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Review

Local Power Distribution—A Review of Nanogrid Architectures, Control Strategies, and Converters

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Abstract: Environmental issues and the global need to extend sustainable access to electricity have fostered a huge amount of research in distributed generation by renewables. The challenges posed by the widespread deployment of distributed generation by renewables, such as intermittent power generation, low inertia, the need for energy storage, etc., call for the development of smart grids serving specific local areas or buildings, referred to as micrograds and nanogrids, respectively. This has led in the last decades to the proposal and actual implementation of a wide variety of system architectures and solutions, and along with that the issue of the power converters needed for interfacing the AC grid with DC micro- or nanogrids, and for DC regulation within the latter. This work offers an overview of the state of the art of research and application of nanogrid architectures, control strategies, and power converter topologies.

Keywords: nanogrids; hierarchical control; grid architectures; interfacing power converters; control strategies; power converter classification

Citation: Santoro, D.; Delmonte, N.; Simonazzi, M.; Toscani, A.; Rocchi, N.; Sozzi, G.; Cova, P.; Menozzi, R. Local Power Distribution—A Review of Nanogrid Architectures, Control Strategies, and Converters. *Sustainability* **2023**, *15*, 2759. https://doi.org/10.3390/su15032759

Academic Editor: Noradin Ghadimi

Received: 28 December 2022
Revised: 29 January 2023
Accepted: 30 January 2023
Published: 3 February 2023

1. Introduction

Several factors including the shift towards ever-increasing use of distributed energy resources (DERs) often small or very small in size and power capacity, the need for efficient energy use, progress of battery energy storage system (BESS) technologies in terms of size, weight, and cost reduction, and the introduction of cheaper controllers and smart metering devices, favor the development and deployment of electric microgrids (MGs) and nanogrids (NGs) not only where access to the power grid (PG) is impossible or economically unviable (e.g., remote communities, especially in developing countries) but also in more commonplace scenarios such as residential and commercial buildings [1,2] where the grid connection is not an issue per se.

While MGs, due to their relatively large size and impact on the development and management of the PG at large, have been the object of significant standardization efforts, NGs—although in a way rather more ubiquitous than the former—are somewhat less clearly defined. Early definitions of NGs, for example, include the following two:

- "a single domain for voltage, price, reliability, quality, and administration" [3], where the accent is on power distribution only, functional aspects of the loads are disregarded, and power sources are not part of the NG, which may or may not include BESS but must feature a controller device. In this case, NGs can be also seen as clusters of a MG;
- "a small power system that uses a combination of renewable and non-renewable energy sources to supply power to small local loads" [4]; here, the accent appears to be more on the size of the system, which is seen as a miniature replica of larger power systems, with its own energy sources, storage, loads, and some controlling entity.

Other definitions are referenced in [2].

From the architecture point of view, neither definition can be seen as an absolute delimitation of the NG concept. However, the concepts of MG and NG themselves can be seen as misleading due to a direct link to a scale concept. From the grid architecture point of view, it could be easier to define single domain grids, clusters of single domain grids, and power grid.

Irrespective of the definition of choice, a few common—although non-universal—features of both AC and DC NGs are:

- local access to some type of DER;
- use of BESS;
- connection to the PG (with some islanding capability).

These are key factors giving NGs attractiveness in terms of sustainability (thanks to renewable sources such as PV and wind), efficiency (reduced losses due to proximity between energy sources and loads), reliability and resilience (islanding capability—at least for a limited time—thanks to DERs and BESS), and power quality (short-term voltage stabilization provided by BESS).

These features, similar to those of MGs, inevitably require that the NG be equipped with a variety of static energy converters [5], e.g.,:

- DC/AC converters to connect DERs with DC power output such as photovoltaic (PV) plants or fuel cells (FCs), as well as BESS, to AC loads, or when a bi-directional connection of a DC NG to the PG is required;
- DC/DC converters for intra-NG level shifting to power DC loads of different type and sizes, and for voltage boost in battery charge circuits;
- AC/DC converters for the point of common coupling (PCC) between the PG and a DC NG, or at the interface between an AC NG and BESS.

The increasing diffusion of NG installations and the rapid progress of converter and power semiconductor device technologies make the field of NG converters a very hot and dynamic research area; this paper aims at proving the reader with a reasoned review of recent developments.

This paper is organized as follows. Section 2 gives an overview of system architectures and classification. In Section 3 we focus in particular on islanded architectures. Then, NG control strategies are presented in Section 4, while Section 5 deals with NG converter architectures and topologies. Finally, conclusions are drawn in Section 6.

2. Nanogrid Architectures

MGs can be classified based on their topology in three major groups, namely, AC, DC, and hybrid [6,7], as schematically shown in Figure 1. NGs can operate as AC, DC, or hybrid structures, too [5,8], but they usually have a smaller capacity and serve a smaller area (e.g., a single building or load) [9–11].

Another common trait between MGs and NGs is the ability to operate both in islanded and grid-connected mode [5].

Most of the power transmission in the world is based on AC technology, which historically imposed itself on DC transmission mainly thanks to easy transformer-based voltage step-up for long-distance dispatch [12,13].

In the case of the AC NG of Figure 1a, energy flows into the AC NG feeder from the utility grid as well as from DERs that may be DC sources, such as PV arrays or batteries, requiring DC/AC converters; however, AC/DC/AC back-to-back converters are often utilized with AC power sources including wind farms, micro-turbines, or tidal power stations, to adapt the voltage level and frequency produced by the AC generators to the grid requirements [14]. On the other hand, large segments of residential and commercial loads consist of low power electronics such as personal computers, battery chargers, or LED lighting systems that require AC/DC conversion to be connected to an AC NG.

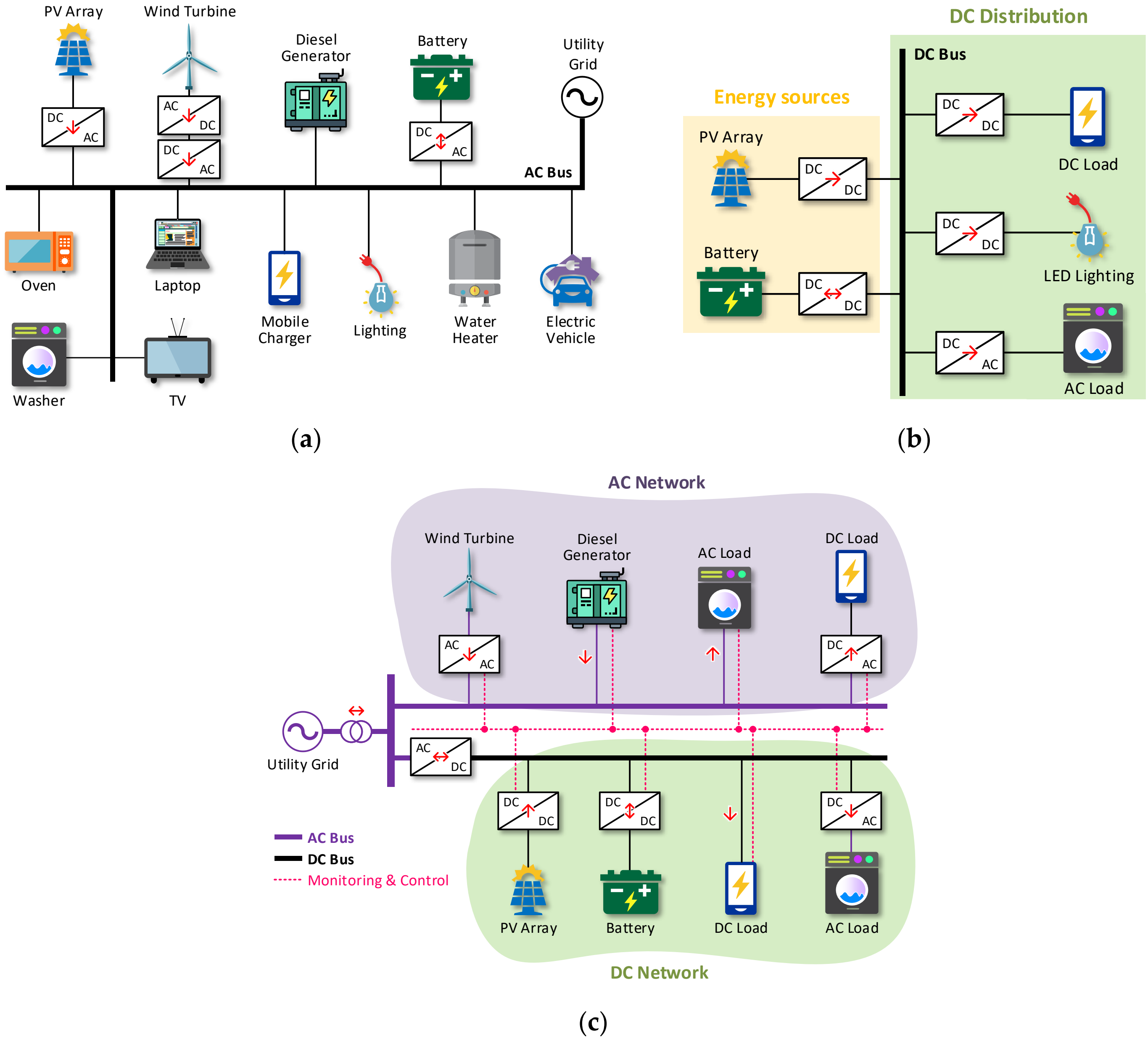


Figure 1. Examples of NG architectures: AC grid (**a**), DC grid (**b**), hybrid AC-DC grid (**c**).

Connecting these DC loads directly or through high-efficiency DC/DC converters to the bus of a DC NG (Figure 1b) would reduce the need for energy conversion stages and improve the overall efficiency and reliability of the system [15,16]. Recently, DC NGs have thus become increasingly attractive, also due to the improved performance and reduced cost of native DC systems such as PV, BESS, electric vehicles (EVs), and FCs, which can be connected to a DC grid efficiently and reliably [6,17]. In fact, avoiding double conversion from DC to AC on the generation side and from AC to DC at the load end, the system complexity is reduced and its efficiency and reliability are increased [11,14,18]. Moreover, the absence of reactive power in DC distribution lines reduces power losses and voltage drops, increases the capacity of electrical lines, and helps to avoid electromagnetic interferences [14]. In [19], the transmitted power is found to increase up to a factor of ten moving from AC to three-line DC distribution. Finally, synchronization issues are avoided [15]. Table 1 summarizes the advantages of the DC NGs over the AC NGs.

Table 1. Advantages of DC NGs over AC NGs.

Advantages	References
Energy conversion stages reduction	[15,16]
Overall efficiency improvement	[6,11,14–17,19]
Reliability improvement	[6,11,15–17]
Absence of reactive power and less losses	[6,11,14,15]
Augmented transmit power capability	[6,14,16,19]
No electromagnetic interference	[6]
Complexity reduction	[6,15,16]
No synchronization problems	[6,11,14,15]
Control algorithm simplification	[6,15,17]

Future DC NGs will likely use two voltage levels: a high-voltage DC (e.g., 380 V) for home appliances or EV charging, and a low-voltage DC (LVDC) (e.g., 48 V) for supplying computers and low-power electronics [5,9,15,20], hence the need for efficient DC/DC conversion.

The DC NG is connected to the utility grid via a bidirectional AC/DC converter that has to be properly controlled to compensate for the voltage ripple arising on the DC voltage bus: ref. [21] discusses a zero-sequence operation mode of the converter and gives a summary of other ripple mitigation approaches.

Refs. [9,22] for example considers a commercial power system scenario with a large amount of non-linear loads such as lighting appliances, computers, monitors, adjustable-speed drives for air conditioning, etc. A traditional grid scenario, where each load is supplied in AC, is compared with DC-based architecture demonstrating that the latter is convenient from the efficiency, reliability, and economic points of view. A DC bus voltage equal to the peak value of the standard 230 V AC line is shown to be the best solution for supplying DC native AC loads. This prevents the overload of the input rectifiers of the power supply units by lowering the amount of current flowing.

Ref. [23] describes a home-level, small power DC NG with AC interface with the PG. A comparison between the modified DC version of the home appliances and the legacy AC ones is carried out in order to show the convenience of the DC distribution. Ref. [24] also presents a residential-level NG implementation featuring a LVDC bus with an additional AC grid interface. Ref. [25] demonstrates the benefits of DC migration showing results of efficiency improvements of various system components in a commercial building supplied by 380 V DC and providing local 24 V plugs for small loads.

Finally, a hybrid NG (see Figure 1c) combines separately controlled AC and DC distribution lines to exploit the advantages of both AC and DC grids [26–28]: DC loads and DERs can be connected to the DC bus, while AC loads and DERs can be connected to the AC bus, potentially eliminating the need for DC/AC/DC or AC/DC/AC conversion, thus increasing efficiency and reducing complexity and cost. In hybrid MGs [29], as for NGs, the design can be optimized to minimize the cost of investments and maximize energy efficiency through the optimal sizing of DERs, loads, and ESSs following different approaches: a combination of different particle swarm optimization (PSO) based algorithms in [30], a multi-objective optimization of the mathematical model of the MG/NG aimed at minimizing daily energy consumption and greenhouse gas (GHG) emissions [28], or through a time-of-use approach to reduce the cost of energy [31].

Ref. [32] presents a case study of hybrid AC-DC NG, part of a larger campus-level MG. The NG can operate in islanded mode in case of MG faults. The NG is equipped with two sets of PV arrays—separately connected to AC and DC subsystems—and a BESS used by both the subsystems to level-off the PV output power. The DC distribution bus features a 48 V DC voltage while the AC bus is a four wire, three-phase bus with 120 V line-to-neutral voltage. DC/DC buck converters interface a set of PV arrays with the DC subsystem. The other set of PV arrays is connected to the AC subsystem via DC/AC inverters. The AC and DC buses are interlinked through bidirectional AC/DC converters that transfer power between the two subsystems and regulate the bus voltage amplitudes. The NG is connected with the higher-level MG on the AC side.

Most NGs, conceived as the evolution of an existing part of a legacy AC grid, are characterized by a hybrid topology, allowing us to take advantage of the DC distribution while maintaining the possibility to power AC loads and to exchange energy with an upper-level distribution grid (usually in AC).

The architecture of a power system impacts its scalability, reliability, robustness, resilience, and cost. This means that it is possible to draw another classification for MGs and NGs considering the type of bus used for power distribution. An interesting comparative analysis of DC MG architectures which can be extended to AC and hybrid MGs and NGs was given in [33]. Here single-bus (Figure 2a,b), multi-terminal (Figure 2c), ladder-bus (Figure 2d), ring bus (Figure 2e) and zonal-bus (Figure 2f) structures are compared in terms of bus voltage levels, BESS connection, inherent stability, expandability to multiple buses, and reliability. Each of these solutions has its strengths and drawbacks, and more research in this area is necessary to reduce their complexity level and solve extant problems. However, in the absence of standardization, numerous optimal system architectures can be defined in relation to the chosen physical variables and to the requirements of the loads.

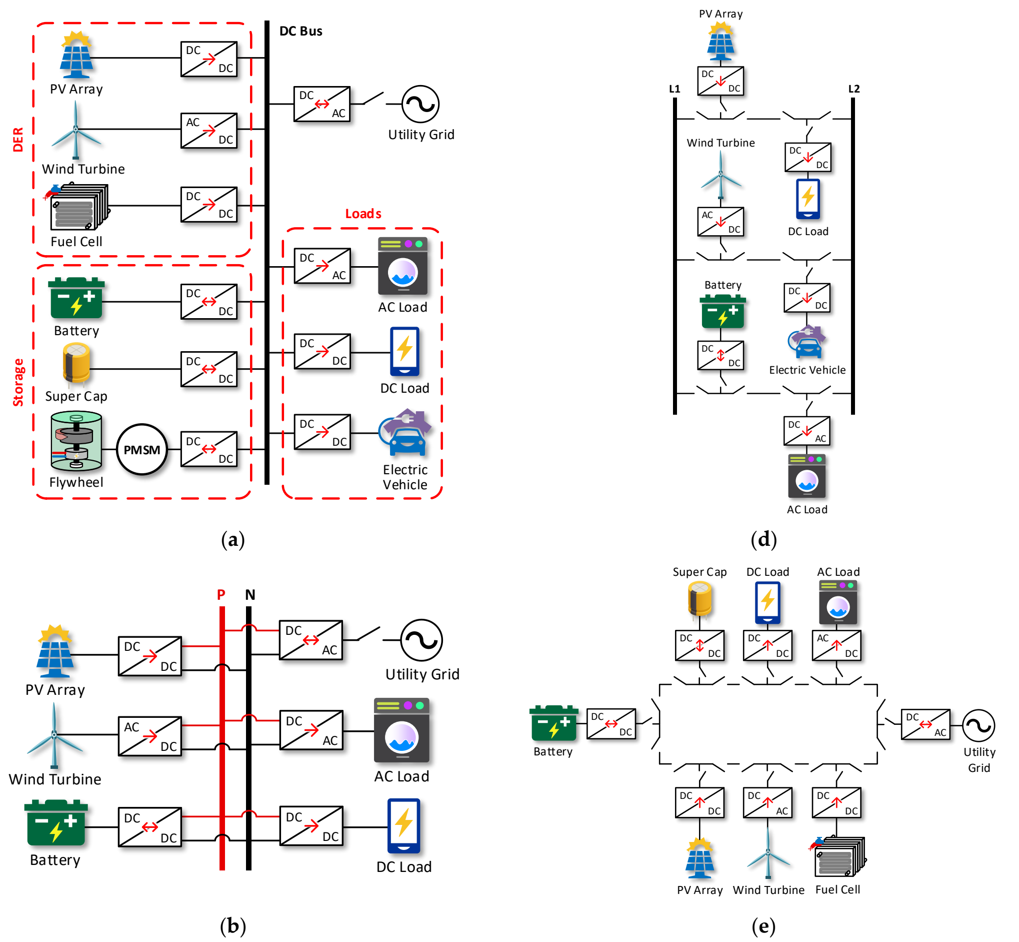
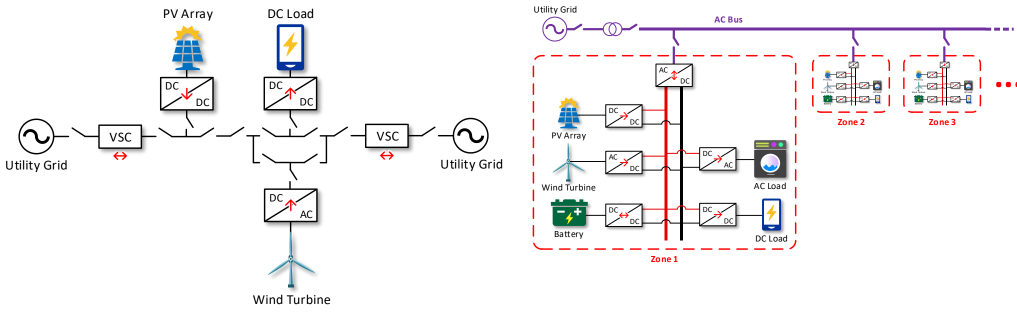


Figure 2. *Cont.*



(**c**) (**f**)

Figure 2. DC NG classification based on bus structure: single-bus (**a**,**b**), multi- terminal (**c**), ladder-bus (**d**), ring-bus (**e**), zonal-bus (**f**).

3. Islanded Nanogrids

Traditional examples of islanded NGs are vehicles including airplanes, ships, or cars; only recently was the idea of a bidirectional energy exchange with the grid taken into consideration. Other examples are niche applications where it is physically impossible to provide energy from the grid, for example, satellites and space applications [34]. Apart from these, in some areas of developing countries and isolated rural communities, the investment cost of grid connection of residential or commercial loads can be higher than that of the installation of an islanded NG [35]. Poor grid reliability and availability is a strong drive toward the deployment of autonomous NGs [36]. For these reasons, islanded grids represent a specific and hot field requiring research and standardization with its requirements for power conversion stages.

Figure 3 shows a general diagram of an islanded NG.

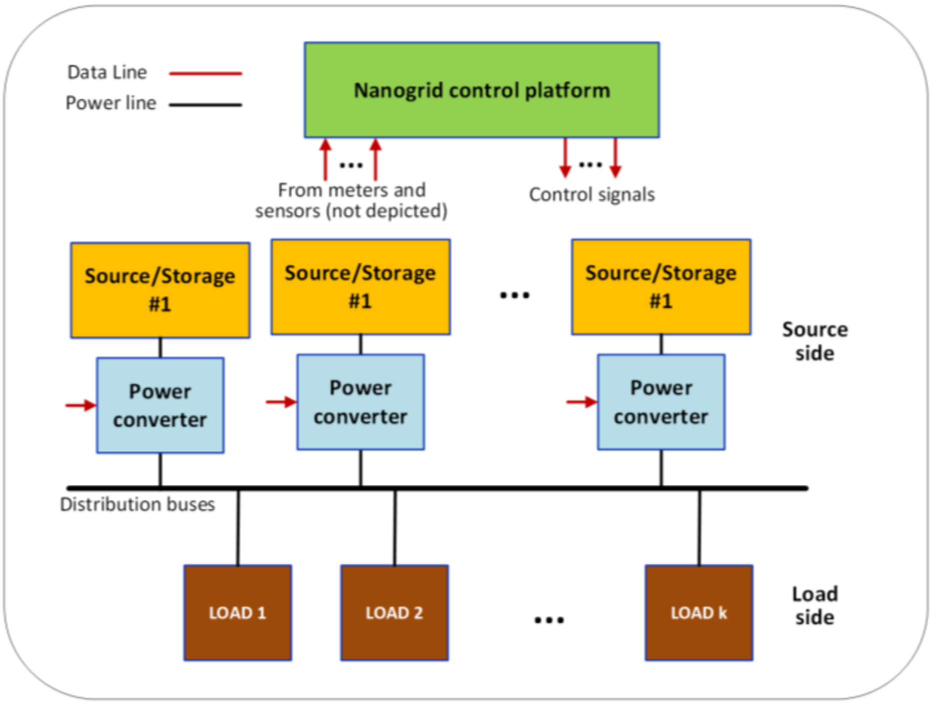


Figure 3. Diagram of an islanded NG [37].

These NGs are simpler than grid-connected ones because they do not include bidirectional power converters and transformers to interface them with others NGs or the utility grid. There can be more than one distribution bus, for example in hybrid AC-DC NGs, or when different voltage levels are needed by the loads.

The control platform that manages the whole system can be developed in different ways, with different topologies, such as the centralized, decentralized, and distributed ones shown in the next section. The controller receives signals from meters and sensors that monitor environmental parameters (e.g., solar irradiation or wind speed), currents, voltages, and the status of sources, storage elements, converters, and loads, and generates the signals to control the power converters and power switches. For simplicity, Figure 3 does not show power line switches, meters, and sensors.

The literature features numerous works regarding these autonomous electrical distribution systems with different architectures and distribution structures. Some of them address the problem of bringing electric energy to isolated rural areas, as in [38], where an islanded NG is implemented to supply 10 households and an irrigation pump in Bangladesh, or in [17]. An even smaller solution is presented in [39], describing a very low power NG powered by a PV panel deployed in a mountain area in Haiti to improve the living conditions of the inhabitants.

When continuity of service is required, island-operated NGs powered by renewable energy sources (RES) are often provided with one or more cogeneration units or other non-intermittent energy sources. For example, in [40] an electrolyzer cell is installed alongside a PV plant in order to ensure 24 h power supply. In [41] a diesel generator provides 29% of the whole energy demand, complementing PV panels (50%) and wind generation (21%). Nevertheless, there are examples of islanded NGs relying only on RES and storage systems, as in [42], where a 5-room residential unit is powered by a PV plant assisted by a BESS.

Finally, we may have another kind of islanded operation (where islanded is synonymous with isolated from an external utility grid) when multiple NGs are connected together and coordinated in order to exchange energy in a smart way to satisfy the global energy requirements. An example is presented in [43], where the authors explain the novel concept of a self-organizing NG (SONG) whereby multiple NGs are interconnected in a flexible and automated way through a common shared DC bus (48 V). Each NG interfaces with the bus by means of a market node that provides energy and energy price management rules, along with cybersecurity functionalities. Market nodes are also conceived as the central control unit of the corresponding NG as they compute the setpoints for each power conversion block. The power exchange between different NG components is achieved through a single-inductor multiport DC/DC converter.

Optimal sizing of renewable energy sources—mostly PV panels—and the BESS are key issues for islanded NGs [44], together with maximum power point tracking (MPPT) of PV modules and bidirectional converters for battery control [45]. MPPT algorithms can be split between direct and indirect methods. In the former case, the MPPT is done directly through measurement of the actual voltage and current; in the latter, the search relies on a database of previously measured characteristics and parameters of the specific PV source obtained under various conditions of irradiance and temperature, or on mathematical fitting functions [46]. Another critical issue for islanded NGs is the ability of stable and autonomous operation. For this reason, islanded NGs should implement load shedding strategies and storage device monitoring [47,48]. Energy management needs a dedicated optimization algorithm for the battery charging scheduled, depending on the specific RES or conventional energy source powering the system [49]. Effective control strategies for islanded DC NGs have been demonstrated based on hierarchical control of power balance and bus voltage, with no need for communication links [50,51]. The same can be said for AC islanded NGs, where V-f control strategies can be implemented for the robustness of the system [52].

Prototypes developed by different institutes, research centers, universities, as well as some commercial installations, are already providing results on the effectiveness and efficiency of islanded NGs [53]. Low-cost monitoring systems will also be an important piece of the puzzle for the viability of NG installations serving the needs of isolated communities in developing countries [54]. In fact, residential islanded NGs represent a bottom-up approach to satisfying the energy demand quite in line with the United Nations goal of affordable and clean energy [55].

In cases where there is the possibility of grid connection, the NG can be considered as a simple passive load, or a passive/active electronic load from the electricity provider point of view [56]. If the NG is connected to the grid through a rectifier or a unidirectional converter, the grid provides energy only when needed. In this case, storage can be downsized or avoided, reducing the investment cost at the expense of making the system less flexible. On the other hand, active participation of NG clusters or MGs in the real-time market with bi-directional power exchange with the utility grid has been shown to be economically beneficial for both consumers and the aggregator [57].

4. Nanogrid Control Strategies

Together with the specific NG architecture, the adopted control strategy is another key aspect impacting the choice and design of power converters. For this reason, before addressing the topic of converters for NGs, we will give here an overview of recent research results obtained in the field of NG control. Considering the possible definitions of NGs, where a NG can also be seen as a scaled MG, we will give an overview of the literature on the control strategies applied to MGs that can be easily adopted for NGs. If a NG is considered as a single domain that interacts within a MG, it is of key importance to consider how it interacts with the other NGs and what MG control strategy can be used.

Given the complexity of energy grids, the approach followed in the development of their control system is typically hierarchical [58], with a variety of possible solutions. As early as in 2010, Guerrero et al. [59] proposed a general approach to hierarchical control of MGs derived by the multilevel hierarchical control of the International Society of Automation-95 (ISA95) standard. The 6 levels envisioned by this standard can be reduced in this context to 4 (levels 0–3). As the considered level increases, stability and robustness of operation of the lower levels require a decreasing bandwidth (BW) of downward control and reference signals. The resulting 0–3 levels (Figure 4) are the following:

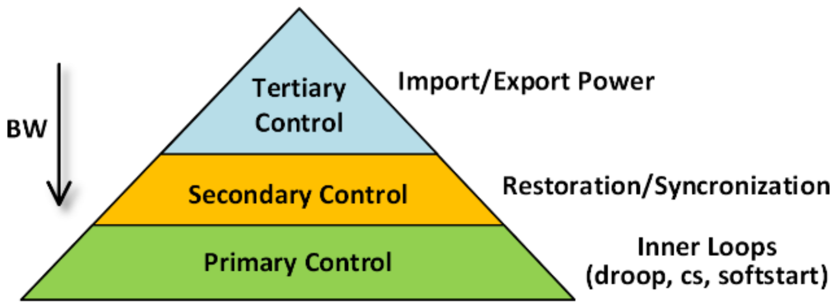


Figure 4. Hierarchical control levels proposed in [59]. Derived by the multilevel hierarchical control of the International Society of Automation-95 (ISA95) standard.

Level 0—Inner control loops: The regulation of each power module is performed at this level. Both feedback and feedforward control loops can be implemented to regulate the output voltage and the current while keeping the system stable. This level supports load sharing among parallel-connected power converters.

Level 1—Primary control: At this level a droop-control technique is typically applied for stability and damping which emulates the physical behavior of conventional sources; virtual impedance emulation can also be implemented.

Level 2—Secondary control: Some parameters of the primary control are passed to the secondary control to ensure that the electrical levels in the MG/NG are those required. This level can also include a synchronization control loop for seamless connection/disconnection with the utility grid to ensure smooth transitions between grid-connected and islanded modes.

Level 3—Tertiary control: This level controls the power flows between the MG/NG and the utility grid. Here, storage and source dispatching are scheduled by the distribution or transmission system operator.

Figure 5 shows a hierarchical control structure with conventional droop control for AC MGs proposed in [58]. The secondary control is used not only to synchronize all the MG units, but also to manage the synchronization between the MG with the main utility grid. Above secondary control, the tertiary control is used for controlling and managing the power flows between the MG and main grid. At this level, one of the tasks can be power re-distribution among DERs. The optimum economic operating point is reached by regulating the set point of each resource unit [60].

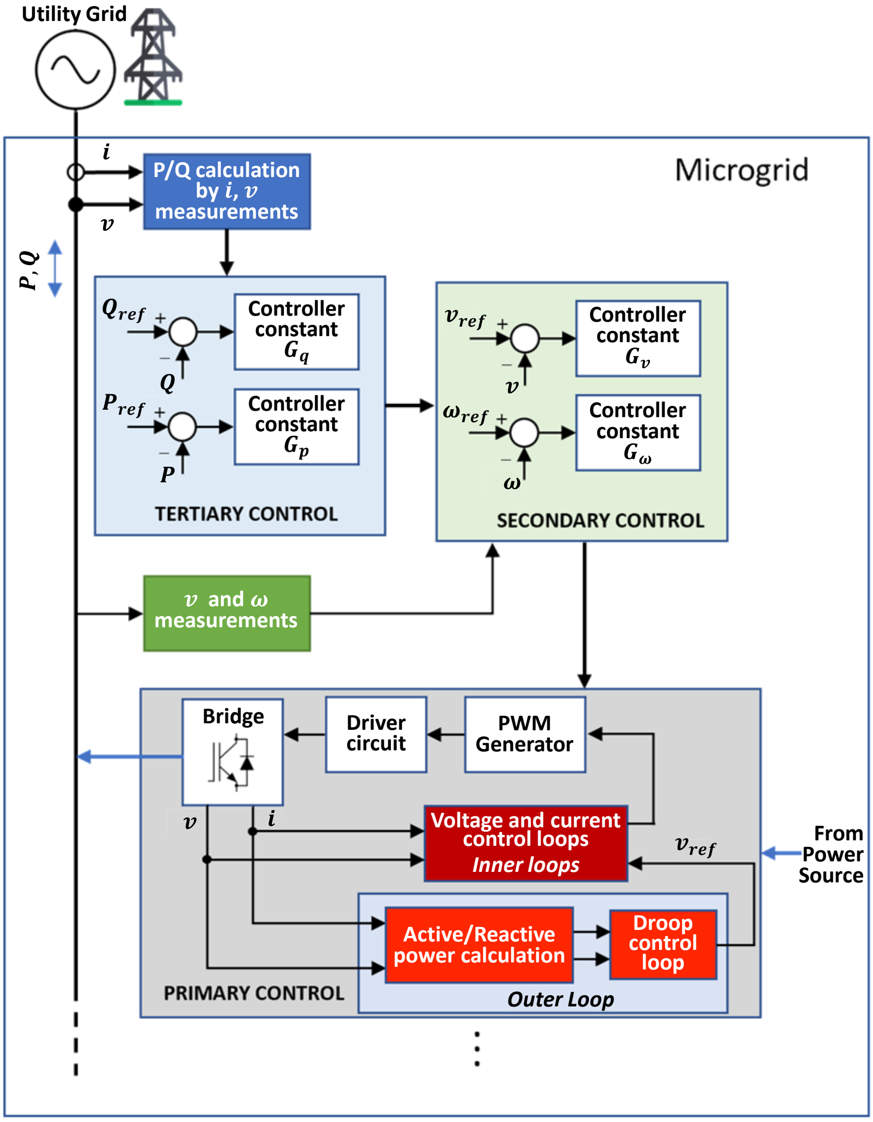


Figure 5. Hierarchical three-level control structure of an AC MG with parallel-connected inverters [58].

Considering the voltage amplitude E_i and the angular frequency ω_i of the i-th inverter connected to the AC grid bus, the equations of the conventional P-ω and Q-E droop characteristics shown in Figure 6 are the following:

$$\omega_i = \omega_0 - G_{\omega\_i} \cdot P_i \tag{1}$$

$$E_i = E_0 - G_{E\_i} \cdot Q_i \tag{2}$$

where P_i and Q_i are active and reactive power, respectively, at the output of the *i*-th inverter, ω_0 is the angular frequency at no load, E_0 is the inverter output voltage at no load, and G_{ω_i} and G_{E_i} are the angular frequency droop coefficient and voltage droop coefficient of the *i*-th inverter, respectively.

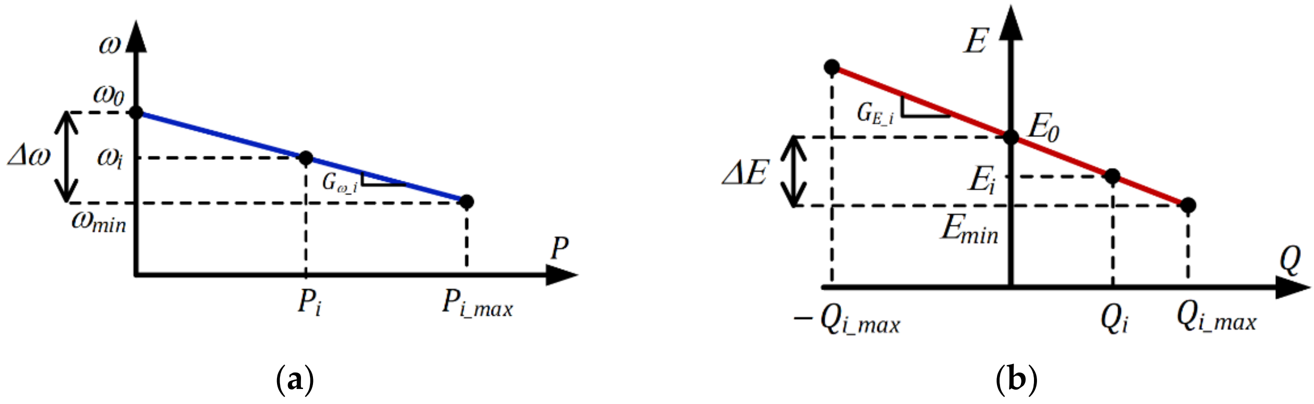


Figure 6. Conventional droop characteristics: (**a**) *P*-*ω*; (**b**) *Q*-*E*.

Droop coefficients are calculated using Equations (1) and (2) as follows:

$$G_{\omega\_i} = \frac{\Delta\omega}{P_{i\_max}} \quad (3)$$

$$G_{E\_i} = \frac{\Delta E}{Q_{i\_max}} \quad (4)$$

where $\Delta\omega$ and ΔE are the maximum accepted deviation of angular frequency and voltage, respectively, and P_{i_max} and Q_{i_max} are the nominal active and reactive power supplied by the inverter, respectively.

One of the distinct advantages of droop control is that it does not require critical communication connections between parallel-connected converters, which improves the system reliability [61,62].

By droop regulation, the primary control achieves the required power sharing at the expense of some deviation of angular frequency and voltage from their rated values. Secondary control—implemented by a higher-level hierarchical entity (e.g., a supervisor unit)—then takes charge sensing the MG voltage amplitude and frequency and compensating the deviations.

An interesting review of droop control techniques [63] shows solutions featuring an intermediate control loop in addition to the conventional ones, with voltage and frequency performance improvement of inverters parallel-connected with the AC grid bus.

The droop regulation can be applied also in DC MGs or NGs. Of course, in this case the control operations are different from those required in AC MGs. While in an AC MG two units are required to control frequency and voltage, in a DC MG the control is applied to voltage alone. Of course, it follows that the control of AC and DC MGs has to be implemented with different algorithms and approaches. However, the control strategies can share the same classification:

- Conventional Droop Control: It is one of the popular decentralized control strategies [64], adopted to minimize or eliminate the current circulating between converters without a communication link. It also provides good voltage regulation;
- Virtual-Resistance-based Droop Control: The disadvantages of the conventional droop control method are overcome using a virtual droop resistance [65] that is a function of the voltage at the output of the DC/DC converter connected to the DC bus distributing the electricity to the loads. In this way, the droop characteristic can be non-linear and voltage regulation is improved;

- Adaptive Droop Control: Adaptive control does not require in-depth knowledge of the system for control design, unlike conventional and virtual resistance droop techniques. In fact, in this case the control parameters are self-adapted to satisfy both power sharing and DC bus voltage stability criteria [66].

In any case, the droop units execute control algorithms to guarantee system performance and stability.

The main goals of MG control can be listed as follows [67]:

- Smooth switching from grid-connected mode to islanded mode, and vice versa;
- Efficient regulation of voltages and currents in both islanded and grid-connected modes;
- Efficient proportional load power-sharing;
- Ensure stability with constant power load as well as non-linear ones;
- Coordinate DERs, BES, and other storage devices included in the system;
- Control the power flows in the MG and, if grid-connected, with the utility grid;
- Synchronize the MG with the utility grid;
- Prevent grid failures and avoid black starts;
- Ensure uninterrupted power supply to critical loads (e.g., hospitals);
- Maximize DER potential;
- Minimize transmission losses;
- Optimize generation cost;
- Reduce the cost of load dispatching;
- Optimize the MG energy production to be competitive in the energy market.

A plethora of MG control strategies can be found in the literature. Figure 7 shows in a diagram a possible taxonomy of MG control techniques [68]. In the next sub-sections, we will focus specifically on the classification based on controller function. As shown in [2], the same topologies are applied to NGs for centralized, decentralized, and distributed controls.

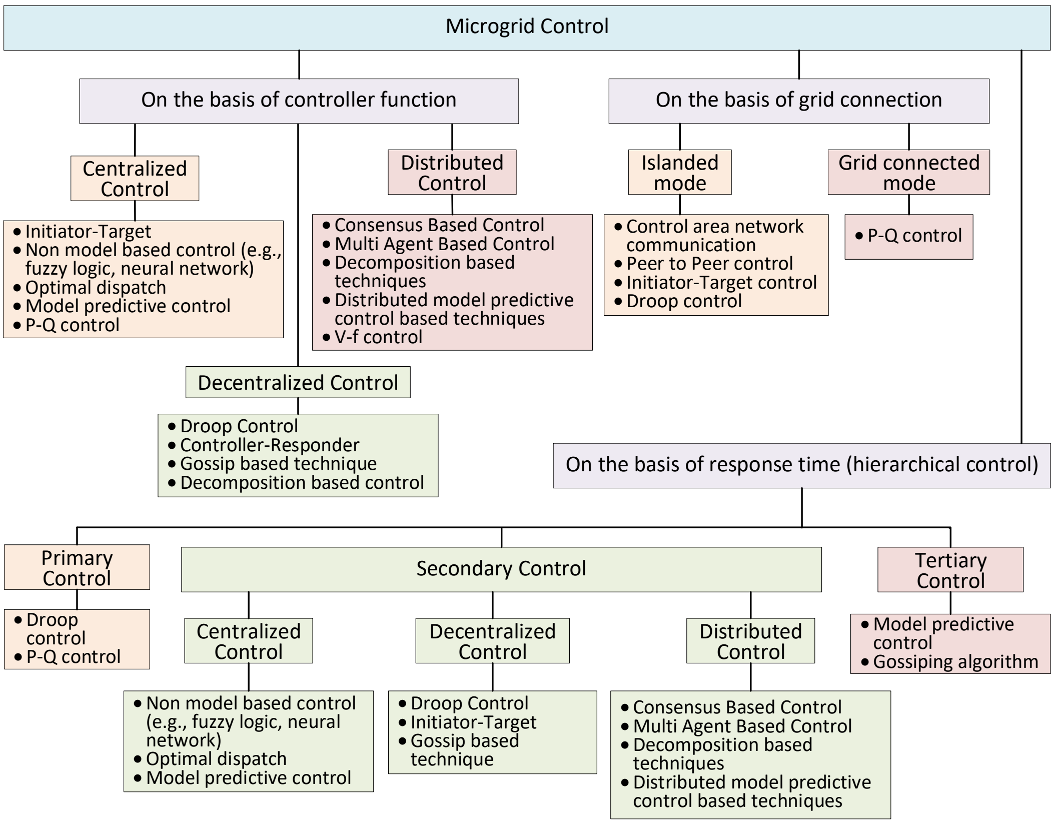


Figure 7. MG control techniques classification [68]. Classification can be made on the basis of controller function (centralized, decentralized, or distributed control), grid connection (islanded or grid connected), and response time (primary, secondary, or tertiary control).

4.1. Centralized Control

In the case of centralized control, the distributed generators of the grid are connected to a control unit such as a microcontroller, a switch, or a server that provides reference values for primary control. In this technique, a MG central controller (MGCC) gathers data from the controlled distributed generators, based on which it performs calculations to determine the control actions necessary to properly manage the power flows in the MG [69]. A schematic diagram of a MG with this type of control is shown in Figure 8. Hierarchically, a device controller operates at the primary control level.

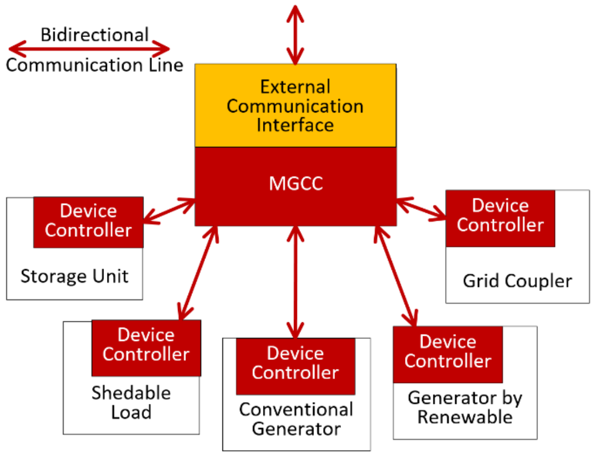


Figure 8. MG architecture with centralized control [70]. The MGCC controls all the peripheral units using an appropriate communication bus.

The control commands need to be transferred to the peripheral units via an appropriate communication bus. The strong reliance on high-speed communication between the MGCC and its monitored and controlled units is the main disadvantage of this method, because any communication fault will affect the performance of the whole MG and may even result in a complete black-out. In addition to poor fault tolerance capability, the major drawbacks of this control method include the need for supervisory control and low scalability. Among the advantages of the centralized controller are the effective controllability of the whole system, the need for a single controller, and the possibility to define general strategies for monitoring and controlling the system.

In DC MGs, the central control is typically implemented with the master-slave architecture shown in Figure 9 for managing parallel operation of multiple distributed sources [71]. In this case, a converter operates as a master voltage source converter controlling slave units feeding the required current as ordered by the master controller.

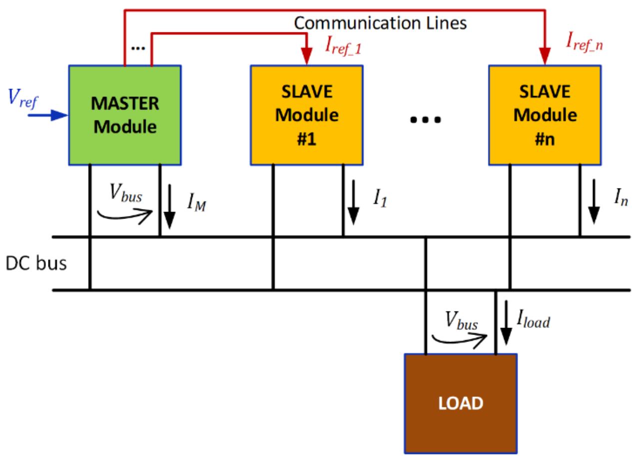


Figure 9. Master-slave control diagram of a grid with DC bus.

Problems related to specific converters can be solved with different methods on a case-by-case basis. For example, PWM controlled DC/DC step-up converters can usually regulate the output voltage over a small range, and works have been published aiming to solve or mitigate this problem. As an example, Guiying et al. in [72] showed the results obtained using a master-slave approach with phase-shift control for an input series and output-parallel full-bridge converter. Features such as flexibility and simple implementation make it suitable for high power and high voltage grids.

In [73], an improved master-slave control strategy based on I-ΔV droop addresses the problem of smooth transition between grid-connected and islanded modes. Here, when the MG is grid-connected, the energy storage converter operates as a slave controlling the current as in conventional master-slave control, while during island detection and islanding it smoothly transitions to voltage control with a droop approach.

A similar master-slave control architecture [74] was employed in a parallelable AC/AC converter for the connection of 60 Hz AC NGs (namely, large ships moored to the dock) to the 50 Hz AC grid to achieve optimum power sharing between the paralleled stages, and to guarantee maximum system availability—albeit in power derating mode—in case of faults.

4.2. Decentralized Control

In decentralized architecture, primary and secondary level controls are implemented in MG units above the converter controls. Different topologies can be found in the literature, with (Figure 10a) or without (Figure 10b) a MGCC controlling distributed generators (DGs) as proposed in [75].

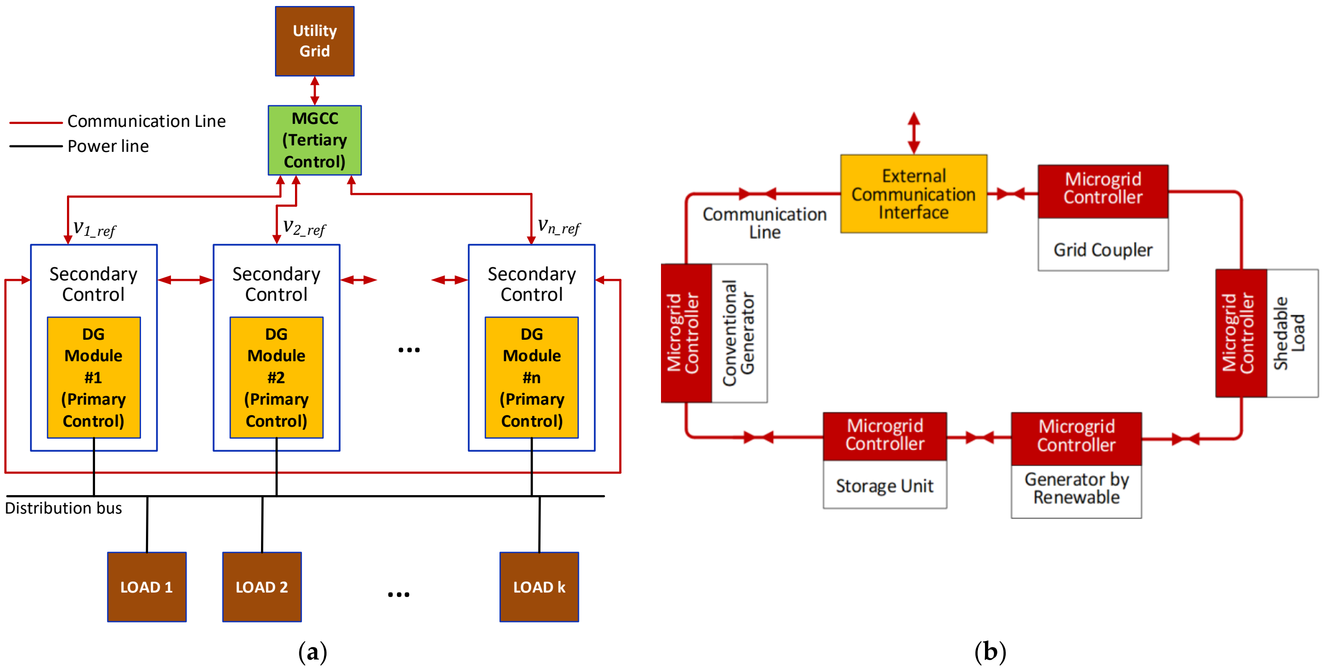


Figure 10. Architectures with decentralized control: (**a**) with control bus [70]; (**b**) without control bus; distributed generators connected to the MGCC for a decentralized secondary control.

The decentralized control strategy is considered the most reliable, but there are limitations due to the absence of or the reduced band of communication links.

4.3. Distributed Control

In the case of distributed control, the controllers of each power electronic unit are connected to a network to form a distributed secondary control mainly aimed at maintaining proper load sharing and steady grid voltage. This approach has the advantages of both centralized and decentralized control architectures.

Figure 11 shows a diagram of a distributed control architecture [76]. Here, each unit uses local variables, such as voltage and frequency, exchanged with its neighbors. The communication link is bidirectional to allow global optimization as in a centralized scheme.

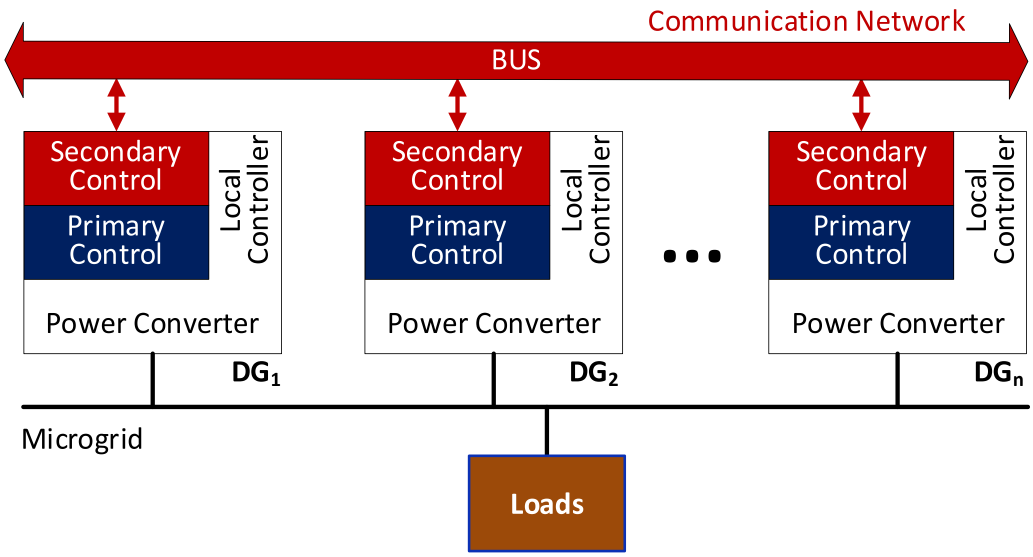


Figure 11. Architecture with distributed secondary control. The controllers of power electronic units are connected to a communication network.

Compared with architectures using single centralized control, this solution reduces the risk of global system failure since the system is immune to one-point failures. It also provides good stability along with reduced communication costs. Moreover, distributed control is highly scalable (a significant increase in distributed generation units makes it quite difficult to up-scale a centralized control system).

The main problems include voltage and frequency restorations, and power-sharing improvements [77].

Techniques used for a distributed secondary control are different. For example [78,79]:

- Multi-agent system;
- Consensus-based techniques;
- Decomposition-based techniques;
- Distributed model predictive control-based techniques.

4.4. Economic, Environmental, Social Considerations

MG and NG operation is directly related to the way they interact with the external environment. In particular, system-level control strategies can have an important impact on the economic, environmental, and social benefits coming from a smart management approach. In this context, the concept of smart grid (micro-, nano-, etc.) is declined within the smart city paradigm, becoming one of its most promising players. It is important to note that to optimize all of the benefits (electrical, economic, environmental) the grid control strategies must follow the evolution of the external environment, namely, energy market prices, pollution level, weather forecasts, etc.

Figure 12 highlights the principal interactions between grid stakeholders and consequent social benefits, obtained according to the adopted control policy.

Detailed discussion of these topics is beyond the scope of this review. Nevertheless, we provide some references as a starting point for further insights. The authors of [80] present a control strategy to optimize the economic dispatch combining information on the SOC of the ESS and the current cost of the energy on the market. In [81], a method is provided to minimize the total pollutant emissions and operating costs, accounting for uncertainties associated with forecasts on the evolution of the system. Ref. [82] presents environmental and economic considerations applied to DC MGs considering carbon emission cost, system operation and maintenance cost, equipment depreciation cost, MG interaction cost, time-of-use price, and renewable energy environmental benefits. In ref. [83] different control strategies are analyzed from the economic point of view, in the particular case of time-of-use tariffs energy market. Economic dispatch can also be optimized through forecasts based on day-ahead hourly and real-time sub-hourly models, evaluating the worst-case scenario (and a high-level of uncertainty), considering the internal energy availability [84]. In refs. [85–87], the authors discuss the MG scheduling problem for the optimization/minimization of economic and environmental costs in the case of EVs grid integration (respectively, vehicle to grid (V2G), plug-in EV, and off-grid systems).

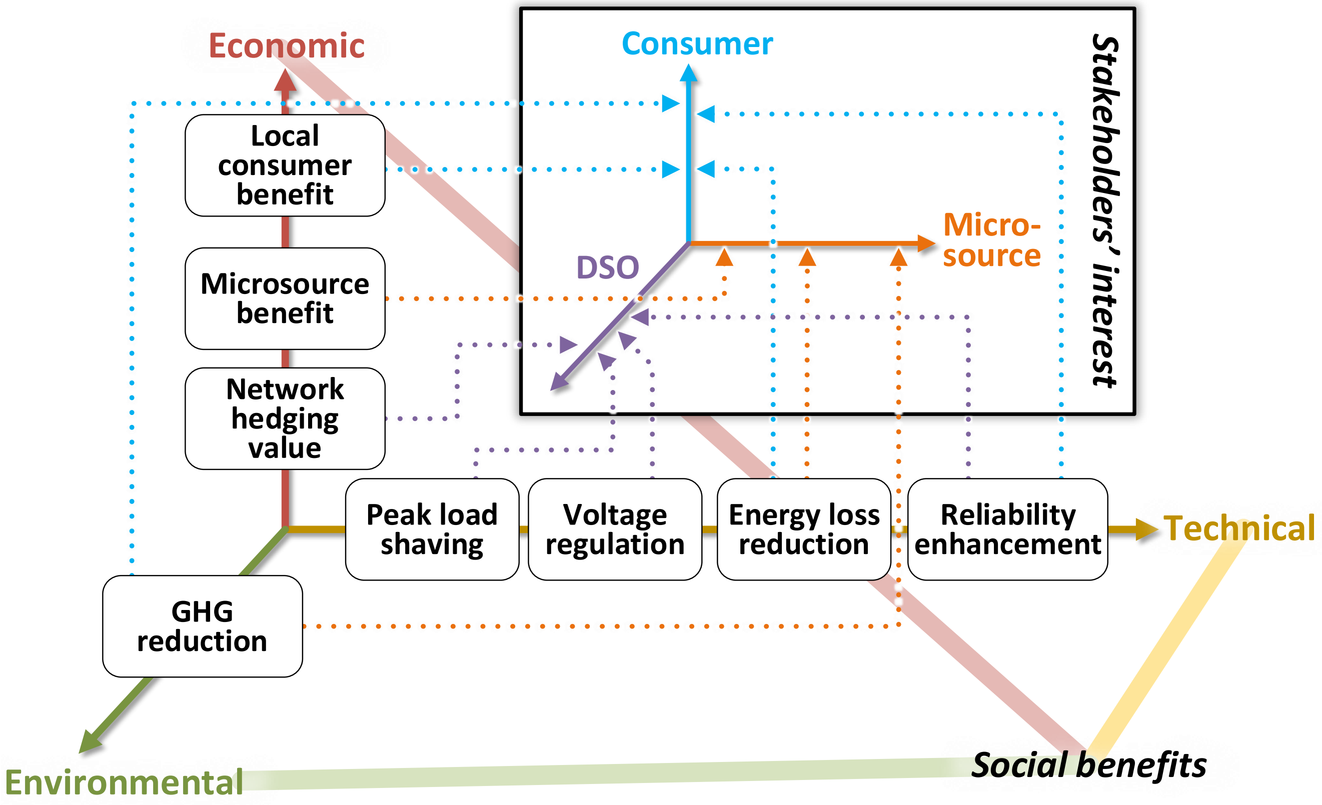


Figure 12. Interactions between grid stakeholders (consumers, distribution system operators (DSO), and micro-source operators) and consequent social benefits, obtained according to the adopted control policy.

Power loss and cyber-attacks are also critical issues that may affect the emerging use of NGs in datacenters; in [88] a new hierarchical control approach is presented for MG power loss mitigation, while in [89] the authors developed a secondary control for DC MG against false data injection attacks.

Finally, refs. [90–93] give a framework-level comprehensive review of MG sustainability, considering economic, environmental, and social benefits, costs and interactions, and discussing how the quality of life is expected to change in the coming years as a result of smart grid adoption.

5. Converters for Nanogrid Architectures

5.1. DC/DC Converters

Since NGs mostly contain DC storage, DC energy sources (e.g., PV plants, FCs, etc.), and smart DC loads, DC/DC converters are widely used. The DC/DC interface converters can be used for different purposes in the NG, and depending on their usage, different topologies can be adopted.

A NG must supply power to different kinds of loads, with widely different voltage levels (e.g., ranging from 5 V DC to 400 V DC). In this scenario, a multi-port converter can be useful to supply power to several loads. In [94], a multi-output converter for NG application is proposed based on a multi-winding transformer. Starting from a 48 V DC bus, it provides three outputs at different voltages: 5 V DC, 20 V DC, and an adjustable output between 50 V and 100 V DC. The first two outputs are unregulated, while the third has a boost converter controlled with a PI regulator. All the outputs are isolated thanks to a multi-winding transformer. In [95], a multi-output converter based on boost topology has been proposed. It provides two outputs, one isolated (48 V DC) and one non-isolated (24 V DC), from a single DC input (24 V DC). Another multi-output converter based on boost topology is described in [96]. This converter does not provide galvanic isolation, but it offers a high step-up ratio. In the proposed design the input voltage is a 12 V DC source and the outputs are 13, 21, and 93 V DC. Figure 13 summarizes possible topology alternatives for DC/DC multiport converters. In general, three possible solutions (which can co-exist in a given architecture) can be identified for the DC/DC multiport: (1) a first solution is based on DC/AC/DC converter using H-bridges and a high-frequency multiport transformer for galvanic insulation; (2) in case a second output is needed, an hybrid topology can be adopted generating a non-insulated DC output; (3) finally, a single-stage switching DC/DC topology converter can be used, without the galvanic insulation. The DC/AC stage represents a full-bridge or derived topologies for a square wave output voltage. The AC/DC stage represents a full-bridge or a rectifier or derived topologies. The DC/DC stage is a buck, boost, or buck-boost converter, or derived topologies.

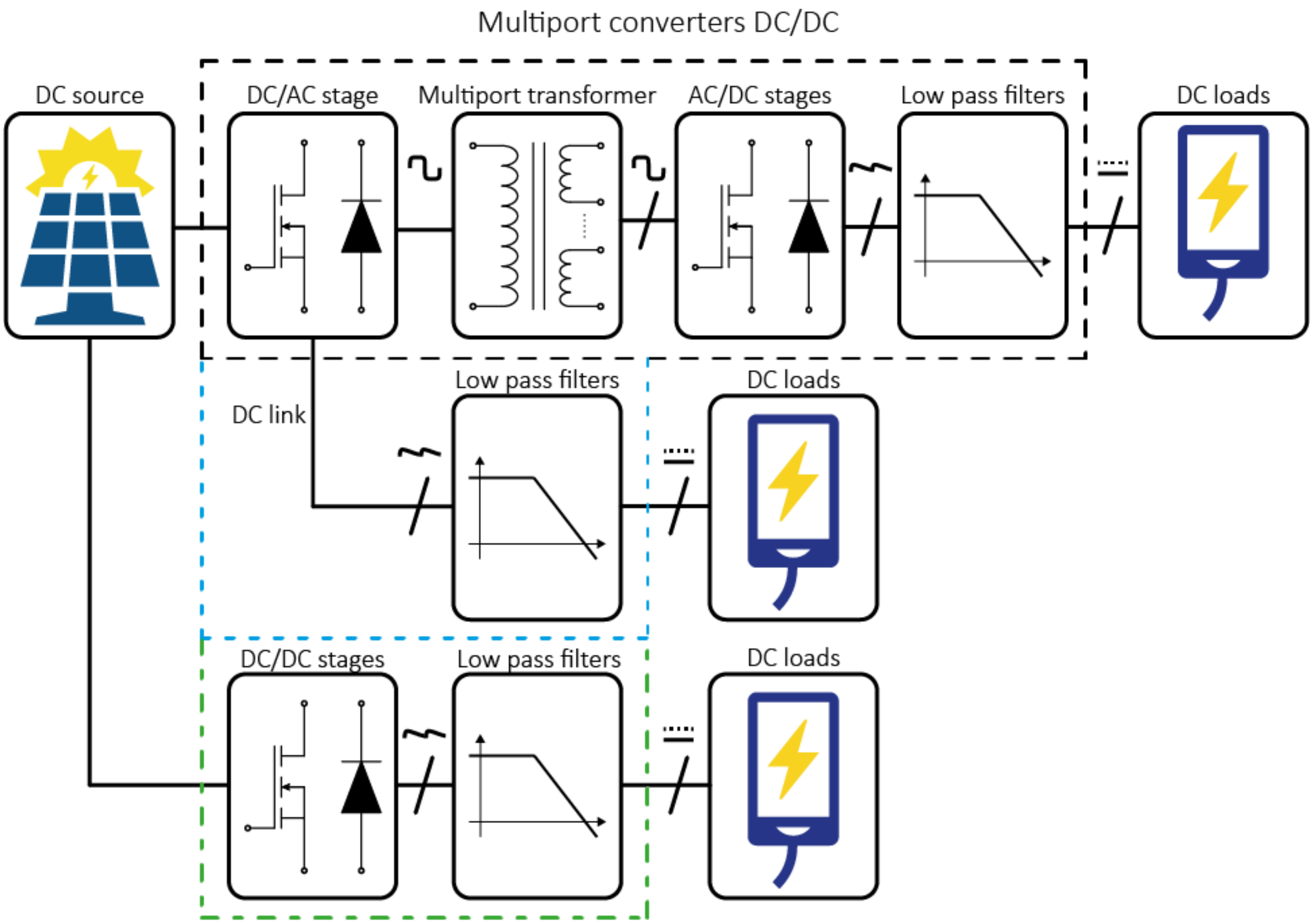


Figure 13. DC/DC multiport converter topology solutions.

In hybrid NG architectures where AC and DC loads coexist, hybrid converters are the optimum choice. In the case of domestic loads, a single-switch circuit derived from a buck-boost converter can be used [97] which converts the input DC voltage into the required AC and DC output voltages. Another buck-boost-derived converter is that of ref. [98]. Here, the authors propose a converter that has the capability of buck-boost DC output voltage along with the buck operation of AC output voltage. In that paper, a three-phase AC load has been considered, but the proposed converter can be modified to supply a single-phase AC load. The main advantages of this converter are the possibility of buck-boost operation at the DC terminal, the positive buck-boost output voltage, and the fact that the inverter at the AC output does not require a dead time. A hybrid converter can also be used in NGs to supply AC loads and DC loads as well as an ESS; ref. [99] reports on the design of a quadratic boost derived hybrid converter with three-phase AC output which thanks to its architecture has better electromagnetic interference (EMI) immunity compared with a traditional voltage source inverter (VSI), and does not require a dead time.

Hybrid converter topologies used for these applications have the advantage that the number of switches can be reduced relative to conventional topologies. In [100], the authors demonstrate a boost-derived hybrid converter with 4 switching devices for 600 W power rating, 48 V input voltage, and 10 kHz switching frequency. An alternative solution is the hybrid switched inductor impedance source converter, where both AC and DC voltages can be regulated independently. Normally, these architectures present significant DC ripple voltage in discontinuous conduction mode, reducing the control capability of wide-variability loads and standalone AC or DC loads. This has been discussed in [101], where an inductor impedance source derived converter has been proposed to enable voltage regulation decoupling. The proposed solution works with 100 W DC and AC output power, 48 V DC link voltage, and 10 kHz switching frequency. Figure 14 illustrates the common traits of hybrid converter topologies. The DC/DC stage is a buck, boost, or buck-boost converter, or a derivation thereof. The DC/AC stage is a full-bridge inverter or derived topology yielding square-wave output voltage.

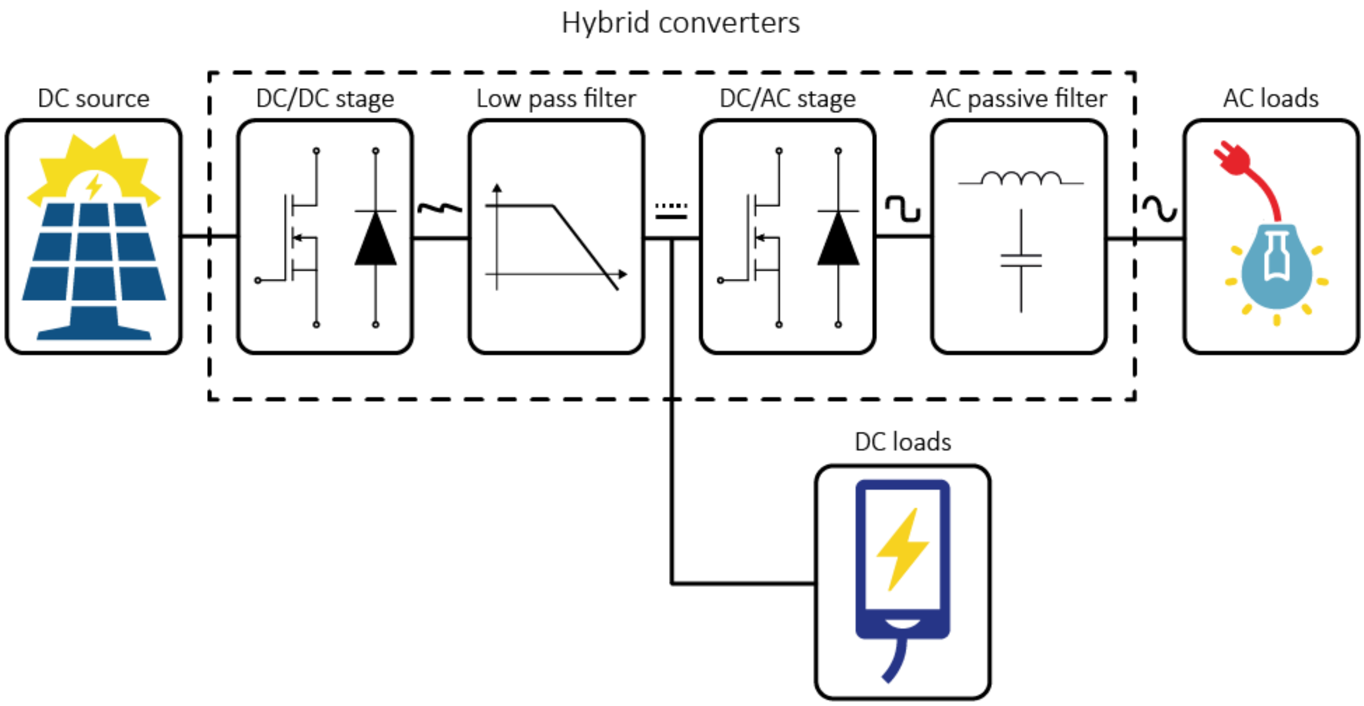


Figure 14. Hybrid converter topology solution.

If the DC/DC converter is used to regulate the NG DC bus, a high-gain converter is recommended. Ref. [102] shows a new configuration of a modified tri-switching state boost converter (MTSSB) that incorporates the voltage lift switched inductor (VLSI) module in the MTSSB converter. The key features of this configuration are continuous input current, lower voltage stress on the switches, and high voltage gain. This converter is designed to output 400 V DC from 20/26 V DC input, and it is rated for 500 W. Other high-gain DC/DC converters are based on coupled inductor and switched capacitors. These converters have the advantage of reaching high voltage gain with high efficiency and low voltage stress across devices. In [103,104], prototypes have been designed to output 380 V DC with 30 V input voltage.

Nevertheless, high voltages pose safety issues; hence, isolation is a key point. In [94,95] multi-port isolated output converters are proposed. The former paper proposes high-frequency operation with the aim of reducing the size of the transformer, the latter features isolation only for the output that strictly requires this safety provision.

Moreover, isolation is key for dual active bridge (DAB) inverters. In [105] a DAB uses a high-frequency isolation transformer to exchange power between an ESS and the NG DC bus. If isolation is not needed, a transformer-less bi-directional converter can be used: the converter proposed in [106] is based on a buck-boost topology and supports buck and boost operation in both power flow directions. This converter also offers high voltage gain (85 to 400 V DC). The prototype handles 1.6 kW and uses Silicon Carbide MOSFETs, with a peak efficiency of 97.5%. Bi-directional converters have many advantages for NG architectures and their possible interconnection. DAB converters can also be extended to triple active bridge (TAB) topologies. This could allow the use of a single converter for the interface of PV array, BES, and DC bus [107]. Active bridge converter topologies are shown in Figure 15. The DC/AC stage is a full-bridge inverter, or derived topologies, yielding square wave output voltage. The AC/DC stage is a full-bridge rectifier, or derived topologies.

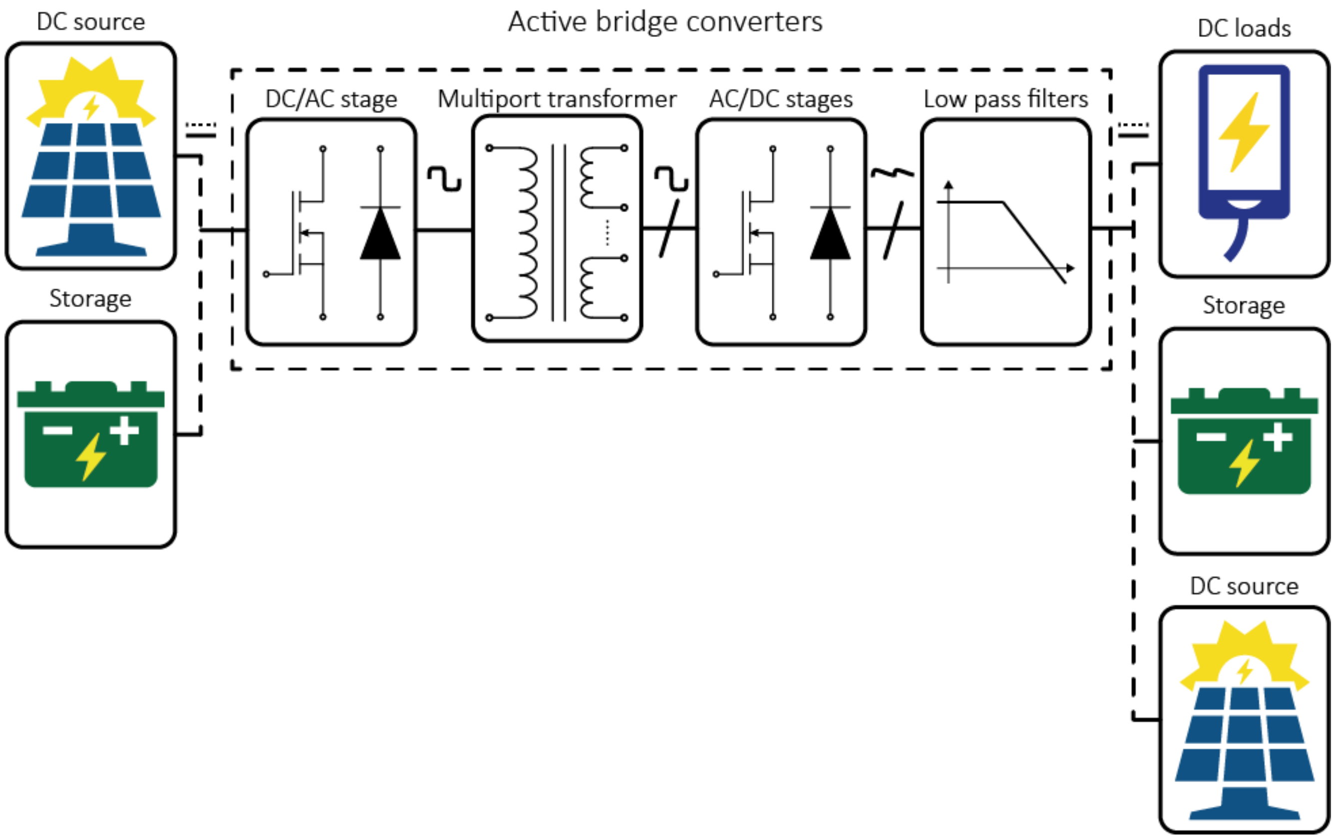


Figure 15. Active bridge converter topology solution.

DC/DC converters are also used in two-stage intermediate bus architectures, where the power transfer between a central DC bus link and a LVDC bus link has to be controlled. In this case, sub-harmonic oscillations may occur between the point-of-load converters and the intermediate bus converter and must be compensated [108].

Efficiency is one of the most important converter figures of merit, which can be improved using coupled inductors that eliminate the reverse-recovery losses of diodes, and also reduce the switching devices voltage stress; consequently, lower voltage devices can be used, thus increasing the converter efficiency [96,103,104]. Another solution that can improve efficiency is the use of LLC resonant topologies, the soft-switching operation of which further reduces losses [109].

Finally, converters with MPPT control are worth mentioning. NGs are usually powered by RES (e.g., PV plants, wind turbines, or thermoelectric generators) and can store energy in batteries. The power flow between RES and BES can be maximized by a DC/DC converter controlled by an MPPT algorithm [109–111].

5.2. DC/AC Converters

DC/AC converters are commonly used for utility grid interfacing and for hybrid NGs. In fact, inverters are key elements in a wide variety of power systems, ranging from single RES to the interface of entire MGs. Topologies differ in relation with requirements, such as grid-tied operation, islanded capability, fault detection performance, etc. The topic of good NGs or MGs interfacing with the utility grid is widely explored in the literature. In [112], an inverter is proposed with triple-loop controller. This solution features a common full-bridge converter with filter inductances and output capacitor, with 3 kVA nominal power, 450 V DC link voltage, and 20 kHz switching frequency. Thanks to the large-bandwidth control of the injected grid current, the converter achieves reference tracking performance, attenuation of grid current harmonics, seamless transitions between grid-connected and islanded modes, and robust stability in the presence of grid perturbations and impedance variations. Ref. [113] proposes a bidirectional converter for residential DC distribution. The architecture, based on a two-stage topology—a full-bridge in series with a bidirectional synchronous DC/DC converter—enables reduction of the DC-link capacitor, with reduced volume and improved power density for power rating of 10 kW, 520 V DC link voltage, and 20 kHz switching frequency.

An important application of inverters is the interfacing of PV modules with the AC grid. In this case, the main goal is achieving good maximum power point tracking of PV arrays; the MPPT can be centralized—i.e., applied to the whole array—or divided among subsystems. Cost is obviously of consequence, and its trade-off with efficiency should be evaluated. Actually, it is possible to obtain good PV string power output optimization without dedicated MPPT, as shown in [114], where the PV strings are interfaced separately to a multilevel inverter, and isolation is obtained through a high-frequency transformer. DC/AC converter topologies are drawn in Figure 16. In general, three possible solutions (which can co-exist in a given architecture) can be identified for the DC/AC converter: (1) a first solution is based on a DC/DC converter to adjust the DC voltage, followed by a DC/AC converter for the PG or AC loads interfacing; (2) when no input voltage adjustment is needed, the DC/DC stage can be avoided, and a single DC/AC stage can be implemented; and (3) finally, in case of the need of a galvanic insulation, a high-frequency transformer can be added followed by a frequency converter.

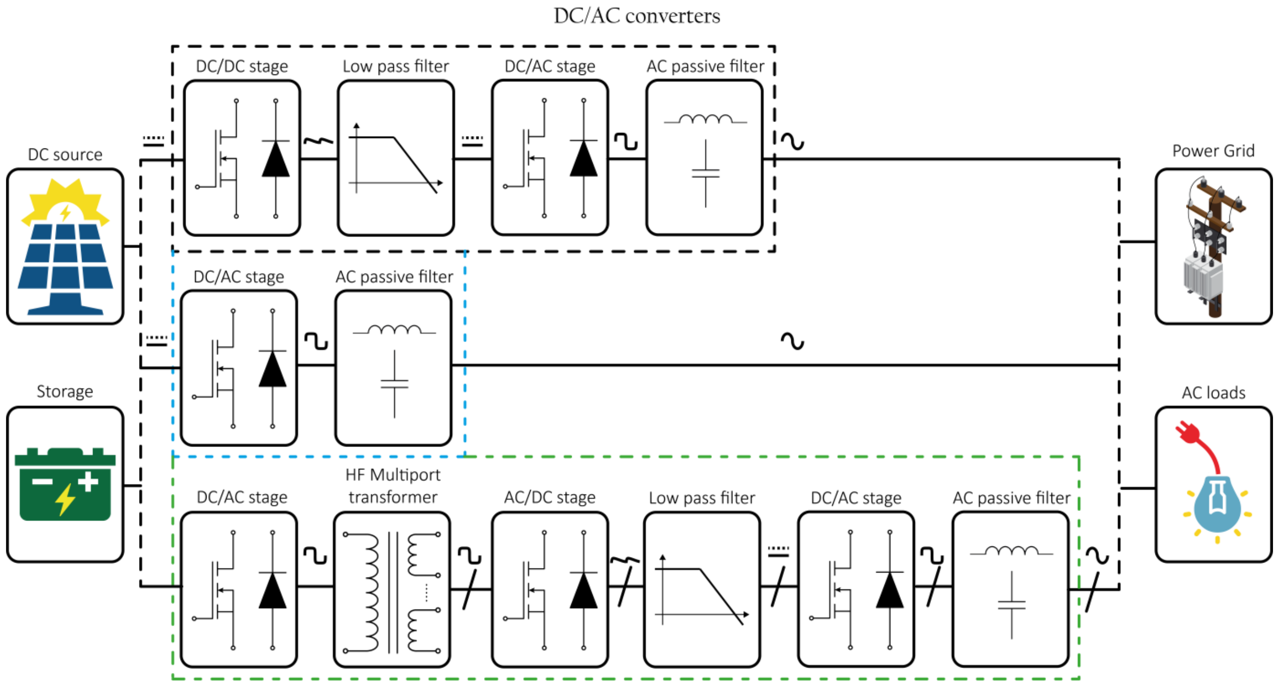


Figure 16. DC/AC converter topology solutions.

All the DC/AC converters used in power-electronics-based distributed power systems interfacing sources and loads are typically designed to feature high efficiency and high power factor. The whole system is commonly conceived as the assembly of several subsystems, which may lead to system integration problems, such as instability phenomena arising from subsystem interaction. Grid-tied inverters in NGs and MGs with renewable energy sources are prone to instabilities in AC distribution systems [115]. The general Nyquist stability criterion can be used to investigate small-signal stability using the source and load subsystem impedance matrices. The literature offers many examples of this kind of analysis, and of simplification of the general Nyquist criterion [116].

5.3. AC/DC Converters

Costs, efficiency, and safety are the main considerations examined in the literature on AC/DC converters. In residential DC NGs, in the absence of storage, the AC/DC converter for grid interfacing is often the dominant source of power loss. In relation to the DC voltage distribution values, an efficiency assessment is proposed in [117].

For AC/DC converters, the problem of grounding must be addressed; transformer grounding configurations include united grounding, unidirectional grounding, and virtual isolated grounding. However, in [118], a transformer-less united grounding solution is shown in a 1.5 kW power coupled-inductor-based converter with buck-boost operation modes and balanced DC output; this solution can be used for interfacing an AC low-voltage grid with a DC NG. For bidirectional exchange, mostly two conversion stages are proposed, a non-isolated rectifier and an isolated bidirectional DC/DC converter. Otherwise, CLLC resonant converters can be used to obtain galvanic isolation of the DC distribution system with a single conversion stage [119].

In NG architectures with PG connection, the grid interface bidirectional AC/DC power converter is a critical component and often takes on the role of energy control center. The converter has to fulfill power quality and EMI specifications both on the DC and the AC side. Ref. [120] discusses AC and DC interface design and proposes a passive plus active filter solution. The DC link capacitor is a key component for the DC voltage ripple filtering in single-phase grid-tied converters; reliability-oriented design and thermal management must also be taken into consideration [121]. Alternatively, architectures are available with reduced-capacitance DC link capacitor [122].

Multiport converters are a promising field of research. They offer the advantage of a higher overview than standard converters working as subsystems. Different solutions can be found in the literature, mostly customized for a specific application and without the possibility of high scalability. In [123], for example, a multiport converter is proposed with capacitive link, and the possibility of galvanic isolation via a high-frequency transformer, designed for NG and MG applications with PV modules, battery, three-phase AC source, and three-phase AC load. The same principle can be applied for single-phase NGs with lower power requirements. Here, an interesting solution is a hybrid split-pi converter, which gives the possibility to work both as a step-up and a step-down converter [124].

Table 2 gives an overview of converters used in NGs, with the main converter characteristics and a generalized efficiency evaluation. The number of outputs (multiport capabilities) and the topology of converters have been taken into consideration. Table shows also the efficiency of different power converters, which is independent by the grid.

Table 2. Summary of converters used for NGs.

Input Voltage	Output Voltage	Bidirectional	Isolated Outputs	Multiport Capabilities	Efficiency (Generalized)	References
DC	DC	Yes	Yes	Yes	Moderate	[107,125–128]
DC	DC	Yes	Yes	No	Moderate	[105,109,129–132]
DC	DC	Yes	No	Yes	High	[133–136]
DC	DC	Yes	No	No	High	[106]
DC	DC	No	Yes	Yes	Moderate	[94,95]
DC	DC	No	Yes	No	Moderate	[137]
DC	DC	No	No	Yes	Moderate	[96]
DC	DC	No	No	No	High	[102–104,110,111,138–144]
AC	DC	No	Yes	Yes	-	[145]
AC	DC	No	No	Yes	Moderate	[118]
AC	DC	No	No	No	High	[146–148]
DC	AC	No	Yes	No	Moderate	[114]
DC	AC	No	No	No	High	[112,115,149,150]
AC, DC	AC, DC	Yes	Yes	Yes	Moderate	[123,151–153]
AC	DC	Yes	Yes	No	High	[119]
AC, DC	AC, DC	Yes	No	Yes	Moderate	[154–157]
AC	DC	Yes	No	No	High	[113,120,122]
DC	AC, DC	No	No	Yes	Moderate	[97,99–101,124,158–161]

For this evaluation, the published results have been compared considering the provided converter simulations and/or experimental data. Two generalized efficiency scales have been used: moderate and high efficiency. For moderate, we considered an efficiency per output of about 90 to 96% at nominal load (e.g., for three-port converters, from 81% to 92%). For high efficiency, we consider a 96% or higher efficiency per output.

6. Conclusions

The development and deployment of NGs is of great research interest worldwide. Reasons can be identified in the increasing use of DERs, the need of efficiency in the production, distribution, and utilization of electric energy, the progress of battery energy system technologies, and the progress in the development of algorithms and metering devices allowing smart supervision. The rapid progress of power semiconductor device technologies and their increasing penetration has resulted in burgeoning research in the field of power converters for NGs. A variety of topologies and architectures are available.

This paper provided an overview of NG architectures and converters. Starting from a review of the converter topologies in use, the optimum converter for a specific NG architecture can be chosen, always factoring in the necessary design precautions concerning the electrical and thermal behavior. In particular, regardless of the overall efficiency, some converters should be able to work in hostile or unfavorable environments, such as a thermally challenging tight electric chassis in a house wall.

Retrofit from current architectures has to be taken into consideration as well. Standardization of voltage and power levels in the NG arena could help improve the return of investment. From this point of view, DC plug integration in current infrastructures is boosted by the definition of power delivery (PD) protocols, in particular when power is transmitted on legacy cables, enabling the ability to add new electrical outlets without major infrastructure investments. An example is the USB type C PD, with as much as 100 W power transmission capability and worldwide standardization for electronic equipment. A great advantage is the use of ubiquitous USB ports, with respect to traditional country-specific electrical outlets. PD through already existing cables also allows the use of various converters with high efficiency and different characteristics, to produce different DC voltage levels from AC or DC depending on the specific application.

Author Contributions: Authors D.S., N.D., M.S. and A.T. designed research. Authors D.S., N.D., M.S., N.R., A.T. and G.S., performed research and wrote the first draft of the paper. Authors P.C. and R.M. revised the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created.

Conflicts of Interest: We have no conflicts of interest to disclose.

Nomenclature

AC	alternate current
BESS	battery energy storage system
BW	bandwidth
DAB	dual active bridge
DC	direct current
DER	distributed energy resource
DSO	distribution system operator
EMI	electromagnetic interference
ESS	energy storage system
EV	electric vehicles
FC	fuel cell
GHG	greenhouse gas
LVDC	low-voltage DC
MG	microgrid
MGCC	microgrid central controller
MPPT	maximum power point tracking
MTSSB	modified tri-switching state boost converter
NG	nanogrid
PCC	point of common coupling
PD	power delivery
PG	power grid
PSO	particle swarm optimization
PV	photovoltaic
PWM	pulse width modulation
TAB	triple active bridge
USB	universal serial bus
V2G	vehicle to grid
VLSI	voltage lift switched inductor
VSI	voltage source inverter

References

1. Boroyevich, D.; Cvetkovic, I.; Burgos, R.; Dong, D. Intergrid: A future electronic energy network? *IEEE J. Emerg. Sel. Top. Power Electron.* **2013**, *1*, 127–138. [CrossRef]
2. Burmester, D.; Rayudu, R.; Seah, W.; Akinyele, D. A review of nanogrid topologies and technologies. *Renew. Sustain. Energy Rev.* **2017**, *67*, 760–775. [CrossRef]
3. Nordman, B.; Christensen, K.; Teleke, S.; Oehlerking, L.; Hong, M. Local power distribution with nanogrids. In Proceedings of the International Green Computing Conference Proceedings, IGCC 2013, Arlington, VA, USA, 27–29 June 2013. [CrossRef]
4. Teleke, S.; Oehlerking, L.; Hong, M. Nanogrids with energy storage for future electricity grids. In Proceedings of the IEEE PES T&D Conference and Exposition, Chicago, IL, USA, 14–17 April 2014. [CrossRef]
5. Boroyevich, D.; Cvetković, I.; Dong, D.; Burgos, R.; Wang, F.; Lee, F. Future electronic power distribution systems—A contemplative view. In Proceedings of the International Conference on Optimisation of Electrical and Electronic Equipment, OPTIM, Brasov, Romania, 20–22 May 2010.
6. Justo, J.J.; Mwasilu, F.; Lee, J.; Jung, J.W. AC-microgrids versus DC-microgrids with distributed energy resources: A review. *Renew. Sustain. Energy Rev.* **2013**, *24*, 387–405. [CrossRef]
7. Nguyen, M.Y.; Yoon, Y.T. A comparison of microgrid topologies considering both market operations and reliability. *Electr. Power Compon. Syst.* **2014**, *42*, 585–594. [CrossRef]
8. Karabiber, A.; Keles, C.; Kaygusuz, A.; Alagoz, B.B. An approach for the integration of renewable distributed generation in hybrid DC/AC microgrids. *Renew. Energy* **2013**, *52*, 251–259. [CrossRef]
9. Salomonsson, D.; Sannino, A. Low-voltage DC distribution system for commercial power systems with sensitive electronic loads. *IEEE Trans. Power Deliv.* **2007**, *22*, 1620–1627. [CrossRef]
10. Nordman, B.; Christensen, K.; Meier, A. Think globally, distribute power locally: The promise of nanogrids. *Computer* **2012**, *45*, 89–91. [CrossRef]
11. Werth, A.; Kitamura, N.; Tanaka, K. Conceptual study for open energy systems: Distributed energy network using interconnected DC nanogrids. *IEEE Trans. Smart Grid* **2015**, *6*, 1621–1630. [CrossRef]
12. Sulzberger, C.L. Triumph of AC. 2. The battle of the currents. *IEEE Power Energy Mag.* **2003**, *99*, 70–73. [CrossRef]
13. Sulzberger, C.L. Triumph of AC—From Pearl Street to Niagara. *IEEE Power Energy Mag.* **2003**, *1*, 64–67. [CrossRef]
14. Asad, R.; Kazemi, A. A quantitative analysis of effects of transition from AC to DC system, on storage and distribution systems. In Proceedings of the Asia-Pacific Power and Energy Engineering Conference, Shanghai, China, 27–29 March 2012. [CrossRef]
15. Dragicevic, T.; Vasquez, J.; Guerrero, J.; Škrlec, D. Advanced LVDC electrical power architectures and microgrids. *IEEE Electrif. Mag.* **2014**, *2*, 54–65. [CrossRef]
16. Stippich, A.; Sewergin, A.; Engelmann, G.; Gottschlich, J.; Neubert, M.; van der Broeck, C.; Schülting, P.; Goldbeck, R.; de Doncker, R.W. From Ac to Dc: Demonstration of benefits in household appliances. In Proceedings of the International ETG Congress 2017—Die Energiewende, Bonn, Germany, 28–29 November 2017; pp. 422–427.
17. Kumar, R.; Behera, R.K. A Low cost distributed solar DC nanogrid: Design and deployment with remote monitoring unit. In Proceedings of the 20th National Power Systems Conference (NPSC), Tiruchirappalli, India, 14–16 December 2018; pp. 1–6. [CrossRef]
18. Rodriguez-Diaz, E.; Vasquez, J.C.; Guerrero, J.M. Intelligent DC homes in future sustainable energy systems: When efficiency and intelligence work together. *IEEE Consum. Electron. Mag.* **2016**, *5*, 74–80. [CrossRef]
19. Starke, M.; Li, F.; Tolbert, L.M.; Ozpineci, B. AC vs. DC distribution: Maximum transfer capability. In Proceedings of the IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, 20–24 July 2008. [CrossRef]
20. Moussa, S.; Ghorbal, M.J.B.; Slama-Belkhodja, I. Bus voltage level choice for standalone residential DC nanogrid. *Sustain. Cities Soc.* **2019**, *46*, 101431. [CrossRef]
21. Khan, A.; Shadmand, M.B.; Bayhan, S.; Abu-Rub, H. A power ripple compensator for DC nanogrids via a solid-state converter. *IEEE Open J. Ind. Electron. Soc.* **2020**, *1*, 311–325. [CrossRef]
22. Sabry, A.H.; Shallal, A.H.; Hameed, H.S.; Ker, P.J. Compatibility of household appliances with DC microgrid for PV systems. *Heliyon* **2020**, *6*, e05699. [CrossRef]
23. Rahman, F.A.; James, R.; Jose, S.; Ahmed, S.; Mohammed, M.S.A.; Kunju, K.B. Solar DC homes: Energy for all. In Proceedings of the TENCON 2019—2019 IEEE Region 10 Conference (TENCON), Kochi, India, 17–20 October 2019; pp. 2428–2432. [CrossRef]
24. Joseph, S.C.; Ashok, S.; Dhanesh, P.R. An effective method of power management in DC nanogrid for building application. In Proceedings of the 2017 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems, SPICES 2017, Kollam, India, 8–10 August 2017.
25. Weiss, R.; Ott, L.; Boeke, U. Energy efficient low-voltage DC-grids for commercial buildings. In Proceedings of the 2015 IEEE 1st International Conference on Direct Current Microgrids, ICDCM 2015, Atlanta, GA, USA, 7–10 June 2015.
26. Wu, X.; Wang, Z.; Ding, T.; Li, Z. Hybrid AC/DC microgrid planning with optimal placement of DC feeders. *Energies* **2019**, *12*, 1751. [CrossRef]
27. Goud, P.C.D.; Gupta, R. Solar PV based nanogrid integrated with battery energy storage to supply hybrid residential loads using single-stage hybrid converter. *IET Energy Syst. Integr.* **2020**, *2*, 161–169. [CrossRef]

28. Bozchalui, M.C.; Sharma, R. Optimal operation of commercial building microgrids using multi-objective optimization to achieve emissions and efficiency targets. In Proceedings of the IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–8. [CrossRef]
29. Lotfi, H.; Khodaei, A. Hybrid AC/DC microgrid planning. *Energy* **2017**, *118*, 37–46. [CrossRef]
30. Bouchekara, H.R.E.H.; Shahriar, M.S.; Irshad, U.B.; Sha, Y.A. Optimal sizing of hybrid photovoltaic/diesel/battery nanogrid using a parallel multiobjective PSO-based approach: Application to desert camping in Hafr Al-Batin City in Saudi Arabia. *Energy Rep.* **2021**, *7*, 4360–4375. [CrossRef]
31. Dahiru, A.T.; Tan, C.W.; Bukar, A.L.; Yiew Lau, K. Energy cost reduction in residential nanogrid under constraints of renewable energy, customer demand fitness and binary battery operations. *J. Energy Storage* **2021**, *39*, 102520. [CrossRef]
32. Shahidehpour, M.; Li, Z.; Gong, W.; Bahramirad, S.; Lopata, M. A hybrid Ac\/Dc nanogrid: The keating hall installation at the illinois institute of technology. *IEEE Electrif. Mag.* **2017**, *5*, 36–46. [CrossRef]
33. Kumar, J.; Agarwal, A.; Agarwal, V. A Review on Overall Control of DC Microgrids. *J. Energy Storage* **2019**, *21*, 113–138. [CrossRef]
34. Yaqoob, M.; Nasir, M.; Vasquez, J.C.; Guerrero, J.M. Self-directed energy management system for an islanded cube satellite nanogrid. In Proceedings of the 2020 IEEE Aerospace Conference, Big Sky, MT, USA, 7–4 March 2020.
35. Sajeeb, M.M.H.; Rahman, A.; Arif, S. Feasibility analysis of solar DC nano grid for off grid rural Bangladesh. In Proceedings of the 2015 International Conference on Green Energy and Technology, ICGET 2015, Dhaka, Bangladesh, 11 September 2015; pp. 1–5.
36. Orner, B.A.; Reilly, D.E.; Chase, A.; Deokar, V.; Linder, S.P.; Goyal, P.; Paradiso, J.A.; Zuckerman, E. Sambaza Watts: A nano-grid for accessing and sharing energy. In Proceedings of the CIRED Workshop, Helsinki, Finland, 14–15 June 2016; Volume 2016, pp. 1–4.
37. Fan, H.; Yu, W.; Xia, S. Review of control strategies for DC nano-grid. *Front. Energy Res.* **2021**, *9*, 644926. [CrossRef]
38. Khan, M.R.; Brown, E.D. DC nanogrids: A low cost PV based solution for livelihood enhancement for rural Bangladesh. In Proceedings of the 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET), Dhaka, Bangladesh, 29–31 May 2014; pp. 1–5. [CrossRef]
39. Wu, L.; Kihinet, W.; Robelo, E.; Bezabih, E.; Longwood, K.; Tshimanga, T.; Saeedifard, M.; Lambert, F.; Harley, R. Development of a solar-power-based nanogrid system for village huts in Haiti Mountain Area. In Proceedings of the North American Power Symposium (NAPS), Denver, CO, USA, 18–20 September 2016. [CrossRef]
40. Neuhaus, K.; Alonso, C.; Gladysz, L.; Delamarre, A.; Watanabe, K.; Sugiyama, M. Solar to hydrogen conversion using concentrated multi-junction photovoltaics and distributed micro-converter architecture. In Proceedings of the 7th International Conference on Renewable Energy Research and Applications, Paris, France, 14–17 October 2018; pp. 744–747.
41. Hamatwi, E.; Davidson, I.E.; Agee, J.; Venayagamoorthy, G. Model of a hybrid distributed generation system for a DC nano-grid. In Proceedings of the Clemson University Power Systems Conference (PSC), Clemson, SC, USA, 8–11 March 2016; pp. 1–8. [CrossRef]
42. Jie, L.R.; Naayagi, R.T. Nanogrid for energy aware buildings. In Proceedings of the IEEE PES GTD Grand International Conference and Exposition Asia (GTD Asia), Bangkok, Thailand, 19–23 March 2019; pp. 92–96. [CrossRef]
43. Liptak, S.; Miranbeigi, M.; Kulkarni, S.; Jinsiwale, R.; Divan, D. Self-organizing nanogrid (SONG). In Proceedings of the 2019 IEEE Decentralized Energy Access Solutions Workshop (DEAS), Atlanta, GA, USA, 5–7 February 2019; pp. 206–212.
44. Ban, M.; Yu, J.; Shahidehpour, M.; Guo, D. Optimal sizing of PV and battery-based energy storage in an off-grid nanogrid supplying batteries to a battery swapping station. *J. Mod. Power Syst. Clean Energy* **2019**, *7*, 309–320. [CrossRef]
45. Murdianto, F.D.; Efendi, M.Z.; Widarsono, K.; Azizi, M. Robustness analysis of PID controller bidirectional SEPIC/Zeta for energy management in DC nanogrid isolated system. In Proceedings of the 3rd International Conference on Information Technology, Information Systems and Electrical Engineering, ICITISEE 2018, Yogyakarta, Indonesia, 13–14 November 2018; pp. 406–411.
46. Lyden, S.; Haque, M.E. Maximum power point tracking techniques for photovoltaic systems: A comprehensive review and comparative analysis. *Renew. Sustain. Energy Rev.* **2015**, *52*, 1504–1518. [CrossRef]
47. Dolara, A.; Grimaccia, F.; Magistrati, G.; Marchegiani, G. Optimal management algorithm for battery energy storage system included in an islanded micro-grid. In Proceedings of the EEEIC 2016—International Conference on Environment and Electrical Engineering, Florence, Italy, 7–10 June 2016; pp. 1–5.
48. Bakar, N.N.A.; Hassan, M.Y.; Sulaima, M.F.; Mohd Nasir, M.N.; Khamis, A. Microgrid and Load Shedding Scheme during Islanded Mode: A Review. *Renew. Sustain. Energy Rev.* **2017**, *71*, 161–169. [CrossRef]
49. Salazar, A.; Berzoy, A.; Song, W.; Velni, J.M. Energy management of islanded nanogrids through nonlinear optimization using stochastic dynamic programming. *IEEE Trans. Ind. Appl.* **2020**, *56*, 2129–2137. [CrossRef]
50. Nguyen, T.L.; Guerrero, J.M.; Griepentrog, G. A self-sustained and flexible control strategy for islanded DC nanogrids without communication links. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, *8*, 877–892. [CrossRef]
51. Kaviri, S.M.; Hajebrahimi, H.; Poorali, B.; Pahlevani, M.; Jain, P.; Bakhshai, A. A supervisory control system for nanogrids operating in the stand-alone mode. *IEEE Trans. Power Electron.* **2020**, *36*, 2914–2931. [CrossRef]
52. Chakraborty, S.; Kumar, D.; Thakura, P.R. PV-fed dual-stage closed loop V-f control scheme of stand-alone microgrid. In Proceedings of the 3rd International Conference on Electronics, Materials Engineering and Nano-Technology, IEMENTech 2019, Kolkata, India, 29–31 August 2019; pp. 2–5.

53. Franco-Mejia, E.; Plazas-Rosas, R.; Gil-Caicedo, A.; Franco-Manrique, R.; Gomez-Luna, E. Pilot nanogrid at Universidad Del Valle, for research and training in control and management of electrical networks in non-interconnected areas. In Proceedings of the 2017 IEEE 3rd Colombian Conference on Automatic Control (CCAC), Cartagena, Colombia, 18–20 October 2017.
54. Blanchard, R.; Little, M. Developing an open access monitoring device for off-grid renewables. In Proceedings of the ICDRET 2016—4th International Conference on the Developments in Renewable Energy Technology, UIU, Dhaka, Bangladesh, 7–9 January 2016; pp. 1–6.
55. Borland, J.; Tanaka, T. Overcoming barriers to 100% clean energy for Hawaii starts at the bottom of the energy food chain with residential island nano-grid and everyday lifestyle behavioral changes. In Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion, WCPEC 2018—A Joint Conference of 45th IEEE PVSC, 28th PVSEC and 34th EU PVSEC, Waikoloa, HI, USA, 10–15 June 2018; pp. 3829–3834.
56. Brusco, G.; Burgio, A.; Mendicino, L.; Menniti, D.; Motta, M.; Pinnarelli, A.; Sorrentino, N. A compact nanogrid with a behavior-tree control for islanded applications and remote areas. In Proceedings of the ICNSC 2018—15th IEEE International Conference on Networking, Sensing and Control, Zhuhai, China, 27–29 March 2018; pp. 1–6.
57. Pei, W.; Du, Y.; Deng, W.; Sheng, K.; Xiao, H.; Qu, H. Optimal bidding strategy and intramarket mechanism of microgrid aggregator in real-time balancing market. *IEEE Trans. Ind. Inf.* **2016**, *12*, 587–596. [CrossRef]
58. Hou, C.; Hu, X.; Hui, D. Hierarchical control techniques applied in micro-grid. In Proceedings of the 2010 International Conference on Power System Technology, Zhejiang, China, 24–28 October 2010; pp. 1–5.
59. Guerrero, J.M.; Vasquez, J.C.; Matas, J.; García de Vicuna, L.; Castilla, M. Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization. *IEEE Trans. Ind. Electron.* **2011**, *58*, 158–172. [CrossRef]
60. Bidram, A. *Distributed Cooperative Control of Ac Microgrid*; University of Texas at Arlington: Arlington, TX, USA, 2014.
61. Liu, Z.; Liu, J.; Boroyevich, D.; Burgos, R. Stability criterion of droop-controlled parallel inverters based on terminal-characteristics of individual inverters. In Proceedings of the 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), Hefei, China, 22–26 May 2016; pp. 2958–2963.
62. Saleh-ahmadi, A.; Moattari, M.; Gahedi, A.; Pouresmaeil, E. Droop method development for microgrids control considering higher order sliding mode control approach and feeder impedance variation. *Appl. Sci.* **2021**, *11*, 967. [CrossRef]
63. Tayab, U.B.; Roslan MA, B.; Hwai, L.J.; Kashif, M. A review of droop control techniques for microgrid. *Renew. Sustain. Energy Rev.* **2017**, *76*, 717–727. [CrossRef]
64. Ferreira, R.A.F.; Braga, H.A.C.; Ferreira, A.A.; Barbosa, P.G. Analysis of voltage droop control method for DC microgrids with Simulink: Modelling and simulation. In Proceedings of the 2012 10th IEEE/IAS International Conference on Industry Applications, Fortaleza, Brazil, 5–7 November 2012; pp. 1–6.
65. Bharath, K.R.; Dayal, A.; Kanakasabapathy, P. A simulation study on modified droop control for improved voltage regulation in DC microgrid. In Proceedings of the 2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT), Kerala, India, 6–7 July 2017; pp. 314–319.
66. Vu, T.V.; Perkins, D.; Diaz, F.; Gonsoulin, D.; Edrington, C.S.; El-Mezyani, T. Robust adaptive droop control for DC microgrids. *Electr. Power Syst. Res.* **2017**, *146*, 95–106. [CrossRef]
67. Hatziargyriou, N. *Microgrid: Architecture and Control*; Wiley-IEEE Press: Hoboken, NJ, USA, 2014; ISBN 9781118720684.
68. Singh, P.; Paliwal, P.; Arya, A. A review on challenges and techniques for secondary control of microgrid. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *561*, 012075. [CrossRef]
69. Kaur, A.; Kaushal, J.; Basak, P. A review on microgrid central controller. *Renew. Sustain. Energy Rev.* **2016**, *55*, 338–345. [CrossRef]
70. Tuckey, A.; Zabihi, S.; Round, S. Decentralized Control of a Microgrid. In Proceedings of the 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, Poland, 11–14 September 2017; pp. 1–10.
71. Hernandez, B.; Giraldo, E.; Ospina, S.; Garces, A. Master-slave operation of DC microgrids: An adaptive control approach with estimation. In Proceedings of the 4th IEEE Colombian Conference on Automatic Control: Automatic Control as Key Support of Industrial Productivity, CCAC 2019, Medellin, Colombia, 15–18 October 2019; pp. 1–6.
72. Guiying, S.; Da, L.; Yuesheng, L.; Yanbin, T. Master-slave with phase-shift control strategy for input-series and output-parallel full-bridge DC-DC converter system. In Proceedings of the 2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA), Hefei, China, 5–7 June 2016; pp. 2546–2551.
73. Zhao, W.; Zhang, X.; Li, Y.; Qian, N. Improved master-slave control for smooth transition between grid-connected and islanded operation of DC microgrid based on I-ΔV droop. In Proceedings of the 2020 IEEE 9th International Power Electronics and Motion Control Conference (IPEMC2020-ECCE Asia), Nanjing, China, 29 November–2 December 2020; pp. 1194–1198.
74. Cova, P.; Toscani, A.; Concari, C.; Franceschini, G.; Portesine, M. Comprehensive control system for parallelable 60 Hz-2MVA harbor AC/AC converters. *IEEE Trans. Ind. Inf.* **2018**, *14*, 2432–2441. [CrossRef]
75. Nasirian, V.; Moayedi, S.; Davoudi, A.; Lewis, F.L. Distributed cooperative control of DC microgrids. *IEEE Trans. Power Electron.* **2015**, *30*, 2288–2303. [CrossRef]
76. Shafiee, Q.; Guerrero, J.M.; Vasquez, J.C. Distributed secondary control for islanded microgrids—A novel approach. *IEEE Trans. Power Electron.* **2014**, *29*, 1018–1031. [CrossRef]
77. Espina, E.; Llanos, J.; Burgos-Mellado, C.; Cárdenas-Dobson, R.; Martínez-Gómez, M.; Sáez, D. Distributed control strategies for microgrids: An overview. *IEEE Access* **2020**, *8*, 193412–193448. [CrossRef]

78. Mumtaz, F.; Safak Bayram, I. Planning, operation, and protection of microgrids: An overview. *Energy Procedia* **2017**, *107*, 94–100. [CrossRef]
79. Yazdanian, M.; Mehrizi-Sani, A. Distributed control techniques in microgrids. *IEEE Trans. Smart Grid* **2014**, *5*, 2901–2909. [CrossRef]
80. Ross, M.; Abbey, C.; Bouffard, F.; Joos, G. Microgrid economic dispatch with energy storage systems. *IEEE Trans. Smart Grid* **2018**, *9*, 3039–3047. [CrossRef]
81. Zafar, R.; Esmaeel Nezhad, A.; Ahmadi, A.; Erfani, T.; Erfani, R. Trading off environmental and economic scheduling of a renewable energy based microgrid under uncertainties. *IEEE Access* **2023**, *11*, 459–475. [CrossRef]
82. Xu, F.; Huo, Q.; Deng, H.; Ding, C.; Lu, Y.; Wei, T. Study on operation optimization of DC micro-grid based on carbon emission constraints. In Proceedings of the 2022 4th International Conference on Power and Energy Technology (ICPET), Beijing, China, 28–31 July 2022; pp. 547–552.
83. Ma, Y.; Song, X.; Chen, Y.; Deng, F.; Piao, C. Economic optimal dispatch for grid-connected AC microgrid considering TOU tariffs. In Proceedings of the 2020 5th International Conference on Power and Renewable Energy, ICPRE 2020, Shanghai, China, 12–14 September 2020; pp. 643–647.
84. Han, J.; Yan, L.; Li, Z. A multi-timescale two-stage robust grid-friendly dispatch model for microgrid operation. *IEEE Access* **2020**, *8*, 74267–74279. [CrossRef]
85. Huang, Z.; Guo, Z.; Ma, P.; Wang, M.; Long, Y.; Zhang, M. Economic-environmental scheduling of microgrid considering V2G-enabled electric vehicles integration. *Sustain. Energy Grids Netw.* **2022**, *32*, 100872. [CrossRef]
86. Singh, B.; Sharma, A.K. Benefit maximization and optimal scheduling of renewable energy sources integrated system considering the impact of energy storage device and plug-in electric vehicle load demand. *J. Energy Storage* **2022**, *54*, 105245. [CrossRef]
87. Kim, J.; Lee, J.; Choi, J.K. Joint demand response and energy trading for electric vehicles in off-grid system. *IEEE Access* **2020**, *8*, 130576–130587. [CrossRef]
88. Jiang, Y.; Yang, Y.; Tan, S.C.; Hui, S.Y.R. Power loss minimization of parallel-connected distributed energy resources in DC microgrids using a distributed gradient algorithm-based hierarchical control. *IEEE Trans. Smart Grid* **2022**, *13*, 4538–4550. [CrossRef]
89. Jiang, Y.; Yang, Y.; Tan, S.C.; Hui, S.Y.R. A high-order differentiator based distributed secondary control for DC microgrids against false data injection attacks. *IEEE Trans. Smart Grid* **2022**, *13*, 4035–4045. [CrossRef]
90. Parag, Y.; Ainspan, M. Sustainable microgrids: Economic, environmental and social costs and benefits of microgrid deployment. *Energy Sustain. Dev.* **2019**, *52*, 72–81. [CrossRef]
91. Suk, H.; Hall, J. Integrating quality of life in sociotechnical design: A review of microgrid design tools and social indicators. In Proceedings of the International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Anaheim, CA, USA, 18–21 August 2019.
92. Saxena, A.; Patil, G.M.; Kumar Agarwal, N.; Singh, A.; Prakash, A.; Sharma, K. Environmental and social aspects of microgrid deployment—A review. In Proceedings of the 2021 IEEE 8th Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering, UPCON 2021, Dehradun, India, 11–13 November 2021; pp. 1–5.
93. Boche, A.; Foucher, C.; Lavado Villa, L.F. Understanding microgrid sustainability: A systemic and comprehensive review. *Energies* **2022**, *15*, 2906. [CrossRef]
94. Bhirud, O.N.; Satarkar, M.F.A.R. Design and analysis of multi-output isolated DC-DC converter for low voltage aplication. In Proceedings of the International Conference on Power Energy, Environment and Intelligent Control (PEEIC), Greater Noida, India, 13–14 April 2018; pp. 815–819. [CrossRef]
95. Ray, O.; Mishra, S. A multi-port converter topology with simultaneous isolated and non-isolated outputs. In Proceedings of the IECON 2013—39th Annual Conference of the IEEE Industrial Electronics Society, Vienna, Austria, 10–13 November 2013; pp. 7118–7123. [CrossRef]
96. Castle, O.D.; El Shahat, A. Single-input-multi-output (SIMO) converter for nano-grids applications. In Proceedings of the SoutheastCon 2017, Concord, NC, USA, 30 March–2 April 2017; pp. 1–5. [CrossRef]
97. Bagewadi, M.D.; Dambhare, S.S. A buck-boost topology based hybrid converter for standalone nanogrid applications. In Proceedings of the IEEE Second International Conference on DC Microgrids (ICDCM), Nuremburg, Germany, 27–29 June 2017; pp. 502–506. [CrossRef]
98. Chauhan, A.K.; Raghuram, M.; Kumar, R.R.; Singh, S.K. Effects and mitigation of nonzero DCM in buck-boost-derived hybrid converter. *IEEE J. Emerg. Sel. Top. Power Electron.* **2018**, *6*, 1470–1482. [CrossRef]
99. Asna, M.; Sakker Hussain, C.K. Analysis of three phase quadratic boost derived hybrid converter. In Proceedings of the International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS-2017), Chennai, India, 1–2 August 2017.
100. Ray, O.; Mishra, S. Boost-derived hybrid converter with simultaneous DC and AC outputs. *IEEE Trans. Ind. Appl.* **2014**, *50*, 1082–1093. [CrossRef]
101. Vakacharla, V.R.; Raghuram, M.; Singh, S.K. Hybrid switched inductor impedance source converter—A decoupled approach. *IEEE Trans. Power Electron.* **2016**, *31*, 7509–7521. [CrossRef]

102. Gore, S.; Maroti, P.K.; Iqbal, A.; Sanjeevikumar, P.; Leonowicz, Z.; Blaabjerg, F. A modified boost converter with Triswitching state and VLSI module for DC nanogrid application. In Proceedings of the IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Madrid, Spain, 9–12 June 2020. [CrossRef]
103. Hassan, W.; Hasan, R.; Lu, D.D.C.; Xiao, W.; Soon, J.L. Performance enhancement of high step-up DC-DC converter to attain high efficiency and low voltage stress. In Proceedings of the IEEE 4th International Future Energy Electronics Conference (IFEEC), Singapore, 25–28 November 2019. [CrossRef]
104. Hassan, W.; Lu, D.D.C.; Xiao, W. Single-switch high step-up DC-DC converter with low and steady switch voltage stress. *IEEE Trans. Ind. Electron.* **2019**, *66*, 9326–9338. [CrossRef]
105. Burgio, A.; Menniti, D.; Motta, M.; Pinnarelli, A.; Sorrentino, N.; Vizza, P. A Laboratory model of a dual active bridge DC-DC converter for a smart user network. In Proceedings of the IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC), Rome, Italy, 10–13 June 2015; pp. 997–1002. [CrossRef]
106. Elsayad, N.; Moradisizkoohi, H.; Mohammed, O.A. Design and implementation of a new transformerless bidirectional DC-DC converter with wide conversion ratios. *IEEE Trans. Ind. Electron.* **2019**, *66*, 7067–7077. [CrossRef]
107. Santoro, D.; Kortabarria, I.; Toscani, A.; Concari, C.; Cova, P.; Delmonte, N. PV modules interfacing isolated triple active bridge for nanogrid applications. *Energies* **2021**, *14*, 2854. [CrossRef]
108. Roy, R.; Kapat, S. Stabilizing DPWM current mode cascaded DC-DC converters in DC nano-grid without clock sharing. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition—APEC, Phoenix, AZ, USA, 14–17 June 2021; pp. 778–782.
109. Cecati, C.; Khalid, H.A.; Tinari, M.; Adinolfi, G.; Graditi, G. DC nanogrid for renewable sources with modular DC/DC LLC converter building block. *IET Power Electron.* **2017**, *10*, 536–544. [CrossRef]
110. Mamur, H.; Ahiska, R. Application of a DC-DC boost converter with maximum power point tracking for low power thermoelectric generators. *Energy Convers. Manag.* **2015**, *97*, 265–272. [CrossRef]
111. Kumar, S.; Krishnasamy, V.; Kaur, R. Unified controller for bimodal operation of CUK converter assisted SEIG-based DC Nanogrid. *IEEE Syst. J.* **2020**, *15*, 1674–1683. [CrossRef]
112. Buso, S.; Caldognetto, T.; Liu, Q. Analysis and experimental characterization of a large-bandwidth triple-loop controller for grid-tied inverters. *IEEE Trans. Power Electron.* **2019**, *34*, 1936–1949. [CrossRef]
113. Dong, D.; Cvetkovic, I.; Boroyevich, D.; Zhang, W.; Wang, R.; Mattavelli, P. Grid-interface bidirectional converter for residential dc distribution systems—Part one: High-density two-stage topology. *IEEE Trans. Power Electron.* **2013**, *28*, 1655–1666. [CrossRef]
114. Keyhani, H.; Toliyat, H.A. Single-stage multistring PV inverter with an isolated high-frequency link and soft-switching operation. *IEEE Trans. Power Electron.* **2014**, *29*, 3919–3929. [CrossRef]
115. Wen, B.; Boroyevich, D.; Burgos, R.; Mattavelli, P.; Shen, Z. Analysis of D-Q small-signal impedance of grid-tied inverters. *IEEE Trans. Power Electron.* **2016**, *31*, 675–687. [CrossRef]
116. Wen, B.; Burgos, R.; Boroyevich, D.; Mattavelli, P.; Shen, Z. AC stability analysis and Dq frame impedance specifications in power-electronics-based distributed power systems. *IEEE J. Emerg. Sel. Top. Power Electron.* **2017**, *5*, 1455–1465. [CrossRef]
117. Habibi, S.; Rahimi, R.; Shamsi, P.; Ferdowsi, M. Efficiency assessment of a residential DC nanogrid with low and high distribution voltages using realistic data. In Proceedings of the IEEE Green Technologies Conference, Denver, CO, USA, 7–9 April 2021; pp. 574–579.
118. Wang, H.; Wu, W.; Li, Y.; Blaabjerg, F. A coupled-inductor-based buck-boost AC-DC converter with balanced DC output voltages. *IEEE Trans. Power Electron.* **2018**, *34*, 151–159. [CrossRef]
119. Kim, H.S.; Ryu, M.H.; Baek, J.W.; Jung, J.H. High-efficiency isolated bidirectional AC-DC converter for a DC distribution system. *IEEE Trans. Power Electron.* **2013**, *28*, 1642–1654. [CrossRef]
120. Dong, D.; Luo, F.; Zhang, X.; Boroyevich, D.; Mattavelli, P. Grid-interface bidirectional converter for residential DC distribution systems—Part 2: AC and DC interface design with passive components minimization. *IEEE Trans. Power Electron.* **2013**, *28*, 1667–1679. [CrossRef]
121. Delmonte, N.; Cabezuelo, D.; Kortabarria, I.; Santoro, D.; Toscani, A.; Cova, P. A method to extract lumped thermal networks of capacitors for reliability oriented design. *Microelectron. Reliab.* **2020**, *114*, 113737. [CrossRef]
122. Dong, D.; Boroyevich, D.; Wang, R.; Cvetkovic, I. A two-stage high power density single-phase Ac-Dc Bi-directional PWM converter for renewable energy systems. In Proceedings of the IEEE Energy Conversion Congress and Exposition, Atlanta, GA, USA, 12–16 September 2010; pp. 3862–3869. [CrossRef]
123. Afshari, E.; Amirabadi, M. Single-stage multiport capacitive-link universal power converter as a solid-state transformer for nanogrid and microgrid applications. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 17–21 March 2019; pp. 382–388. [CrossRef]
124. Khan, S.A.; Pilli, N.K.; Singh, S.K. Hybrid split pi converter. In Proceedings of the IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Trivandrum, India, 14–17 December 2016; pp. 1–6. [CrossRef]
125. Samende, C.; Bhagavathy, S.M.; McCulloch, M. Distributed state of charge-based droop control algorithm for reducing power losses in multi-port converter-enabled solar DC nano-grids. *IEEE Trans. Smart Grid* **2021**, *12*, 4584–4594. [CrossRef]

126. Mukherjee, A.; Rasoulinezhad, R.; Moschopoulos, G. Asymmetrically modulated three port bidirectional current fed-push-pull converter for a DC nanogrid. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC), Phoenix, AZ, USA, 14–17 June 2021; pp. 1421–1425. [CrossRef]
127. Yu, Y.; Wada, K.; Masumoto, K.; Kado, Y. A DC power distribution system in a data center using a triple active bridge DC-DC converter. *IEEJ J. Ind. Appl.* **2018**, *7*, 202–209. [CrossRef]
128. Tao, H.; Duarte, J.L.; Hendrix, M.A.M. Three-port triple-half-bridge bidirectional converter with zero-voltage switching. *IEEE Trans. Power Electron.* **2008**, *23*, 782–792. [CrossRef]
129. Tomas-Manez, K.; Zhang, Z.; Ouyang, Z. Unregulated series resonant converter for interlinking DC nanogrids. In Proceedings of the 2017 IEEE 12th International Conference on Power Electronics and Drive Systems (PEDS), Honolulu, HI, USA, 12–15 December 2017; pp. 647–654.
130. Queiroz, F.; Praça, P.; Freitas, A.; Antunes, F. High-gain bidirectional DC-DC converter for battery charging in DC nanogrid of residential prossumer. In Proceedings of the 2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC), Santos, Brazil, 1–4 December 2019; pp. 1–6.
131. Morais, A.S.; Lopes, L.A.C. Interlink converters in DC nanogrids and its effect in power sharing using distributed control. In Proceedings of the 2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2016, Vancouver, BC, Canada, 27–30 June 2016; pp. 1–7.
132. Burgio, A.; Menniti, D.; Motta, M.; Pinnarelli, A.; Sorrentino, N.; Vizza, P. A two-input dual active bridge converter for a smart user network using integrated power modules. In Proceedings of the Asia-Pacific Power and Energy Engineering Conference, APPEEC, Brisbane, QLD, Australia, 15–18 November 2015; pp. 1–6.
133. Nguyen, B.L.; Cha, H.; Nguyen, T.; Kim, H. Family of integrated multi-input multi-output DC-DC power converters. In Proceedings of the 2018 International Power Electronics Conference (IPEC-Niigata 2018-ECCE Asia), Niigata, Japan, 20–24 May 2018; pp. 3134–3139.
134. De Campos, A.S.C.; Gomes, A.C.; De Morais, A.S. Multi-winding bidirectional flyback converter. In Proceedings of the 14th Brazilian Power Electronics Conference, COBEP 2017, Juiz de Fora, Brazil, 19–22 November 2017; pp. 1–6.
135. Balal, A.; Shahabi, F. Design a multiport DC-DC converter for hybrid renewable nano-grid system. In Proceedings of the 2021 Fourth International Conference on Electrical, Computer and Communication Technologies (ICECCT), Erode, India, 15–17 September 2021; pp. 1–5.
136. Askarian, I.; Pahlevani, M.; Knight, A.M. Three-port bidirectional DC/DC converter for DC nanogrids. *IEEE Trans. Power Electron.* **2021**, *36*, 8000–8011. [CrossRef]
137. Pontes, A.P.; Vieira, H.d.S.; Junior, E.M.S. Isolated high gain DC-DC converter with low input and output current ripple for photovoltaic system applications. In Proceedings of the 2021 Brazilian Power Electronics Conference (COBEP), João Pessoa, Brazil, 7–10 November 2021; pp. 1–8.
138. Iqbal, A.; Gore, S.; Maroti, P.K.; Meraj, M.; Marzband, M. A new triswitching double duty high voltage gain boost converter for DC nanogrid application. In Proceedings of the 2021 IEEE 4th International Conference on Computing, Power and Communication Technologies, GUCON 2021, Kuala Lumpur, Malaysia, 24–26 September 2021; pp. 1–6.
139. Radmanesh, H.; Reza Soltanpour, M.; Eskandarpour Azizkandi, M. A continuous input current DC-DC converter based on coupled inductor for renewable energy applications. In Proceedings of the 2021 12th Power Electronics, Drive Systems, and Technologies Conference, PEDSTC 2021, Tabriz, Iran, 2–4 February 2021; pp. 10–14.
140. Neres, F.d.P.; da Rocha, A.F.; dos Santos, R.L.; Almeida, P.S.; Antunes, F.L.M.; Sá, E.M. A resonant-switched-capacitor step-down DC-DC converter in CCM operation as an LED driver. In Proceedings of the 2019 IEEE 15th Brazilian Power Electronics Conference and 5th IEEE Southern Power Electronics Conference (COBEP/SPEC), Santos, Brazil, 1–4 December 2019; pp. 1–6.
141. Liu, G.; Khodamoradi, A.; Mattavelli, P.; Caldognetto, T.; Magnone, P. Plug and play DC-DC converters for smart DC nanogrids with advanced control ancillary services. In Proceedings of the IEEE International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, CAMAD, Barcelona, Spain, 17–19 September 2018; pp. 1–6.
142. Hassan, W.; Gautum, S.; Lu, D.D.C.; Xiao, W. Analysis, design, and experimental verification of high step-up DC-DC converter to interface renewable energy sources into DC nanogrid. In Proceedings of the IEEE International Conference on Industrial Technology, Melbourne, VIC, Australia, 13–15 February 2019; pp. 1649–1654.
143. Ferreira, J.S.; Almeida, P.S.; Morais, M.B.M.; Martins, G.E.; Sá, E.M. A step-down converter with resonant switching capacitor applied in nanogrids to drive power LEDs. In Proceedings of the 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2017, Florianopolis, Brazil, 17–20 April 2017; pp. 1–7.
144. De Araújo, F.C.; Vasconcelos, M.O.; Aragão, F.A.P.; De Souza, K.C.A.; Sá, E.M. High-gain DC-DC converter with current source characteristics at the output for applications in photovoltaic systems and current injection in nanogrids. In Proceedings of the 2017 IEEE 8th International Symposium on Power Electronics for Distributed Generation Systems, PEDG 2017, Florianopolis, Brazil, 17–20 April 2017; pp. 1–6.
145. Wu, W.; Wang, H.; Liu, Y.; Huang, M.; Blaabjerg, F. A dual-buck-boost AC/DC converter for DC nanogrid with three terminal outputs. *IEEE Trans. Ind. Electron.* **2017**, *64*, 295–299. [CrossRef]
146. Kumar, S.; Mukkapati, A.B.K.; Krishnasamy, V.; Kaur, R. AISMC for islanded operation of wind driven SEIG based DC nanogrid. In Proceedings of the 2019 National Power Electronics Conference, NPEC 2019, Tiruchirappalli, India, 13–15 December 2019; pp. 1–6.

147. Barone, G.; Burgio, A.; Menniti, D.; Motta, M.; Pinnarelli, A.; Sorrentino, N. A printed circuit board suitable for controlling a 22.8kVA IGBT three-phase inverter for DC nanogrids in a laboratory setup. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, 6–9 June 2017; pp. 1–6.
148. Azab, M. Experimental investigation of a self excited induction generator for nanogrid applications. In Proceedings of the 2017 9th IEEE-GCC Conference and Exhibition (GCCCE), Manama, Bahrain, 8–11 May 2017; pp. 1–6.
149. Nag, S.S.; Mishra, S. Current-fed DC/DC topology based inverter. In Proceedings of the 2013 IEEE Energy Conversion Congress and Exposition, ECCE 2013, Denver, CO, USA, 15–19 September 2013; pp. 2751–2756.
150. Pexirra Tome, J.L.; Pires, V.F.; Pina, J.M. Development of an off-grid micro-inverter for a scalable photovoltaic kit. In Proceedings of the IEEE International Symposium on Industrial Electronics, Kyoto, Japan, 20–23 June 2021.
151. Saha, J.; Naga, G.; Yadav, B.; Panda, S.K. A matrix-based solid-state-transformer for a hybrid nanogrid. In Proceedings of the 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Chennai, India, 18–21 December 2018; pp. 1–6.
152. Gunawardena, L.H.P.N.; Nayanasiri, D.R. Networked DC nano-grid based on multi-port power converters. In Proceedings of the IEEE Region 10 Annual International Conference, Proceedings/TENCON, Penang, Malaysia, 5–8 November 2017; pp. 2727–2732.
153. Burlaka, V.; Gulakov, S.; Podnebennaya, S.; Kudinova, E.; Plakhtii, O.; Nerubatskyi, V. An universal bidirectional three-port DC/DC/AC converter with isolated AC port. In Proceedings of the 2021 IEEE 3rd Ukraine Conference on Electrical and Computer Engineering, UKRCON 2021, Lviv, Ukraine, 26–28 August 2021; pp. 367–372.
154. Roasto, I.; Rosin, A.; Jalakas, T. Multiport interface converter with an energy storage for nanogrids. In Proceedings of the IECON 2018—44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, USA, 21–23 October 2018; pp. 6088–6093.
155. Roasto, I.; Rosin, A.; Jalakas, T. Power electronic interface converter for resource efficient buildings. In Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pp. 3638–3643.
156. Hagh, M.T.; Aghdam, F.H. Smart hybrid nanogrids using modular multiport power electronic interface. In Proceedings of the IEEE PES Innovative Smart Grid Technologies Conference Europe, Melbourne, VIC, Australia, 28 November–1 December 2016; pp. 618–623.
157. Ray, O.; Member, S.; Mishra, S.; Member, S. Integrated hybrid output converter as power router for renewable-based nanogrids. In Proceedings of the IECON 2015—41st Annual Conference of the IEEE Industrial Electronics Society, Yokohama, Japan, 9–12 November 2015; pp. 1645–1650.
158. Mostaan, A.; Soltani, M.; Gorji, S.A. Hybrid impedance network-based converter with high voltage gain and no commutation problem. In Proceedings of the 2016 IEEE 2nd Annual Southern Power Electronics Conference, SPEC 2016, Auckland, New Zealand, 5–8 December 2016; pp. 1–4.
159. Meraj, M.; Ali, M.A.; Rahman, S.; Bhaskar, S.M.; Iqbal, A.; Al Hitmi, M.A.E. Switched inductor quazi switched boost converter for nano-grid applications. In Proceedings of the International Conference on Electrical, Electronics and Computer Engineering, UPCON 2019, Aligarh, India, 8–10 November 2019; pp. 1–6.
160. Tomy, A.; Thomas, A.J. Sepic derived hybrid converter with simultaneous AC and DC outputs. In Proceedings of the 2016 IEEE Annual India Conference (INDICON), Bangalore, India, 16–18 December 2016; pp. 1–6.
161. Sarath, R.; Kanakasabapathy, P. Switched-capacitoriswitched-inductor Cuk-derived hybrid converter for nanogrid applications. In Proceedings of the 2015 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC), Melmaruvathur, India, 22–23 April 2015; pp. 430–435.