


Review

A Review of Low-Voltage Renewable Microgrids: Generation Forecasting and Demand-Side Management Strategies

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Abstract: It is expected that distribution power systems will soon be able to connect a variety of microgrids from residential, commercial, and industrial users, and thus integrate a variety of distributed generation technologies, mainly renewable energy sources to supply their demands. Indeed, some authors affirm that distribution networks will propose significant changes as a consequence of this massive integration of microgrids at the distribution level. Under this scenario, the control of distributed generation inverters, demand management systems, renewable resource forecasting, and demand predictions will allow better integration of such microgrid clusters to decongest power systems. This paper presents a review of microgrids connected at distribution networks and the solutions that facilitate their integration into such distribution network level, such as demand management systems, renewable resource forecasting, and demand predictions. Recent contributions focused on the application of microgrids in Low-Voltage distribution networks are also analyzed and reviewed in detail. In addition, this paper provides a critical review of the most relevant challenges currently facing electrical distribution networks, with an explicit focus on the massive interconnection of electrical microgrids and the future with relevant renewable energy source integration.

Keywords: control inverter; demand-side management; energy management; low voltage configuration; microgrids



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1. Introduction

A microgrid (MG) is a small-scale electrical energy network characterized by distributed generation (DG), such as photovoltaic (PV) solar panels [1], wind turbines (WT), heat and power generators (CHP), and other components of control units, manageable loads, and storage units [2]. To achieve a suitable integration between renewable energy technologies and energy storage systems (ESS), it is necessary to include energy management schemes (EMS) that allow strategies for avoiding inappropriate costs in an MG. Moreover, both RE and ESS play an essential role in the costs of implementing a microgrid [3]. Regarding control and management systems, MGs can operate in two modes: (i) when it is interconnected to a grid and (ii) in islanding mode [4], the latter of which requires the maintenance of demand and generation balance, according to energy availability over time [5]. When an MG is connected to a power system at a common coupling point (PCC), it is possible to interact with the electrical distribution network and the operator of this network (DSO), providing generation or demanding power from the grid. Under islanding mode, the MG is disconnected from the corresponding power system, maintaining quality energy services to some critical loads with demand management and control. It can also forecast available generation resources and propose some demand response strategies.

The electrical loads within MGs are typically elements demanding power. They can be composed of a lighting system, a heating ventilation and air conditioning (HVAC) system, residential appliances, industrial loads, plug-in electric vehicles (PEV), a storage system, and other equipment [6].

Residential customers represent an essential part of world energy consumption. Subsequently, MG implementation is increasing to provide distribution networks with a more efficient control and management system in this consumption sector [7]. Fiorini [8] explains how EMS can monitor, measure, and control the energy consumption and production of a system—such as an MG—through control algorithms that can model all possible conditions throughout a given microgrid. Among the conditions, these algorithms must evaluate the availability of energy resources, the status of the storage system, the conditions of the loads or consumption, environmental impact, economic indicators, the status of the network, and the flow of energy from said network. For this reason, the integration of EMS benefits both the end-users of energy and generators and the administrators of electrical transmission and distribution networks. Though the integration of renewable technologies and modern equipment into energy systems has increased, so too have the costs of energy production; these have become a challenge for each country. Demand-side management (DSM) is used to mitigate this challenge. This strategy allows one to control and monitor an end user's energy consumption. Therefore, DSM can manipulate end-users' demands for electricity [9]. The benefits provided by distributed generation and microgrids in the electrical distribution network currently suppose a relevant target due to increases in the interconnection of energy resources that are distributed in Low-Voltage (LV) networks [10].

Most contributions to this field have focused on MG, and they are based predominantly on simulation software. This is a faster and cheaper solution than real case studies, avoiding any experimental system implementation. The elements and components used to simulate supply-side and demand-side scenarios in residential, commercial, and industrial sectors are then defined and emulated. Nevertheless, other contributions are based on real implementation case studies, as can be seen in Table 1. MG implementation thus comprises a remarkable number of contributions and results that allow for easier analysis of this system's integration into distribution networks. Therefore, there are still some opportunities that should be developed and improved accordingly:

- How interconnected electrical microgrids in electrical distribution systems allow passive systems to become active electrical distribution networks. A literary review of projects related to electrical microgrids implemented in distribution networks allows us to analyze trends regarding their integration into electrical systems.
- Explain and analyze why the trend of using microgrids in electrical distribution networks and how they allow the transition from passive energy distribution systems to active systems
- The prediction of resources in energy production is a highly developed component within the field of generation. However, when it is applied to a distributed generation system, forecasting allows both network operators and final energy users to project their systems and infer network decongestion. This situation is due to microgrids supplying interconnected local demands.

Table 1. Microgrid case studies; LV distribution networks.

Ref.	Year	Location Component	System	Control Microgrid	Type System	Management
[11]	2017	Columbus, Ohio	PV, WT, TESS	-	Building	-
[12]	2017	Sydney	PV, WT, ESS, STC	-	Commercial Building	Optimal EMS
[13]	2017	University of British Columbia	PV ESS,	Harmonics detection	Campus, hibryd AC-DC	EMS
[14]	2017	EE. UU, Kayenta Health Center	PV, Diesel Generators, emergency power supply system (EPSS)	MPPT conotrol P-O. Static Transfer Switch	Health care building	All equipment are critical, don't have DSM
[15]	2018	Italy, Electric Power System laboratory of Politecnico di Bari	PV, WT, ESS, Gas-fueled internal combustion engine in cogeneration, gas microturbine in cogeneration layout	-	Comercial/ Education	-
[16]	2018	University of Seville	FC	Model Predictive Control	Education	Model Predictive Control
[17]	2018	Bilbao	PV, ESS	Perturb and Observe algorithm (P&O) for MPPT	Building housing	-
[9]	2018	Graciosa Island in the Canary Islands	PV, ESS	nonlinear mathematical programming model	smart microgrid district	Game Theory for Microgrids
[18]	2018	Brooklyn, New York	PV	blockchain-based information systems	residential community	Energy management trading system (EMTS)
[19]	2018	Venice, Italy	PV, biodiesel engine-generator (BDEG), ESS	blockchain-based information systems	Industrial community	power management systems (PMSs)
[20]	2018	Australia	PV, ESS	Primary, secondary, tertiary	Campus	Time of Use (ToU) tariffs, load level and State of Charge (SOC) of battery, EMS decides
[21]	2019	Finland	PV, WT, ESS	Flexibility for HVAC and Electric water heat (EWH) loads	Residential community	Home EMS
[22]	2020	Coimbra, Portugal	PV, ESS	BMS-V2B	Campus	Building Management System (BMS).

There are several revisions about MGs in the field of control and operation [23–25]; interconnection with the distribution network [26–29]; sustainable trends to apply the MG in the distribution network [30], or MG management [31]. However, and to the best of the authors' knowledge, there is a lack of revisions focused on MG interconnections in LV distribution electrical networks. In this framework, the DSOs should be able to integrate customer demand, interconnected MGs, and bidirectional power flows into such Low-Voltage distribution networks with remarkable renewable integration. Therefore, and based on recent contributions, this paper reviews critical aspects regarding MG interconnection

in LV distribution networks, such as demand and generation management and renewable energy source forecasting technologies. In addition, the advantages and challenges of integrating distributed generation resources into MGs at LV level are also discussed. Some technical implementation limits and drawbacks are also reviewed. This work thus aims to establish the following points:

- A critical review of electrical MG implementation at the LV distribution network.
- An analysis of the relevance of demand and generation forecasting solutions in electrical MGs for their operation and management.
- A detailed discussion of demand management programs to provide a more efficient scenario of renewable energy source integration into MGs.
- A revision of current solutions to facilitate MG integration and avoid relevant additional power system investments.

This paper is structured as follows: Section 2 presents the methodology. Section 3 describes LV MG configurations and advantages of LV MGs over existing conventional network, Section 4 discusses generation and demand forecasting approaches, Section 5 reviews recent LV MG management and control strategies, and demand-side management programs for LV MGs (load displacement) are reviewed in Section 6; Section 7 comprises the discussion; and Section 8 examines our conclusion and future challenges for the industry.

2. Methodology

For the development of this review, the following methodology is proposed and used by the authors:

1. Data collection: several searches were carried out in the ScienceDirect, IEEE, and GoogleScholar databases according to keywords, types of articles, and publication time searching criteria. The keywords used for the searching process were Micro-grid, Low-Voltage, Residential, Configuration, Commercial, industries, among others. The types of publications selected were relevant research works and thematic reviews. From this initial classification process, the most relevant contributions were taken from the selected databases, according to the requirements set for the development of the document.
2. Selection and filtering of information: the references were ordered in a bibliographic manager, we proceeded to filter the information by keywords, title, and abstract to organize the information by relevance. Indeed, the identified contributions were classified according to the sections developed in this work, such as the configurations of LV distribution networks with integrated MGs, generation and demand forecasting approaches, LV MG management and control, as well as demand-side management programs for LV MGs.
3. Distribution of topics to be reviewed: by analyzing the information of the selected contributions. The relationship among the selected topics with significant similarity and relevance is identified and discussed.
4. Analysis of selected information: through a critical analysis of the references, being then possible to infer the conclusions presented in this work.

Figure 1 displays a general scheme of the methodology proposed for this review.

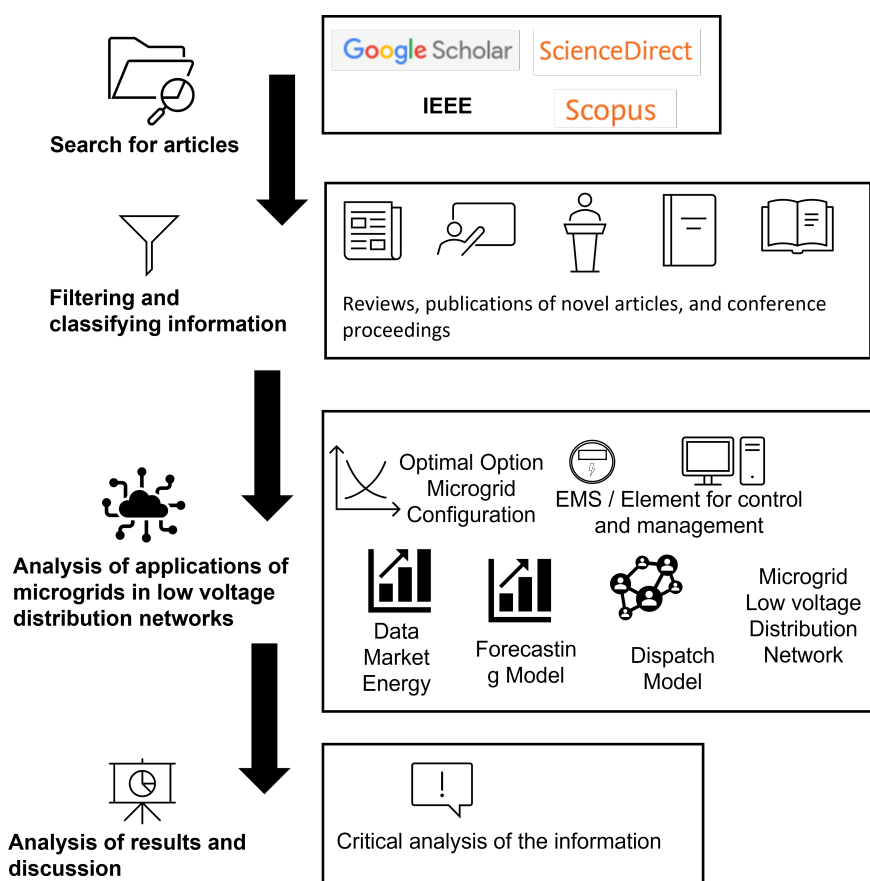


Figure 1. Proposed methodology, general scheme.

3. Low-Voltage Microgrids

According to the field-specific literature, MGs can be classified depending on different parameters, such as level of voltage, supervisory and management control, type of interconnection phases, and type of application. Xu et al. [32] describe the characteristics of the different microgrid configurations presented in Figure 2. Hirsch [11] explains the advantages of applying MG campus/institutional, which can be used for demand reduction and optimization of the demand profile according to energy resources. In addition, MG military application can also give energy security in critical infrastructures. Remote MGs are used in regions with poor access to public energy services, such as rural areas. Finally, MG applications in distribution networks (residential, commercial, and industrial) allow for the integration of customers as individual prosumers. Moreover, groups of prosumers are able to communicate and provide greater stability at the LV level without significant investment in these networks. Furthermore, LV MGs commonly combine renewable energy sources [33], PV installations [34,35], electric vehicle charging [36,37], and hybrid storage systems [38], aiming to provide auxiliary services for local LV networks [39,40]. Recently, multi-microgrid systems provide additional reliability of distribution systems and enhance system resiliency under contingencies [41]. According to the American National Standard ANSI C84.1, voltages in an electrical system can be classified by the criteria depicted in Table 2. MGs connected to LV distribution networks can then be used to supply residential buildings, low-demand industrial buildings, low-demand commercial buildings, and low-demand buildings.

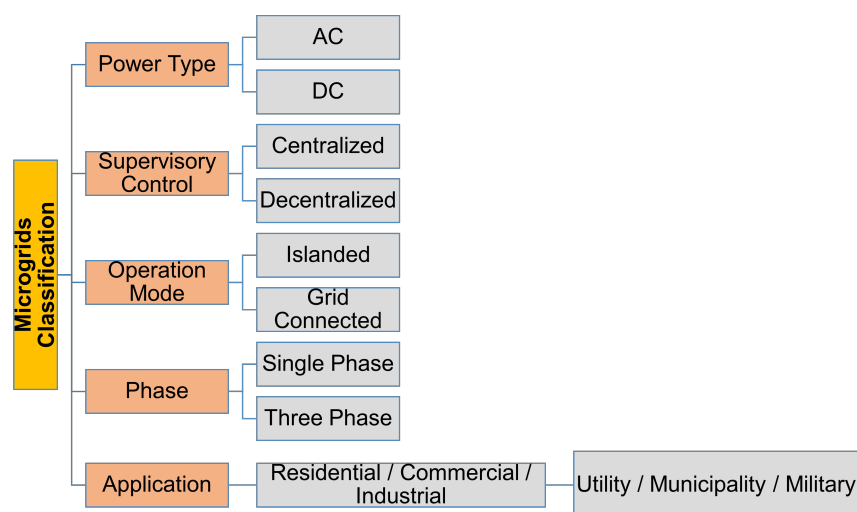


Figure 2. Microgrids classification.

Table 2. Range voltage according ANSI C84.1.

Voltage Class	Range
Low voltage (LV)	≤ 1000 V
Medium voltage (MV)	> 1000 V and ≤ 100 kV
High voltage (HV)	> 100 kV and ≤ 230 kV
Extra high voltage (EHV)	> 230 kV and ≤ 1000 kV
Ultra high voltage (UHV)	> 1000 kV

Rebollal et al. [42], in their review of norms and standards used in MGs and distributed generation, compare parameters that should be used to evaluate the interconnection and disconnection states of MGs in the downstream network. These parameters should be considered in addition to the tolerances and values allowed for electrical grid-codes, such as voltage, frequency, response time, synchronization, power factor, and steady-state among other conditions. Among the international standards analyzed, they include IEC/IEEE/PAS 63547, IEEE 929, IEEE 1547, UNE/EN/IEC 62109, IEC 62898-1, IEC 62898-2, IEC 62898-3-1, and IEEE P2030.8. Note that it is necessary to develop a technical framework to converge all the technical suggestions given by these international standards. Although other protocols are used to automatize power systems and implement them in MGs—such as DNP3 and IEC104; they are no longer in use due to the implementation of IEC61850, used for automation of power transformation centers and electrical distribution networks [43].

The use of MGs in LV distribution networks has the following advantages, over existing conventional LV networks:

- Any direct dependence on public networks to supply the local demand connected to the LV distribution network is avoided. MGs also reduce the distribution system's losses, since the loads are closer to the source of microgeneration [44]. Electrical storage systems can also be located close to the demand and the interconnection bus [45]. Moreover, the integration of a peer-to-peer (P2P) system promotes the purchase of energy from among MGs, reducing distribution losses and increasing network operation efficiency [46].
- MGs are able to be contingency systems in the distribution network and energy management [47], minimizing losses and improving the voltage profile according to the load connected to the network [48,49]. MGs also allow for changing the traditional distribution network configuration from a radial to mesh layout [50]. This reconfiguration improves the LV distribution network response, being able to restore the network under technical failures [51].

- MGs allow both integration and control of the different EV technologies connected to the LV distribution network for optimal charging and discharging processes, depending on the needs of the LV distribution network operator [52]. In addition, MGs allow managing the power flow within the LV distribution network [53], becoming a link between the distributed generation and the distribution network [54].
- MGs are elements of the LV distribution network that, through appropriate incentives, can become mechanisms to regulate voltage and frequency within such LV distribution networks [55]. MGs thus guarantee a reliable electricity supply to customers [56], being considered as a backup supply source in the event of a mains power outage [57]. From their different generation sources, MGs have the ability to allow the LV distribution network to adapt accordingly under extreme atmospheric and weather events [58]. In addition, MGs also allow the programming and configuration of distribution networks as a demand response program [59].
- MGs reduce greenhouse gas emissions from LV distributed generation connected to the distribution network by managing their energy resources. Therefore, MGs are positively in line with the Sustainable Development Goals (SDG). More specifically, Goal 7 focused on obtaining access to accessible, reliable, sustainable, and modern energy [60].

4. Generation and Demand Forecasting Approaches

Effective energy balancing relies upon two fundamental factors: (i) the corresponding energy generation reserve that can be specified to the power station, and (ii) the expected demand and renewable generation forecasting [61]. Forecasting at the MG level has developed significantly in recent years [62], and it has enhanced both the management and the use of conventional and renewable energy sources within MGs. Moreover, financial matters of energy trade with other MGs and the main grid can also be improved [63]. Nevertheless, and due to the variability of renewable resources [64] and the need to decide how much generation power is used from controllable assets [65], the main objectives of most forecasting methods at the MG level are focused on estimating both renewable resources and demand simultaneously. Forecasting of energy resources is required by the MGS, since they mainly depend on such sustainable resources. These resources can be inconsistent due to the fact that they rely on stochastic boundaries, such as solar irradiance, climate, and wind speed [66]. On the other hand, energy demand forecasting is needed to make microgrids possible and proficient in their determination of likely electric demand [67]. Forecasting processes can be carried out at different time intervals, such as very short-term (seconds to hours), short-term (hours to one week), medium-term (weeks to a month), and long-term (months to a year) [68]. Nonetheless, the short-term time interval is mainly used in relation to an MG's ideal activity [69]. The forecasting accuracy of energy demand and renewable resources plays a fundamental role in successful exchanges on electricity markets [70]. The accuracy of these approaches is usually evaluated by a variety of metrics, such as mean absolute error (MAE), mean absolute percentage error (MAPE), and root mean squared error (RMSE) [71]. Other performance metrics that are not widely used are correlation coefficient (R), mean bias error (MBE), mean relative error (MRE), and mean square error (MSE). A review and comparison of these metrics can be found in [72].

Recent studies focused on forecasting energy resources are summarized in Table 3. In addition, forecasting demand contributions are given in Table 4. In these studies, different forecasting approaches—such as machine learning [73–79], deep learning [80–86], and ensemble learning [87,88]—are used and implemented for evaluation. Note that the ideal approach relies upon the application, necessary horizon, and time step; hence, various procedures can be effectively executed [89].

Table 3. Renewable energy resources forecasting: a comparison of approaches.

Ref.	Year	Forecasting Horizon	Forecasting Approach	Forecasting Model	Forecast Accuracy
[79]	2017	Hours	Machine learning	Back propagation neural network	MAPE
[76]	2018	Hours	Machine learning	Artificial neural network	RMSE
[78]	2019	Hours	Machine learning	Adaptive neuro fuzzy interference	RMSE, MAE, MSE, MBE, RME
[75]	2019	Hours	Machine learning	Physical hybrid artificial neural network	MAE, RMSE
[83]	2019	Hours	Ensemble learning	Long short-term memory recurrent neural network, feed-forward neural network	RMSE
[87]	2019	Day	Deep learning	Long short-term memory recurrent neural network	RMSE, MAE
[80]	2019	Hours	Deep learning	Multi-headed convolutional neural network	MBE, RMSE, MAPE, MAE
[86]	2019	Hours	Deep learning	Deep recurrent neural network, Long short-term memory	RMSE, MAPE, MAE
[66]	2020	Hours	Machine learning	Artificial neural network	MAPE, MSE
[77]	2020	Minutes	Machine learning	Artificial neural network	RMSE

Table 4. Energy demand forecasting: a comparison of approaches.

Ref.	Year	Forecasting Horizon	Forecasting Approach	Forecasting Model	Forecast Accuracy
[63]	2018	Day	Machine learning	Neuro fuzzy inference	RMSE, MAE, MAPE
[74]	2019	Hours	Machine learning	<i>k</i> -neighbors, Self-organizing maps	MAPE
[73]	2019	Day	Machine learning	Support vector machine	RMSE, MAE
[88]	2019	Hours	Ensemble learning	GBRT, Xgboost, Decision tree, Seq2Seq	MAE, RMSE
[81]	2019	Hours	Deep learning	Long short-term memory recurrent neural network	MAE, MAPE
[69]	2020	Hours	Ensemble learning	Support vector regression, Long short-term memory	RMSE, MAE, MAPE, MSE, R
[85]	2020	Hours	Deep learning	Long short-term memory recurrent neural network	MSE
[82]	2020	Hours	Deep learning	Multi-layer perceptron artificial neural network	RMSE, MSE, R
[84]	2021	Hours	Deep learning	Bidirectional long short-term memory	RMSE, MSE, R

5. Low-Voltage Microgrid Management and Control

Samadi et al. [90] affirm that the two most important challenges affecting MG operation are: (i) the development of intelligent controls for the MG elements, allowing them to work within an optimal range; and (ii) optimal energy management system (EMS) to maintain stability between generation and demand. The EMS of an MG is in charge of verifying and monitoring the energy flow between each element connected to MG [91]. In addition, the EMS is based on verifying the status of the distributed generation system, the status of the load, the operation of the system, the operating and maintenance costs, the technical and economic restrictions of the system [92], the reduction in the amount of

GHG emissions [93], and the status and operating costs of ESS [31]. Figure 3 depicts the information exchanged between the EMS and the rest of the system. Harmouch et al. [94] identify three categories of EMS: (i) centralized EMS applied for a specific rule, (ii) decentralized EMS, and (iii) distributed EMS. Decentralized and distributed EMS have more flexibility for the operation of a group of MGs. EMS can be configured as autonomous and grid-connected to an MG network, with different operational requirements. A grid-connected EMS aims to obtain the highest income according to the market. An EMS in autonomous mode meets a user's needs by controlling the loads connected to the MG [95]. Recent studies, summarized in Table 5, use EMS systems to connect MGs at LV distribution networks.

Table 5. EMS system in a microgrid: Low-Voltage networks.

Ref.	Year	System Component	EMS	Type Microgrid
[92]	2018	PV, WT, VE	Optimization model compare the state of charge of the two storage systems	Home with V2G
[94]	2018	PV, WT, BESS, Critical loads that are not controllable, controllable loads	Decentralized multi-agent EMS (DMA-EMS)	Cluster multiple microgrid
[96]	2018	PV, WT, BESS, combined cooling heat power μ -CCHP unit, TESS,	Genetic algorithm	Industrial
[97]	2018	BSSS, EV, PV, WT, Electrical controllable loads (ECL), Thermal controllable (TCL) loads such as refrigerator (REF), air conditioner (AC) and electric water heater (EWH)	Two-stage mixed-integer linear programming (MILP)	Home
[98]	2018	BSSS, EV, PV, WT, curtailable loads, shiftable loads	Stochastic model predictive control (SMPC)	Community
[99]	2019	PV, WT, BESS	Model predictive power and voltage control (MPPVC) method	Hybrid AC-DC
[100]	2019	PV, BESS	Adaptive neuro fuzzy inference system (ANFIS), Training by clustering and neuro-fuzzy Min-Max classifier	Multiple
[101]	2019	PV, WT, BESS, Fixed Load	economical storage management system (ESMS)	Home microgrid
[102]	2019	PV, WT, BESS	method of Lagrange multipliers and power scheduling algorithm with dynamic programming (DP)	Home microgrid
[90]	2019	PV, WT, DIESEL, MT, FC, ESSS	EMS based on multi-agent systems MAS	Multiple microgrid
[103]	2019	PV, WT, BESSS, Phosphoric Acid Fuel Cell (PAFC), Micro-gas Turbine (MT), and electrical storage as Battery Energy Storage System (BESS)	Modified Particle Swarm Optimization	Community Microgrid
[104]	2020	PV, WIND	Self-evolving type-2 fuzzy logic	Multiple microgrid
[105]	2020	PV, WIND	Rolling Time Horizon RTH-based EMS.	Home with
[106]	2021	PV, WT, BESS	hierarchical energy management system (HEMS)	Home Microgrid
[107]	2021	PV, WT, BESS, Hybrid Energy Storage System (HESS), Thermal and electrical loads	Fuzzy Logic Control (FLC)	Home Microgrid
[108]	2021	PV, WT, microturbine, solid-oxide fuel cell (SOFC)	Based on frequency control	Home community
[109]	2021	PV, BESS	Decentralized field (MF) control	Home Microgrid
[95]	2021	PV, WT, FC, Microturbine (MT) , BESS	Quantum particle swarm optimization	Multiple microgrid
[93]	2021	PV, fuel cell (FC), micro-turbine (MT), diesel generator (DE), battery ESS	Optimization navigator (BARON) algorithm	Multiple microgrid

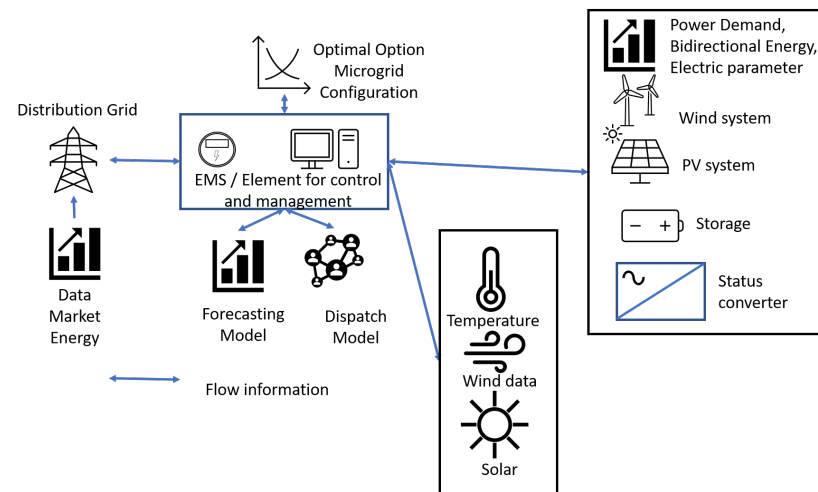


Figure 3. EMS information flow.

With regard to renewable energy sources, both standalone and combined renewables must be connected to the power systems through DC–DC and/or DC–AC power converter topology [110]. Power converters are defined as a kind of electronic circuit used for energy conversion that convert electrical energy from a certain supply into energy suitable for loads (e.g., voltage or current with suitable frequency and/or amplitude) [111]. With the current displacement of synchronous generators by inverter-based sources supplied by renewables [112], larger frequency deviations, due to lower rotating inertial energy, have emerged as additional drawbacks to be solved by providing ancillary services from renewables [113] and MGs [114]. There are two types of converters in MGs: grid-followers and grid-formers (see Figure 4); grid-tied inverters operate as grid-following sources tracking the voltage angle of the grid to control output. Nevertheless, and even with inverter fast frequency support, frequency regulation still depends on the remaining synchronous generators [115]. Table 6 summarizes and compares the characteristics of recent contributions focused on grid-following methods for MGs. In addition, Tables 7 and 8 summarize recent control strategy approaches for residential power inverters with voltage levels lower than 1000 V.

Grid Following Inverter

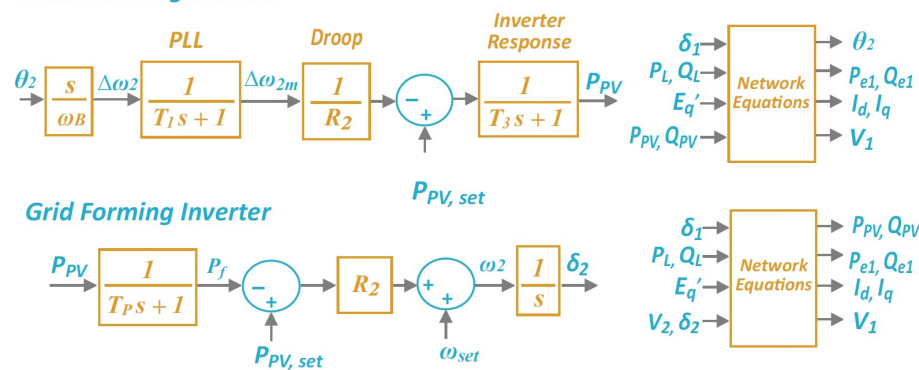


Figure 4. Grid-following and grid-forming inverter models.

Table 6. Analysis of contributions based on grid-following inverter MG control.

Refs.	Control Method	Advantages	Drawbacks/Challenges
[116–118,118–138]	Droop Control	No need for communication link, excellent flexibility, high reliability, easy implementation, and a combination of a variety of DGs with different power ratings	Compromise between voltage/frequency regulation and power sharing, feeding under unbalanced conditions, harmonic load sharing and voltage harmonic compensation, coupling inductances, line impedance, renewable energy sources, active and reactive power sharing, load dependency, and islanding detection algorithm.
[118,119,127,130,139–141]	Central control	Current sharing is perfect even during the transient phase, different power rating inverters can be connected without changing the control structure, and voltage regulation.	The high cost of communication infrastructure installing. Difficult to handle nonlinear loads.
[119,121,124,127,130,132,135,138, 139,141–149]	Master/Slave Control	Transfer of information between the master controller and the slave's controllers. Reduction of the complexity and the cost while increasing the reliability.	If the master unit fails, the whole system will fail.
[118,129,132,136,139–142,149–157]	Averaging Control for Voltage Regulation and Current Sharing	All the inverters in the microgrid take part in the voltage, frequency, as well as the current regulation, demonstrating the democratic nature of this controller.	Need for optimization of the grid power management, current sharing, and the voltage control issues.
[118–120,139,158–163]	Angle Droop Control	Capable to regulate system frequency to its set point without any steady state error and no communication channel between sources allowing for reducing the frequency deviation and improving the voltage quality and enhancing reliability. Likewise, it ensures that appropriate power sharing can be performed under weakness conditions of the system by choosing a high angle gain. This method also agrees with harmonic power sharing among DERs.	the selection the high angle gain has a negative effect on system stability, the inaccurate real and reactive power sharing and GPS communications. Lack of synchronism between DG and low dynamics and slow response in some cases.
[118,139,164–172]	Multi Agent System (MAS)	Agent independency reducing the need for information manipulating, increasing the reliability and robustness of the control system, plug and play capability, and learning agents can be taught previous behaviors by themselves.	Stability of voltage and frequency along increasing scheduling duration.

Table 7. Inverter control approaches (I).

Ref.	Year	Power Control	Control Equations	Control Targets
[173]	2021	Autonomous droop control (ADC) and decentralized optimal control (DOC)	$P_{PV} = \min(MPP, P_{droop});$ $Q_{pv} = Q_{droop}$	Keeping bus voltage, power factor range and power capacity. Voltage limit ≤ 1.095 pu
[174]	2020	The droop method: hierarchical (primary, secondary, and tertiary) control method	$\omega_i = \omega_{nom} - m_i P_i;$ $V_i = V_{nom} - n_i Q_i$	Droop control strategy derived from integrator current sharing designed and improved.
[175]	2020	Two voltage control methods: P control and PQ control	$\frac{g \cdot V_{nom}}{n \cdot (n+1)/2} = (RP + XQ) \cdot \sum_{j=1}^n \frac{1}{V_j}$	P control reduces active power output when the inverter voltage exceeds the specific upper voltage limit. PQ control, first, supplies reactive power to reduce the voltage rise
[176]	2020	Finite control set FCS model predictive control (MPC). Droop control	$\begin{bmatrix} V_c \\ I_f \end{bmatrix} = A_d \begin{bmatrix} V_c \\ I_j \end{bmatrix}^k + B_d \begin{bmatrix} V_i \\ I_0 \end{bmatrix}$ $A_q = e^{AT_s}; B_d = \int_0^{T_s} e^{A\tau} B d\tau$	P offers a wide range of operation and adaptation flexibility
[177]	2020	PI controllers and integrate Cost Optimization Based Microgrid EMS Using Genetic Algorithm (GA)	$Min(J) = \sum_{t=0}^T C_{u_{grid}} + P_{u_{grid}}$	Loss reduction strategy, operated with an automatic centralized controller, designed with the IEC 62040-3 standard
[178]	2020	The load side PC (LPC) and machine side PC (MPC)	$i_{qref}(n) = i_{qref}(n-1) +$ $k_i(\omega_{err-mod}(n-1)) +$ $k_p(\omega_{err-mod}(n))$	Offers a wide range of operation and adaptation flexibility
[179]	2020	Drop control with Newton's algorithm for island operation	$\begin{pmatrix} \Delta p \\ \Delta q \end{pmatrix} = \begin{pmatrix} D^{p\theta} & D^{pv} \\ Q^{Q\theta} & D^{Qv} \end{pmatrix} \begin{pmatrix} \Delta \theta \\ \Delta v \end{pmatrix}$	Algorithm for the power flow for small signal stability of microgrids
[180]	2020	Inter-phase power transfer with droop control	$P_{load} > (P_{PV}^{MPPT} + P_{bat}^{max} +$ $P_{droop}^{max}) \phi_x;$ $SOC_{min} \leq SOC \leq SOC_{max}$	Intra-phase power management strategy
[181]	2019	Single-phase control strategy. PV, Group or residences	$I_{xp} = g_{1p} \hat{v}_x \cdot e^{j\theta_{jx}};$ $I_{xq} = g_{1q} \hat{v}_x \cdot e^{j\theta_{jx} - \frac{\pi}{2}}$	Avoiding overvoltage's; assuming that the currently available power at the DC-side is the same as the injected power on the AC-side
[182]	2019	Linear Quadratic Regulator with added Integral action (LQRI) with active power filter (AFP)	$\frac{d}{dt}x = [A]x + [B]u + [E]v_g;$ $u = [d_d, d_p]^T; v_g = [v_{gd}, v_{gq}]^T$	fast response, less overshoot and reduced THD system.
[183]	2019	Droop Control and Model predictive control under different circumstances of variable load conditions and fluctuating wind speed	$P = Re[V_g I_f] =$ $\frac{3}{2}[V_{g\alpha} I_{f\alpha} + V_{g\beta} I_{f\beta}];$ $Q = Im[V_g I_f] =$ $\frac{3}{2}[V_{g\beta} I_{f\alpha} - V_{g\alpha} I_{f\beta}]$	WT-DG-battery-converter hybrid energy for domestic load in Pakistan by handling intermittent nature of RE resources, and abrupt load variations

Table 8. Inverter control approaches (II).

Ref.	Year	Power Control	Control Equations	Control Targets
[184]	2019	Droop control and centralized-decentralized voltage regulation scheme	$P_j^{PV,h} \in [P_j^{PV,h,min}, P_j^{PH,h,max}];$ $Q_j^{PH,h} = \alpha_j^h + \beta_j^h \cdot P_j^{PV,h}$	Coordinated Var compensation for overvoltage mitigation
[185]	2019	Master-slave or multi-master topologies, modified vector control and Intra-phase Power Management	$G(s) = \frac{\omega_0 - s}{\omega_0 + s}$ $\begin{bmatrix} d \\ q \end{bmatrix} = T \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$ $P_{Total,\phi} = P_{PV}^{max} + P_{Bat}^{max} + P_{Droop}^{max}$	A cooperative control and power management to ensure that the loads on all three phases are supported with as much RES as possible
[186]	2019	Self-normalized estimator (SNE) based algorithm. PV-BES Microgrid	$V_t = [2(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)/3]^{1/2};$ $i_{LA}(t) = \sum_{k=1}^n i_{La_n} \sin[\sigma_k \omega t + \lambda_k]$	Fluctuations in insolation and temperature, grid outage conditions, and load variations are considered
[187]	2019	Fuzzy logic and Angle control by single loop proportional-integral (PI)	$C(s) = K_p + \frac{K_i}{s};$ $K_p = \frac{-\omega_c \cdot \sin(\theta)}{G(j \cdot \omega_c)}; K_i = \frac{-\omega_c \cdot \sin(\theta)}{G(j \cdot \omega_c)}$	The energy management unit (EMU) contained a short-term and a long-term control unit
[188]	2019	Proportional integral Controller (PI) and sliding mode control (SMC) are chosen to attain the control outputs of the system	$\eta(P_{PV} + P_{ESU}) + P_g = P_L;$ $I_{ESU}^{ref} = \frac{1}{V_{ESU}} \left(\frac{P_L - P_g}{\eta} - P_{PV} \right)$	Stability and reliability of the entire system are operating under various operating modes and demonstrated through the laboratory experiments
[189]	2019	Voltage control	$V_{nom} + \left(\frac{n \cdot (n+1)}{2} \right) \cdot V_{incr} = V_{limit}$	The impact of P control (limiting P to prevent voltage rise) on the operation and overall generation
[190]	2019	PV, Plugging Electric Vehicles and Batteries. Coordinated control scheme	$P_{g,t} - P_{c,t}^{PV} + P_{d,t}^{PV} + P_{c,t}^{PEV} + P_{d,t}^{PEV} -$ $P_{def,t} = P_{L,t}^{\omega,t} - P_{PV,t}^{\omega,L}$	Stochastic dual dynamic programming (SDDP) algorithm is then applied to solve the optimization problem with uncertainty
[191]	2019	Decoupled Control Strategy	$P_{DC} = V_{DC} C_d \frac{d}{dt} V_{DC};$ $P_{AC} = I_{m,j}^2 R_f;$ $V_{DC} C_d \frac{d}{dt} V_{DC} = I_{m,j}^2 R_f$	Offering conventional power electronic-based converter topology, known as Electric Spring (ES) a decoupled dual-function capability. The modified (ES) is able to achieve PV-grid interface by injecting the local available PV power into grid

6. Demand-Side Management in Low-Voltage Microgrids

The appropriately consolidated activity of distributed energy resources and DSM in a microgrid establishes a powerful correspondence plan that can assume a significant part in lessening energy shortcomings by adjusting supply and demand [192]. DSM procedures—such as flexible load shape, strategic load growth, strategic conservation, flexible load shape, peak clipping, and load shifting [193]—are used to change customer demand profiles in response to emergency conditions or energy market costs [194]. Moreover, DSM offers demand response (DR), which is considered as an alternative solution to the costly investment of upgrading conventional distribution networks [195]. Therefore, the role of DR as a considerable potential for elastic demands in active distribution network management (ADNM) becomes crucial. Based on the control mechanism of the DSM strategy, DSM can be divided into two classes: incentive-based and price-based [196]. Some incentive-based approaches are the following: direct load control (DLC) [197], interruptible/curtailed (I/C) load programs [198], demand bidding/buyback (DB) [199], capacity markets (CM) [200], ancillary service markets (ASM) [201], and emergency demand response (EDR) [202]. For price-based approaches, the following approaches are used: fixed pricing, time-of-Use

(ToU) [203], dynamic time-of-use (dToU) [204], critical peak pricing (CPP) [205], real-time pricing (RTP) [206], and Vickrey–Clarke–Groves (VCG) [207].

Flexible loads and distributed energy resources can contribute to a distribution network in voltage management. In the decongestion of a distribution network, the management of electrical losses by reducing the distance between loads and source generation increases service reliability [208] and system resilience [209]. Different resources can be also considered as ‘flexible loads’, such as storage systems, heating, ventilation, and air conditioning (HVAC) systems that are used in residences and businesses [210], water heater systems, refrigeration units, and electric vehicles are also considered ‘flexible loads’ [211]. Among the different strategies, load shifting is considered the most relevant load management procedure, shifting loads from peak to valley hours, which can be carried out automatically or manually [212]. Loads can be divided into four types [213]: (i) critical loads, being essential to the system and must always be connected to the grid; (ii) controllable loads, which correspond to a flexible demand with variable profiles; (iii) price-sensitive loads, whose demand depends on the price of energy and the hours of connection to the grid; and (iv) thermal loads, related to thermal comfort conditions or boiler control for established conditions. MGs can then reduce the maximum demand values in distribution networks through a coordinated dispatch of generation and demand. Consequently, different DSM strategies are applied to coordinate available renewable resources and demand requirements. This coordination gives those in charge of the distribution network the ability to postpone future expansions within the electrical infrastructure connected to MGs [214].

7. Discussion

According to the contributions reviewed in previous sections, we deduce the following points:

- The integration of electrical MGs into LV distribution networks presents a remarkable acceptance among both supply-side and demand-side sectors. Different benefits are identified by end-users, also known as ‘prosumers’. Additional benefits are also apparent regarding the environment by reducing fossil fuel dependence and optimizing the use of renewable energy resources. Most LV MG projects integrate a relevant number of PV installations and storage system technologies. However, in turn, these complement other types of distributed generation technologies that could be integrated into the energy supply systems of distribution network users.
- In terms of forecasting approaches, we analyze machine learning, deep learning, and assembly learning solutions. Other methods are based on satellite and numerical predictions, but only minor contributions have currently focused on these methods. Current trends are characterized by the use of machine learning models for both demand and resource forecasting.
- Authors propose different modeling approaches for generation resource or demand forecasting, which means that at least two models are required for an MG. It would be more efficient to propose a single model to forecast both demand and supply-side. Note that such models based on artificial intelligence require a large amount of data for their learning processes. Therefore, it is proposed to evaluate alternative methodologies to achieve more efficient learning processes with reduced data volumes.
- Energy management in MGs also tends to converge on the use of a modern learning tool through programming and the optimal use of energy resources, thus minimizing the use of interconnected networks for energy consumption. Management systems based on known techniques—such as droop control or frequency control—are still being developed to manage resources.
- The results present current trends of residential users as prosumers of small-scale MG integration. It is also possible to integrate multiple prosumers, so-called MG communities or clusters. Note that hybrid MGs and plug-in electric vehicles, as dynamic storage network elements, would allow for integrating these solutions by using V2G technologies.

- DSM approaches applied to electrical MGs are used as a response strategy to demand profiles, providing a more flexible control focused on the electrical loads of the corresponding MGs. Different studies outline some benefits of DSM control strategies. They propose that different services should be provided by distribution network operators and MG users. When applied to MGs, DSM solutions commonly divide electrical loads into critical, controllable, price-sensitive, and thermally controlled categories. This categorization can optimize the application of DSM in relation to different MG configurations.
- Regarding inverters for MG control, modern power systems often integrate recent technologies into their operations. These solutions include IoT and blockchain, among others. The Multiagent System (MAS) control method [215,216] can respond to current computational challenges through omnipresent, intelligent, autonomous, human-oriented, and supportive attributes. It is based on foundation for intelligent physical agents standards by representing each major autonomous component in the microgrid as an intelligent software agent [217]. Both relevant characteristics and aptitudes improve the extension and flexibility of future power systems by allowing reconfiguration options and the integration of new agent communication technologies. Furthermore, MAS improves robustness and reliability of the system due to the ability to tolerate uncertainties [218], capability to improve the efficiency of computations, and ability to cooperate, negotiate, or compete with other agents at the stage of decision-making processes.
- Nowadays, some protocols explain the issues of electrical MGs. However, there is currently a need to integrate the standards of electronic MGs with standards of distributed generation (DG) in the distribution network levels and with resistance standards. This integration is necessary since the electrical MGs will allow distributed generation to be integrated on a larger scale on the LV distribution network, which will address a transition from passive electrical networks to active distribution networks.

8. Conclusions and Future Challenges

This paper reviews current trends in electrical microgrids in Low-Voltage distribution networks. The integration of microgrids has increased considerably due to end-users at distribution networks using Low-Voltage renewable generation as a way to manage their demand and significantly reduce their energy bills. Consequently, the power distribution systems are undergoing a process of transition from passive electrical networks to active networks. This transition requires large investments, which will allow for optimizing the operation of the system (such as reducing energy losses, improving the voltage profile, being a more resilient system) as well as improving reliability through the automation and integration of distributed generation resources and electrical microgrids. Under this framework, it is necessary to discuss in detail how these active elements are changing the way of analyzing, planning, and operating the distribution network market, as well as to evaluate the control strategies and the reliability of these networks. In this paper, the relevance of renewable energy resources and demand forecasting solutions in microgrids connected at Low-Voltage distribution networks are discussed. A balance between generation and demand is necessary to maintain, maximizing energy resources of micro-reservoirs and reducing their consumption from the grid. Forecasting models of renewable resources and demand for end-users provide relevant information, depending on the accuracy of such predictions and the time period being considered. Although there are several forecasting models and proposals in the specific literature, it is still necessary to continue working on these forecasting approaches. Indeed, very short-term prediction models typically focused on 10 min time intervals should be improved due to the stochastic nature of renewable resources—mainly wind and solar, and their rapid oscillations.

Depending on the type of configuration and distributed generation technology used for integration, microgrids push conventional distribution networks to use integration technologies that allow for energy transitions. Many end-users can become prosumers,

which affects a distribution network operator's current technical standards and configurations. Additionally, different types of controls need to be explored for application in Low-Voltage microgrids, as do their main characteristics and advantages. Subsequently, this paper highlights the need to propose alternative and more coordinated solutions of microgrids (and clusters of multiple microgrids) in Low-Voltage networks, since the dynamic behavior of end-users of such networks varies over time and produces conditions that microgrids must detect in order to maintain grid reliability and service availability. The implementation of microgrids in distribution networks thus requires more studies focused on innovative systems that allow for increased interaction with future electrical networks. This paper thus encourages the development of alternative coordinated and combined microgrid applications in Low-Voltage networks to enhance grid resilience and flexibility under the current energy transition.

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Abbreviations

The following abbreviations are used in this manuscript (by alphabetical order):

AC	Alternating current
CHP	Combined heat power
DC	Direct current
DG	Distributed generation
DSM	Demand side management
DSO	Distribution system operator
EMS	Energy management system
ESS	Energy store system
GHG	Greenhouse gas
HVAC	Heating ventilation and air conditioning
LV	Low-voltage
MAE	Mean absolute error
MAPE	Mean absolute percentage error
MBE	Mean bias error
MG	Microgrid
MRE	Mean relative error
MSE	Mean square error
PCC	Point common coupling
PEV	Plug-in electric vehicles
PV	Photovoltaic system
P2P	Peer-to-peer
RMSE	Root mean squared error
SDG	Sustainable development goals
STC	Solar thermal concentrators
TESS	Thermal energy storage system
WT	Wind turbine

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