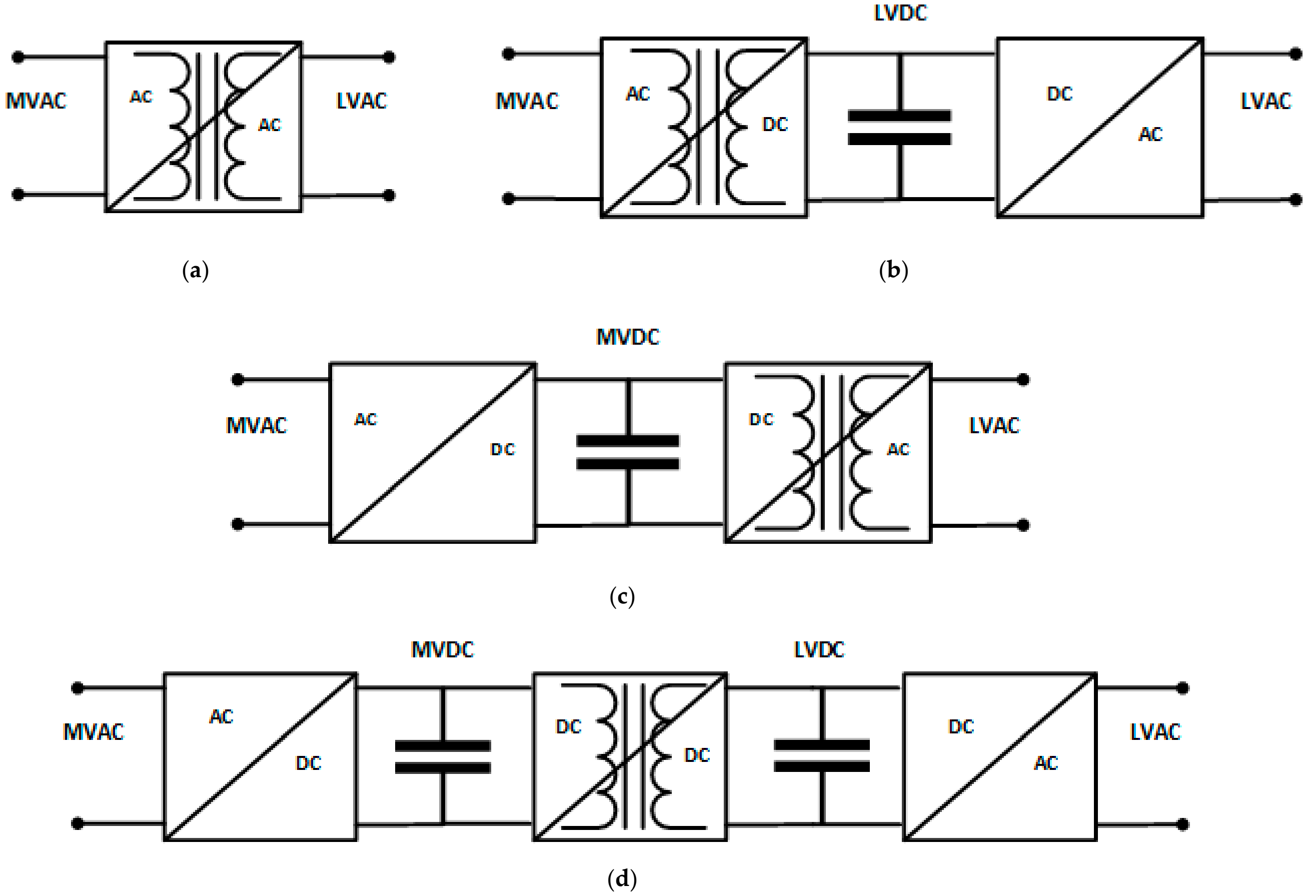


(**k**)

Figure 2. Power electronic converters implemented in NGs/MGs: (**a**) two-level VSC configuration [48], (**b**) NPC configuration [17], (**c**) dual buck-boost AC/DC converter [51], (**d**) PFC converter [46], (**e**) MCSP converter [47], (**f**) ECC converter [45], (**g**) tri-switching double duty ratio boost converter [53], (**h**) conventional DAB converter, (**i**) three-port bidirectional DC/DC converter [56], (**j**) multi-port DAB converter [58], (**k**) buck-boost voltage balancer [36].



(**a**) (**b**) (**c**) (**d**)

Figure 3. SST configurations, (**a**) single-stage topology, (**b**) two-stage topology with LVDC link, (**c**) two-stage topology with MVDC link, (**d**) three-stage topology.

Table 2. Overview of some proposed converters implemented in NGs.

Reference #	Converter Type	Efficiency	Features of the Configuration
[45]	AC-DC	>96%	• Two-stage single-phase grid interface converter • Non-isolated • Bidirectional
[55]	DC-DC	>96%	• Coupled-inductor converter • Non-isolated • Unidirectional
[62]	DC-AC	86–96%	• Multistring PV inverter • Unidirectional • With galvanic isolation
[63]	DC-DC	86–96%	• Interleaved buck/boost • Multiport capability • Bidirectional • With galvanic isolation
[64]	DC-ACDC-DC	86–96%	• Boost-derived hybrid converter • Unidirectional • Non-isolated • Supporting DC and AC outputs simultaneously
[65]	AC-DC	>96%	• Self-excited induction generator with Cuk converter • Unidirectional • Non-isolated
[66]	DC-DC	86–96%	• Based on buck converter • Multiport capability • Non-isolated
[67]	DC-DC	86–96%	• Single-input, multi-output boost-based converter • Non-isolated • Unidirectional
[68]	AC-DCDC-DC	>96%	• DAB-based micro inverter • Bidirectional • Multiport capability • With isolation
[69]	DC-DC	86–96%	• Two-input DAB converter • Multiport capability • Bidirectional • With isolation
[70]	AC-DC	86–96%	• LLC-based converter • Multiport capability • Bidirectional • With isolation

4. Nanogrids Control Strategies

As smaller-scale versions of MGs, NGs can use the same control strategies. The control methods for NGs can be categorized based on their operational purpose, communication structure, and response time [71]. Depending on their connection to the grid, NGs can operate in either grid-tied or islanded mode. Control systems are further divided into three hierarchical layers: primary, secondary, and tertiary, each defined by its respective response time and functionality. Droop and P-Q control are employed in primary level due to their decentralized nature and ability to provide real-time power sharing and stability without requiring complex computations or communication. Advanced techniques like MPC, while fast in operation, are typically applied at the secondary and tertiary levels, where their optimization capabilities align with longer timescale tasks such as economic dispatch and power exchange coordination. Within these layers, three main control approaches—centralized, decentralized, and distributed—are employed, which are discussed in detail before exploring the specifics of each control level. The detailed discussion of all control techniques is beyond the scope of this paper; however, Figure 4 shows the comprehensive classification of NGs/MGs control [4,19,71].

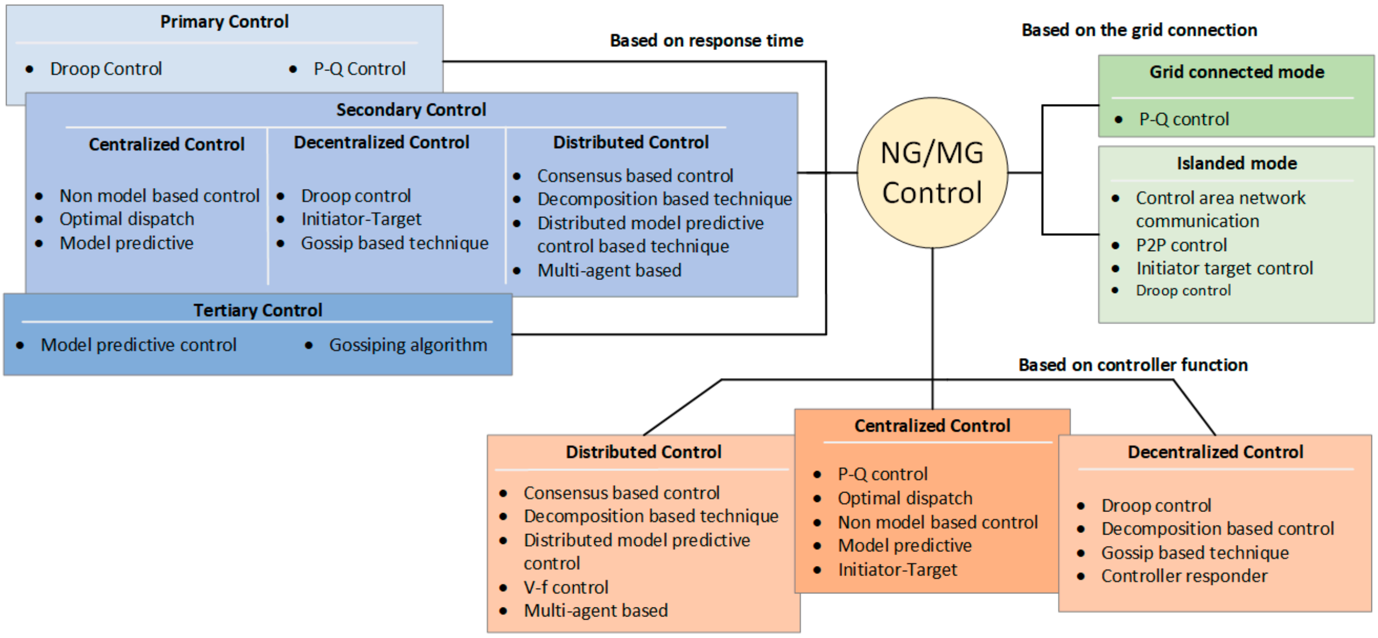
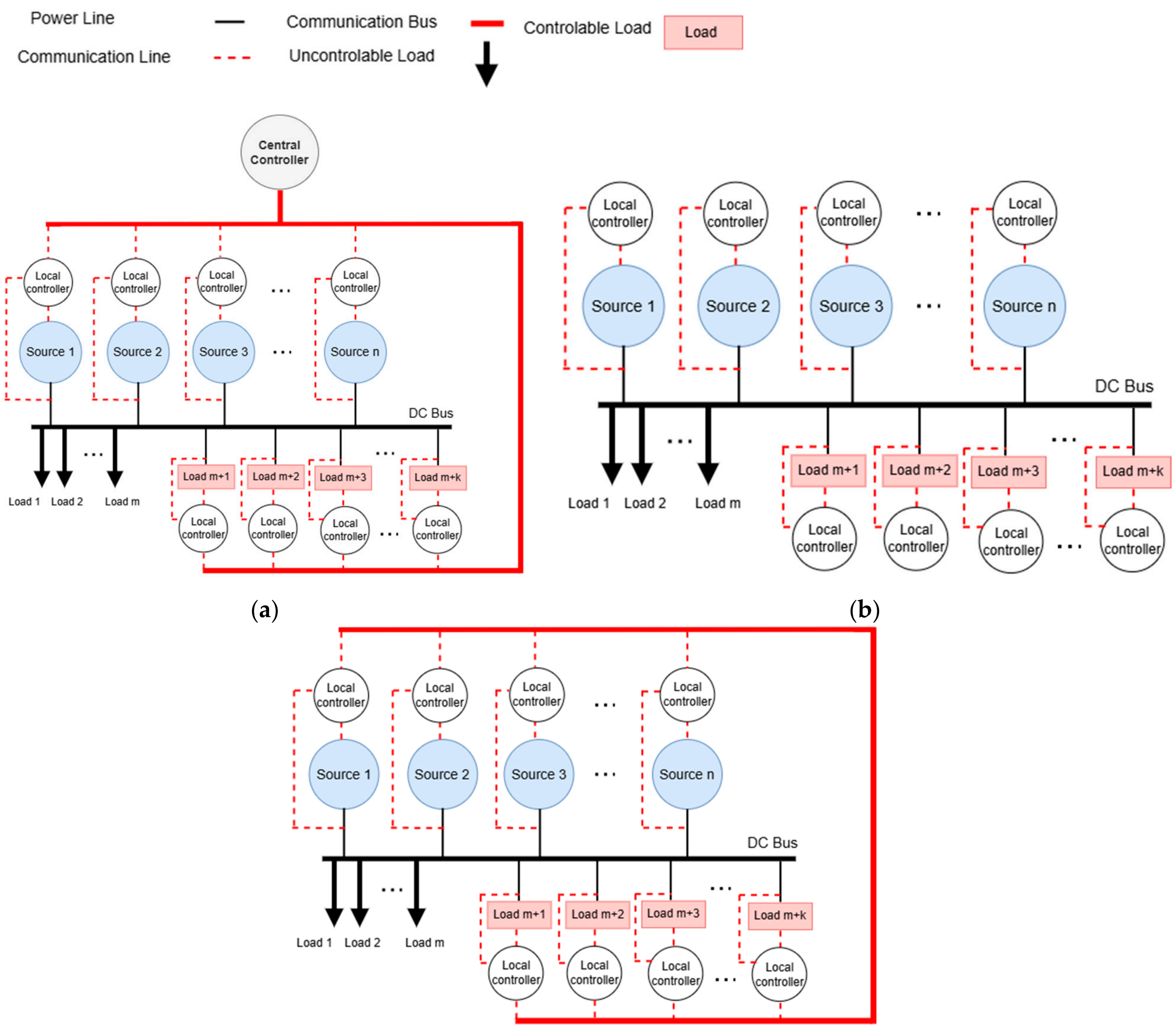


Figure 4. Control classification of NGs/MGs.

4.1. Centralized Control

The central strategy, as depicted in Figure 5a, oversees power requests, directs dispatch from sources, and manages communication within the NG, using data from smart meters and sensors. However, centralized approach poses reliability concerns; a failure in the central controller or communication can cause a complete system breakdown. Moreover, the need for high-speed communication raises costs [4,71].



(**a**) (**b**) (**c**)

Figure 5. Control strategies in nanogrids: (**a**) centralized control, (**b**) decentralized control, (**c**) distributed control.

4.2. Decentralized Control

In this approach, each load/source is solely controlled by a local controller, based on local measurements only, thus eliminating the need for communications and a master control unit, and giving the system plug-and-play capability. This method offers enhanced reliability compared to centralized control and proves to be cost-effective due to elimination of communications that is essential in centralized control. Power lines serve as the communication path in this control. The absence of complete inter-node communication in this control method may lead to a deficiency in optimal response, potentially allowing the widening of faults occurring in a single node of the physical system [14,71]. The widely adopted technique in decentralized control is droop control, which is explained in Section 4.4. Figure 5b illustrates the structure of decentralized control.

4.3. Distributed Control

Distributed control approach, depicted in Figure 5c, makes a compromise between the centralized and decentralized structures, allowing communication between selected (usually adjacent) nodes while minimizing dependence on communications, contributing to security improvement [72]. The common techniques in this category are DBS and power line signaling (PLS). DBS serves as a distributed control method in NGs, leveraging the DC bus as a communication path among various sources/loads connected to the bus. In DBS, system components communicate to coordinate their actions, exchanging information about system status, power demand, and other relevant parameters through the DC bus. This method is an extended version of the voltage level signalling (VLS) technique, which considers several DERs by defining their voltage levels as set values [18]. In VLS method, as the load changes, the DC bus voltage is adjusted to a new working voltage level for connected sources based on the load current. While VLS can be useful for load shedding or redistribution based on the current values and voltage levels, it lacks the flexibility to accommodate new distributed sources, since it requires consideration of new working voltage levels [18]. The combination of droop control for local sources and VLS leads to DBS control, facilitating power sharing among sources [17,18,71].

Implementing DBS in NGs contributes to efficient power management and enables implementation of various EMSs to harness renewable energy sources, utilize AC grid, and support loads. However, in comparison with other methods, DBS may introduce higher complexity in communication infrastructure. Furthermore, the system's reliability in operating across various modes is limited due to the inflexibility of the DC bus to accommodate a broad voltage range [73].

As another distributed control method, PLS addresses the drawbacks of DBS method. PLS involves modulating analog data onto electrical power lines, enabling devices to communicate, exchange information, and coordinate their actions. PLS is particularly beneficial in situations where establishing dedicated communication lines are impractical or cost prohibitive. While PLS facilitates load management, allowing devices to coordinate and optimize their operation based on real-time information, it is susceptible to electrical noise and interference from devices sharing the same power line [71–73].

4.4. Hierarchical Control

The implementation of effective control techniques in NGs is pivotal to accomplishing energy management objectives. These objectives encompass tasks such as regulating bus voltage, ensuring uninterrupted load supply, preventing source overload, and facilitating seamless communication among NG components and external grids for power sharing [71]. Typically, hierarchical control structures, characterized by three layers (primary, secondary, and tertiary), are adopted in MGs and NGs, integrating centralized, decentralized, and distributed control strategies. This approach optimizes the coordination of distributed energy resources, allows for flexible operation in both grid-connected and islanded modes, and integrates advanced techniques for improved control accuracy. Overall, it ensures efficient and resilient energy management in complex and dynamic systems.

The primary layer governs current and voltage in interfacing converters utilizing droop control and PI controller [17,71]. Some studies related employing droop control in NGs are provided in the following, showing the applicability of this method at primary level. In the secondary layer, a regulated DC bus voltage is maintained at the point of connection of converters and higher-level grids, achieved through the implementation of DBS or PLS. Also, dispatch commands to the units originates at this layer. Finally, the tertiary layer orchestrates large-scale energy management, power dispatch, and power sharing, through optimization algorithms and communication links with other MGs/NGs utilizing power line signaling [17,19].

Droop control emerges as the most common strategy in MGs and NGs to manage voltage and frequency regulation. It operates as a decentralized control strategy within the primary control layer. The term "droop" signifies the proportional sharing of the power among the participating units determined by the disparities from the nominal values. Another objective of droop control is to eliminate circulating current [17,18]. Droop control uses the P-f and Q-V droop characteristics of individual DERs to adjust their shares of active and reactive power in proportion to their relative ratings, resulting in a common voltage and frequency at the point of connection. This allows multiple sources to share the demand proportionally without requiring communication between them. In DCNGs, the P-V droop characteristic is used. While droop control is relatively simple and enhances system stability through localized control, it may not guarantee precise regulation under varying conditions.

DCNGs maintain power balance through BESSs, which operate in charging mode when surplus power is available and discharging mode during power deficiencies, considering the battery SoC and other constraints. Achieving state of charge (SoC) balance among multiple batteries is crucial for optimal system operation and loss reduction. This is often addressed through droop control techniques documented in the literature. An adoptive dual-droop control, incorporating an inner loop for current and an outer loop for voltage, is proposed in [73] to provide SoC balance among distributed energy storage systems in a DCMG, ensuring microgrid reliability and the controlled speed of power sharing of converters. Properly designed droop control coefficients enable dynamic SoC balancing for the entire system without the need for communication between the units. Droop parameters are designed inversely proportional to the SoC, enabling the battery with a higher SoC to dispense more power than the one with a lower SoC; this continues until the SoC balance is reached and the converters' power outputs are harmonized. However, in this approach, the coefficients for SoC balancing are considered for discharging mode only, and batteries are charged at maximum power during the charging mode, irrespective of their SoC. This can result in heightened losses and an unbalanced SoC among batteries.

In a related development, a communication-less fast I-V droop control for power sharing between DCNGs equipped with PV systems and battery storage is presented in [22], catering to electrification needs in rural areas. This strategy assesses the accessibility of distributed sources in various operational states, such as battery charging and discharging, through continuous monitoring of bus voltage and battery SoC. It effectively minimizes distribution losses by facilitating timely power exchange and contribution of PV and battery converters, considering the SoC. However, the stability of the DC bus voltage during rapid mode transitions and load fluctuations within the NG is not demonstrated. Addressing this concern, ref. [74] proposes a modular self-organizing NG employing an auto-adjust control method. The control method utilizes a multi-coefficient droop control based on battery SoC, DC bus voltage, and extra energy from PV. This ensures that, regardless of source operation (PV or battery) and potential load changes, the bus voltage is maintained at the reference value in real-time.

The implementation of a two-level hierarchical control, integrated with a DAB converter, establishes a robust system with adaptive control, facilitating connection to other NGs and enabling efficient power sharing [75]. Primary control, incorporating droop control and converter control, manages DC bus voltage regulation within the NG. Secondary control, driven by a centralized controller, fine-tunes the DC bus voltage using a correction parameter derived from the deviation produced by droop control [75]. However, the impact of SoC imbalances among batteries may be an issue. When batteries are concurrently charging and discharging, without considering their individual SoC levels, the DC bus voltage may deviate from the setpoint value during power delivery or absorption.

4.5. Energy Management System (EMS)

EMS plays a crucial role in the optimal integration of energy sources and loads in NGs, ensuring power balance. Functioning as the intelligence behind the decision-making process, EMS dynamically orchestrates the operation of various components such as renewable sources, energy storage systems, and controllable loads, while contributing to enhancing energy efficiency, maintaining system stability, and coordinating source dispatch through real-time monitoring and effective communication [72]. The NG's EMS must handle load changes without interfering with primary control, and it should be fast enough to adjust commands in response to variations. In a centralized EMS, the optimization techniques can be implemented to generate the dispatch commands efficiently [76]. Objective functions can be defined based on various purposes such as lowering energy cost, reducing dependence on the grid, and cutting CO_2 emissions. To solve optimization problems, EMS employs algorithms such as model predictive control (MPC), heuristic and metaheuristic algorithms, neural network (NN), and fuzzy logic control for strategic decision-making [77].

The modular nature and plug-and-play characteristic of DCNGs controlled under decentralized regime, allow for scalability and flexibility in implementing tailored EMS strategies, considering specific grid characteristics [72,73]. Combining time-of-use (ToU) scheduling with energy storage management via droop control reduces electricity bills in an EMS scenario described in [43] by reaching net-zero energy status. One of the shortcomings of the model used in [43] is that the stochastic behavior of the load has not been considered.

Most of the EMSs in grid-connected systems utilize battery storage as the backup energy source. To reduce grid dependency, ref. [78] proposes an EMS for a DCNG using a DBS control method with a DAB converter for bidirectional power flow. Decision making is based on the operating modes defined by the DC bus voltage level limits. The AC grid only supplies the NG during energy shortages, while the battery size may be increased to enhance self-sufficiency in other modes of operation. Achieving a compromise among size, cost, and self-sufficiency is important in applications where the size and cost of the system are the main restrictions [78].

Despite EMS improvements, uncertainties inherent in renewable sources, and limitations in the size of battery energy storage system raise concerns about system reliability and dependence on the main grid. Power sharing among NGs in a neighborhood is a viable solution to the problem of providing power locally within a microgrid and reducing energy costs. However, a higher-level EMS in the neighborhood is required to coordinate NGs for optimal power exchange [15,79].

4.6. Communication

The common communication methods adopted in NGs fall under wired and wireless categories. At NG scale, wired communication is generally more reliable, while wireless communication may offer a more cost-effective solution [17]. In NGs, PLC, as a wired approach, involves establishing a communication network over the existing power lines, allowing for advanced data exchange, control, and optimization across the entire NG. The noise associated with power lines can reduce the efficacy of this technique and is considered a drawback. While PLC and long-range wide-area network (LoRaWan) can be implemented for longer distances, Bluetooth, Ethernet, and Wi-Fi are more suitable for shorter distances [17,71].

5. Power Sharing Among Nanogrids

The modern LV distribution system is progressively aiming for greater independence from the main AC grid, particularly in residential areas, seeking reliability and self-sufficiency. A nanogrid, equipped with essential components, can fulfill its power requirements using local resources like solar PV and batteries; however, sustaining the system remains uncertain. During power deficit periods, instead of relying on the AC grid, the NG can request power from neighboring prosumers through a secure local platform, fostering collaborative resource management and addressing challenges posed by renewable source unpredictability and transmission line congestion. This P2P power sharing initiative envisions interconnected energy communities, collectively contributing to a sustainable local energy ecosystem.

The P2P network is comprised of a virtual layer, as shown in Figure 6, ensuring secure participant interactions, and a physical layer functioning as either a traditional distribution grid or an MG [80]. Numerous projects in different countries, such as Japan [6], South Korea, and the US [24], have implemented P2P power sharing, utilizing centralized and decentralized platforms (see Table 3). While centralized hubs coordinate and optimize energy exchanges, the decentralized platform allows direct exchanges among participants, promoting resilience and sustainability, particularly in MGs and NGs, where distributed energy sources collaborate within a localized network [80]. The components of P2P power sharing network are shown in Figure 6 [24]. Power sharing among NGs or MGs requires optimization through objective functions, considering various constraints. The objective functions are mainly designed to minimize cost, losses, and component sizes, or maximize efficiency of the system [24,80]. P2P mechanisms introduce specific challenges and concerns such as increased power losses, shared electricity prices, higher node voltages, preserving participants privacy, and load and generation predictions.

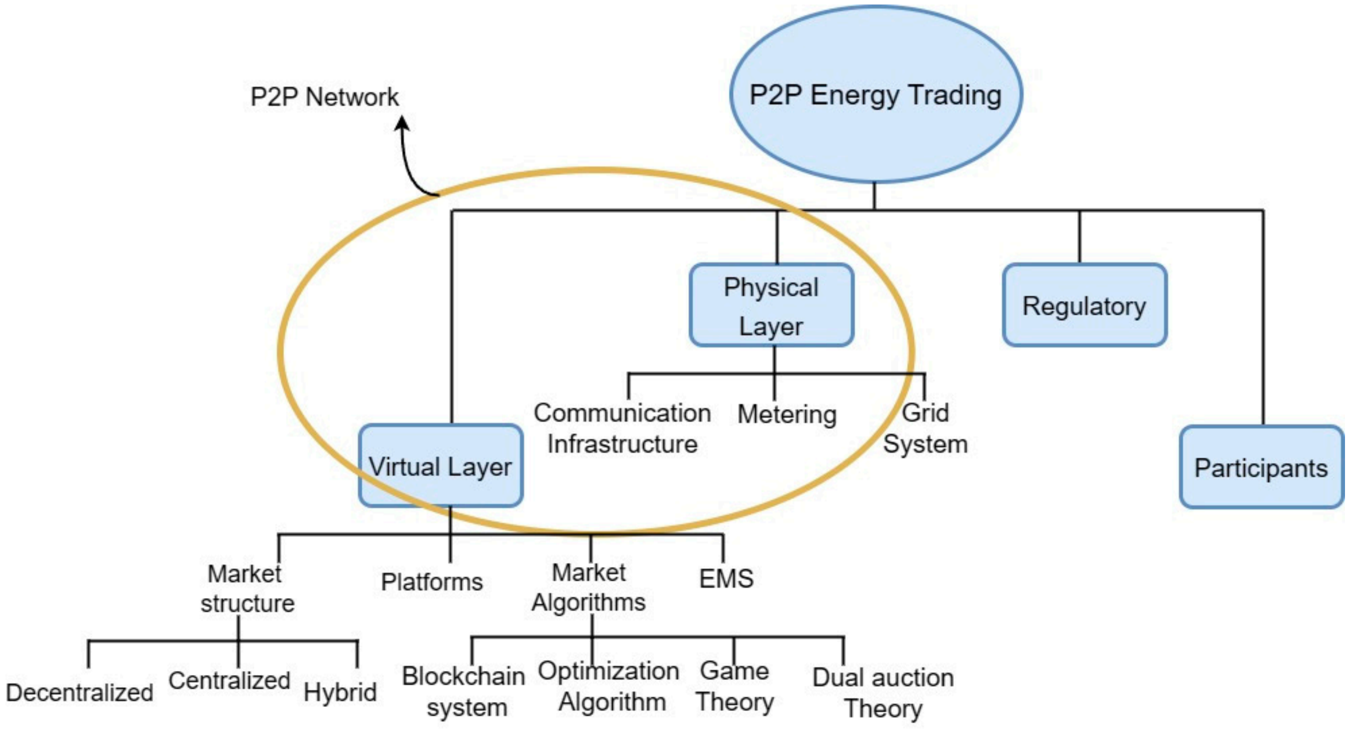


Figure 6. P2P energy trading components.

In MGs/NGs with a DC bus and P2P power sharing, monitoring power flow is vital for community energy trading. The challenge arises with multiple distributed sources, creating complex power flows through the DC bus. To address this, reference [81] proposes power electronics-based control using a carrier frequency superimposed on DC voltage or current. Each distributed source (DS) injects a controlled active power carrier, allowing power loads (PL) to identify sources and measure DC power. This method is called Source-to-Load

Power Signaling. In [82], a P2P power-sharing system has been proposed that considers both hardware and cyber aspects and employs a central controller for information and energy exchange. The lack of consideration for social energy costs in online optimization is a shortcoming of this system that has been addressed in [23]. Social energy cost includes energy trading expenses, energy storage system operation cost, and the cost of controlling loads [23]. Reference [23] introduces a real-time optimization model enabling day-ahead power sharing planning with different building types. The two-stage power sharing introduced in [83] provides both social energy cost and participant prices, offering behind-the-meter activity.

In [84], PV and battery sizes are optimized while maximizing social welfare, incorporating a coordinator for P2P interactions with the system operator. In the proposed open-energy system for P2P power sharing [85], peers independently control their sources, loads, and storage, with the help of EMS, while being connected to a common bus to exchange power; however, the system is relying on both utility grid and local generation. A central EMS coordinates interaction by forecasting load demand, regulating bus voltage, and measuring battery SoC, ensuring power balance [85].

A central coordinator for power sharing in a DC community MG, introduced in [27], uses prosumer meter information to coordinate power sharing, distribution losses, and energy balance. The proposed model reports higher efficiency through system size optimization, considering system nonlinearity and other constraints; however, its feasibility for varying load profiles and source numbers remains to be examined [27]. Reference [83] proposes a hybrid power sharing structure where the prosumers can exchange power and trade energy with both the grid and other peers. Each prosumer communicates with the corresponding community manager which is in coordination with other community managers and the grid operator. Then, based on the type of load/source, different electricity schedules such as ToU and P2P power sharing can be implemented. This increases the ability of energy management, simplifies optimization constrains, and gives more freedom to prosumers; however, to expand the system, coordination among a high number of community managers would need more specific optimization constraints.

Layered cooperation of community energy trader (CET) with energy trading manager and distribution system operator at higher levels, results in proper large-scale energy exchange (e.g., among clusters of MGs), while providing energy balance at each stage [86]. Through a hierarchical framework in an MG, the distribution losses are reduced due to well-planned power sharing, with the help of a reliable communication system. Furthermore, to optimize power sharing, power losses such as converter losses need to be considered in the cost function. The NGs’ power generation, load demand, and battery SoC for each time slot are calculated for different energy management and power sharing scenarios. Optimized power sharing reduces component sizes and source power losses, subsequently lowering energy costs for customers/prosumers [87]. However, the inclusion of EVs may alter losses and affect system size.

Blockchain System

Blockchain technology introduces a decentralized framework for facilitating P2P energy trading, addressing many challenges of traditional centralized systems. At its core, blockchain operates as a distributed ledger, where every participant (node) maintains an updated copy of the entire transaction history, ensuring transparency and eliminating the need for a central authority. Each transaction added to the blockchain is validated through consensus algorithms, such as Proof of Work, Proof of Stake, and Byzantine Fault Tolerance. These algorithms establish agreement across the network, verifying transactions’ authenticity and accuracy [88].

Transactions are stored into blocks, each containing key details like sender and receiver information, transaction amount, and timestamps. These blocks are linked sequentially, with every block containing a cryptographic hash of the preceding block, ensuring an immutable chain of records. This hash acts as a unique digital fingerprint, making it nearly impossible to alter past transactions without detection, thereby enhancing the security and integrity of the blockchain. This decentralized, secure, and transparent structure makes blockchain particularly well-suited for managing energy exchanges in a P2P setting, allowing energy producers and consumers to trade seamlessly and securely.

Some projects featuring blockchain-based energy trading are listed in Table 3. By employing blockchain, verified participants' privacy is preserved, as their only available information is their wallet address [89,90]. Blockchain enables the inclusion of many customers, fostering a more resilient, efficient, and democratized energy grid [91]. A smart grid management system based on blockchain technology is proposed in [88], benefiting from features like smart contracts and smart energy meters using the Internet of Things (IoT) to gather data from participants. Similarly, [90] proposes a platform for P2P energy trading based on blockchain technology, emphasizing security and transparency through anonymous encrypted messages and multiple signatures.

Table 3. Overview of previously proposed P2P power sharing technologies.

Reference #	Features of the Technology Proposed by the Reference
[27]	• introducing an efficient P2P energy trading model based on nonlinear programming techniques • highlighting role of power electronic converters in achieving an optimized power sharing model
[92]	• localized energy trading among EVs and other peers as prosumers; dynamic pricing favoring both trade sides • EV charging station with reduced dependence on the grid and increased role of PV in charging process
[93]	• highly secure transactions via blockchain technology • analyzing side effects of P2P trading, such as bus voltage violation and system losses • introducing a flexible P2P model
[91]	• highly reliable energy trading through decentralized P2P power sharing • considering measures to oversee the issues caused by P2P energy trading in physical networks
[94]	• Peer energy cloud in Germany at residential scale • creating virtual market platforms for energy trading • exploring novel methods for recording and predicting device-specific electricity usage • leveraging collected data for energy trading by operators
[95]	• blockchain-based P2P platform • investigating P2P trading types suitable for blockchain technology • smart contract for trading • extended financial advantages beyond initial investment expenses
[96]	• Piclo, online P2P platform • intermediary service for local energy market pairing of generation and consumption • gathering data, billing, and making contracts • decision-making for trading and pricing guided by user preferences

Table 3. *Cont.*

Reference #	Features of the Technology Proposed by the Reference
[97]	• EnerPort project • Energy trading among MGs • blockchain-based platform • presenting different trading models corresponding to P2P trading variations • considering physical and virtual infrastructures for trading

6. Potential Challenges

6.1. Technical and Control Challenges

As NGs develop in residential neighborhoods, the use of low-inertia RESs, especially solar PV, will increase in future buildings, causing voltage and power fluctuations due to their variable/intermittent nature, causing power quality issues and grid losses [15]. This issue becomes more serious when NGs are interconnected [39,98], and maintaining stability and power quality for the NGs operating in islanded mode becomes challenging, due to lack of main grid support. To address this issue, some compensators have been proposed, such as the static synchronous compensator (STATCOM), though they are more useful on the MV side [39]. Demand-side management has drawn attention to alternative ideas such as flexible loads to mitigate power distribution imbalances [39], where critical loads (CLs) and noncritical loads (NCLs) make up the demand side [39]. The power and voltage variations of CLs in NGs can be managed by connecting an electric damper in series with them. However, the inverter, output filter, controller, and transformer that make up the power electronics-based electric damper, could increase the NG's complexity and cost.

RESs such as solar PV generate DC voltage output, and to make power balance in the system it is crucial to integrate ESSs which are inherently DC type. Moreover, greater AC or DC voltages are needed for typical AC loads, whereas LED lighting, digital electronics, and EVs function more efficiently at 48 to 400 V DC. Additionally, the double-line-frequency ripple in the DC-side current of NGs, originating from single-phase AC-DC conversion in residential units, leads to increased power losses as well as shortening of lives of energy storage and DC-link capacitors. Even though film capacitors can be used to solve this problem, they are known to have shorter lives than electrolytic capacitors [16]. Providing different DC bus voltage levels with minimized conversion stages, and decoupled power flow management can help mitigate the DC current ripple. Several hybrid NG topologies reported in the literature that exhibit desirable features are constrained by single-level DC voltage control methods or non-standard or restricted voltage levels [99,100]. While some studies suggest appropriate voltage levels to link several sources and loads, the implementation necessitates complicated control procedures for multiple ports, common mode problems persist because of inadequate isolation [101], and higher number of switches makes them less efficient [99]. Moreover, using step-up/step-down converters to interface DC loads or sources increases the required power electronics, and contributes to increase in losses and expenses. Also, the PV interfacing converter with MPPT control may remain unused when PV power is not available. This leads to cost and space inefficiency of the nanogrid [99,100].

An issue in hybrid NGs is fault protection, which is as critical as power balance and energy management. While advanced technologies for protection against AC faults exist, DC fault protection is challenging due to the lack of zero-crossing points in DC current waveforms, making DC faults uninterruptible by conventional AC circuit breakers (CBs) [102]. Modified DC CBs are available; however, they are larger, more expensive, and more complex [102]. Moreover, the lower voltage levels in NGs make it difficult for current limiters to detect faults, and the small impedances between nodes can cause DC faults to spread rapidly and aggressively [103]. Proposed solutions like overcurrent protection require overrated power electronics, while techniques like distance protection and signal processing are better suited for larger systems [102,103]. Fault isolation using contactors and power electronic interfaces offers a more straightforward solution [102,103].

Additionally, the literature on the grounding issue in DC NGs/MGs is not as developed as it is for AC systems, which brings us to our next concern: the grounding problem in hybrid NGs. A potential difference between AC and DC grounds can be troublesome in a system without galvanic isolation, particularly for a hybrid system that contains both AC and DC subsystems [103]. These issues become more critical in an MG composed of interconnected NGs, exchanging energy. A DC fault in one NG can degrade the power quality of the network, especially when grid support is limited due to protective devices [103]. If the main grid is unavailable, the fault can spread across connected NGs, leading to greater instability and disruptions throughout the network.

An energy management system is intended to optimize the operation of the NG through GHG emission minimization, reliability maximization, maximization of utilization of renewable energy sources, energy cost minimization, or energy storage lifecycle maximization. Optimizing one objective function may influence the other ones. For instance, prioritizing the energy storage device's maximum lifespan may lead to poor utilization of renewable energy sources and increased reliance on the grid. Maintaining NG's reliability, optimal functionality, and affordability requires careful EMS selection [104].

6.2. Transaction and Regulatory Challenges

In addition to the technical difficulties discussed earlier, there are regulatory and transactional factors to consider while integrating NGs. Even though some of these problems have been covered by researchers [16], it will still be challenging to completely integrate NGs into the current distribution networks in the absence of defined rules and clear regulatory frameworks similar to those for ACNGs/MGs. Encouraging trust among prosumers, and utility companies, as well as facilitating the widespread deployment of NGs, requires regulatory compliance in addition to clearly specified safety standards, energy management, and energy trading rules [80,105].

A challenge lies in creating a standardized pricing system for NGs, especially in community settings where multiple NGs interact. Establishing transparent pricing and ownership rights is crucial for promoting decentralized energy trading and creating a fair market for prosumers. Additionally, since NGs can potentially act as competitors to utility grids, policies that define grid interconnection and energy compensation must be clarified to encourage cooperation between prosumers and utilities [80,105].

Cybersecurity and privacy are also critical as NGs expand and use advanced communication and metering technologies. Unauthorized access or cyber threats, such as false data injection attacks, can compromise system control and energy trading. To address this issue, reference [99] introduced a secondary control mechanism to detect and mitigate false data injection attacks in DC microgrids.

Environmental concerns, such as GHG emissions and battery recycling, need to be addressed through well-defined protocols. For example, fuzzy techniques and stochastic programming have been proposed to optimize power dispatch while minimizing pollutant emissions, considering uncertainties in price, load, and generation forecasting [106].

Economically, ensuring cost-effectiveness is essential. Reference [107] proposes an economic dispatch model that integrates available local generation into a two-stage process. The first stage involves a day-ahead hourly and real-time, sub-hourly model, while the second stage verifies the day-ahead dispatch feasibility by considering uncertainties in renewable energy sources and load demand [107].

Lastly, adhering to existing grid safety standards is imperative for NGs to maintain the stability, reliability, and resilience of the main grid. Establishing regulatory compliance is thus a fundamental requirement for the successful deployment and scaling of NGs within the current distribution grid framework. A brief overview of the issues raised by NGs' integration into the distribution grid is provided in Figure 7.

Figure 7. Potential challenges in integrating NGs in distribution power grid.

7. Conclusions and Future Work

The growing demand for a reliable and sustainable energy supply highlights the important role of nanogrids (NGs) in small geographical areas, where they support local loads and maximize the utilization of renewable energy sources in households. Interest in NGs has surged due to advances in semiconductor technology, the decreasing costs of renewable energy sources particularly solar panels, progress in energy storage systems, and the development of control systems with energy management and metering devices. The simplicity, compact size, cost-effectiveness, and modularity of NGs make them an appealing solution for remote areas, attracting research interest.

This paper provided an overview of NG structures and configurations, along with their applications. Starting with the fundamental concepts of NGs, it explored their main topologies and delved into the algorithms and energy management methods used for controlling energy sources and balancing power flow within the system. Hierarchical control methods incorporating primary, secondary, and tertiary layers were discussed, demonstrating how they coordinate and control power electronics within the system to maintain voltage regulation in both islanded and grid-connected modes. Additionally, the implementation of peer-to-peer (P2P) power sharing through blockchain technology in NGs has shown potential benefits, such as reduced electricity bills, enhanced demand–response capabilities, secure transactions, and minimized energy costs.

Looking ahead, as the demand for electric vehicles (EVs) continues to rise, it is crucial to explore their integration into NGs, taking potential system constraints into account. Also, deploying highly efficient power electronic converters with inherent advantages like soft switching and fault current limitation could simplify converter control and energy management processes. Since EV charging can significantly increase power demand at the residential level, particularly when combined with other high-power loads, conventional battery energy storage systems (BESSs) at homes may struggle to meet this demand effectively, highlighting the need for alternative solutions and detailed analyses to address these challenges in the future work. One promising approach involves integrating hybrid energy storage systems (HESS), such as BESS combined with flywheel energy storage system (FESS) or ultracapacitors (UCAP). These hybrid configurations leverage the complementary characteristics of different storage technologies, with BESS providing high energy density for sustained power delivery and FESS or UCAP offering superior power density and rapid response for managing transient peak loads. Exploring the feasibility, control strategies, and cost-effectiveness of HESS in residential applications presents a valuable opportunity to advance nanogrid energy management systems and address the evolving energy needs of modern households.

Furthermore, practical pilot implementations, derived from laboratory research, should be prioritized to assess the real-world applicability of findings reported in the literature. Additionally, machine learning techniques can be employed to optimize decision-making processes, predict energy consumption patterns, and adapt to dynamic changes, thereby enhancing the efficiency of NGs. Finally, further studies are necessary to establish comprehensive standards and regulations for NGs, particularly for DC and hybrid NGs. These regulations should encompass power exchange protocols and pricing standards to ensure smooth integration and operation of NGs within the broader energy grid.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	**Definition**
ACNG	AC nanogrid
BESS	Battery energy storage system
BTM	Behind the meter
CB	Circuit breaker
CET	Community energy trader
CHB	Cascaded H-bridge
CL	Critical load
DAB	Dual active bridge
DBS	DC bus signaling
DCM	Discontinuous current mode
DCMG	DC microgrid

DCNG	DC nanogrid
DER	Distributed energy resource
DG	Distributed generator
DS	Distributed source
ECC	Energy control center
EMS	Energy management system
ESS	Energy storage system
EV	Electric vehicle
FESS	Flywheel energy storage system
G2V	Grid to vehicle
GHG	Green house gas
HESS	Hybrid energy storage system
HF	High-frequency
IoT	Internet of things
iTCM	Integrated triangular current mode
LF	Low-frequency
LoRaWan	Long-range wide-area network
LV	Low voltage
MCSP	Multi-cell series-parallel
MG	Microgrid
MMC	Modular multi level converter
MPC	Model predictive control
MPPT	Maximum power point tracking
MV	Medium voltage
NCL	Noncritical load
NG	Nanogrid
NN	Neural networks
NPC	Neutral point clamped
NZE	Net zero emission
OES	Open-energy system
P2P	Peer-to-peer
PFC	Power factor correction
PL	Power loads
PLC	Power line communication
PLS	Power line signaling
PV	Photovoltaic
PWM	Pulse width modulation
RES	Renewable energy source
SCL	Smart critical load
SoC	State of charge
SST	Solid state transformer
STATCOM	Static synchronous compensator
TCM	Triangular current mode
THD	Total harmonic distortion
ToU	Time of use
TSDDC	Tri-switching double duty ratio boost converter
UCAP	Ultracapacitor
V2G	Vehicle to grid
V2H	Vehicle to house
V2X	Vehicle to grid or house
VLS	Voltage level signaling
VPP	Virtual power plant
VSC	Voltage source converter
ZVS	Zero voltage switching

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