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Review on Multi-Objective Control Strategies for Distributed Generation on Inverter-Based Microgrids

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Abstract: Microgrids have emerged as a solution to address new challenges in power systems with the integration of distributed energy resources (DER). Inverter-based microgrids (IBMG) need to implement proper control systems to avoid stability and reliability issues. Thus, several researchers have introduced multi-objective control strategies for distributed generation on IBMG. This paper presents a review of the different approaches that have been proposed by several authors of multi-objective control. This work describes the main features of the inverter as a key component of microgrids. Details related to accomplishing efficient generation from a control systems' view have been observed. This study addresses the potential of multi-objective control to overcome conflicting objectives with balanced results. Finally, this paper shows future trends in control objectives and discussion of the different multi-objective approaches.

Keywords: distributed energy resources; inverter; microgrid; multi-objective control; renewable energy

1. Introduction

Nowadays, distributed generation (DG) has become a key system for electricity production. Despite some advantages in DG, some limitations exist in their performance related to achieving single objectives when actual trends show works with multi-objective approaches [1,2]. The DG overcomes issues presented in centralized generation (CG) with improvements such as: Optimizing installation costs, providing its use to people living in places far from large cities [3] and establishing an expanded system of energy consumption that optimizes it is susceptible to the overwhelming effect of the blackouts [4]. These outcomes aid to reduce carbon dioxide (CO_2) emissions through fossil fuels utilization with renewable energy sources (RES) [5]. Microgrids (MGs) are a set of distributed generation unit that incorporates electrical storage systems to interact with a cluster of loads connected at the point of common couplig (PCC) of the grid. This system provides solutions for the reliable integration of distributed energy resources (DER) and CO_2 mitigation on the atmosphere [6]. The MG features are: High quality service, robustness, and sustainability. MGs inject energy into the conventional grid or they can function independently for local consumption in island mode depending on conventional grid demands [7].

The current trend shows that the massive production of electricity is expected from the DG. At this time, MGs consist of generation plants of up to 300 MW with projection to further growth [8] with further benefits in energy consumption such us becoming a key support of massive electrical-mobility implementation [9]. MGs schemes are known in DC or AC. The first one have a strong impact on research due to their simpler structures of electrical control systems [10]. In particular, no electrical devices are needed like DC/AC voltage source inverters (VSI), variables such as reactive power or harmonics are not presented, and a high degree of efficiency and reliability is obtained over AC generation (ACMG) [11–13]. Despite DC advantages, the major power generation is done in AC due to the intense demand for residential and industrial applications [14,15]. Futher approaches consider hybrid MGs to take advantage of the production and distribution trend in DC without neglecting the majority demand for AC [16–18]. This context emphasizes the VSI support for this sources of electrical generation in a concept known as inverter-based MGs (IBMGs).

Although IBMGs enhance local resiliency, improve operation, and stability of distribution systems, they present reliability and stability issues. For example, due to low inertia from VSI the MG presents instability as introduced in [19] and these resources do not have enough inertia as the traditional synchronous generators used in CG. Reference [20] mentions the deviation of voltage and frequency variables when the MG is disconnected from the main grid and operates in island mode. This phenomenon critically affects loads dependent on stable values of voltage and frequency. The issue of imbalanced loads produced by the different values of line and output impedance is addressed in [21], where a complex control technique is needed to stabilize a multivariable system. Other effects are related to non-linear loads [22] represented by power converters with total harmonic distortion (THD). This study highlighted the requirements to design a robust controller for disturbance rejection by sudden demand changes.

Considering these problems, authors have carried out research to strengthen the performance of IBMG through control systems. The design of feedback regulators has generated proposals such as [23,24], where the benchmarked droop power control is used to maintain the voltage and frequency values. Researches implemented advanced control systems to address robustness in IBMG; Patarroyo-Montenegro et al. [25] proposed a linear quadratic regulator (LQR), or [26] a sliding mode control (SMC) to overcome non-linear load effects on grid management. Other authors like [27] contemplated extended objectives like power flow control, voltage and frequency regulation problems, unbalanced load conditions, and harmonic generation.

Other researches have proposed complex control structures by merging advanced algorithms to get better results than conventional control systems on IBMG. To get better transient response, [19] sed a model predictive control (MPC) to get an anticipated response based on knowledge of dynamic plant's model. Another paper like [28] addressed the uncertainties problem in the VSI model, the control design was aimed on filter parameters. The control structure had a better performance on scenarios where uncertainties were overcome. Other authors have developed controllers tuned by mathematical methods. For instance, [29] applied particle swarm optimization (PSO), [30] used artificial neural network (ANN), or a combination of these methods as in [31].

So far, several research have been carried in the control of IBMGs. Various reviews have studied different architectures. For example, the authors of [32] studied different four-leg VSI structures on MG in island mode. This work presented the key advantages and disadvantages in applying different reference frames to control voltage and frequency variables on VSI. Other works like [33] presented the hierarchical control in IBMGs. The topic was specialized in the primary control structure of a MG. In this context, various schemes were observed such as systems with or without communication methods. The control droop was emphasized with its different formulations that conform a broad spectrum of voltage and frequency regulation through active and reactive powers. The authors of [27] studied the hierarchical control of IBMG based on island mode control. Key features of primary, secondary, and tertiary hierarchical regulation structures were analyzed. The objectives addressed were efficient control for consensus on RES, active and reactive power sharing, load dependency, dynamic stability, and islanding detection. Other authors like [34], published a study of different control schemes used in IBMG. The analysis was deepened in the regulation of the DG's internal control loop with various methods such as basic control like proportional-integral-derivative (PID) and dead-beat, optimal control like linear quadratic regulator (LQR) or model predictive control (MPC), experience-based algorithms such as fuzzy, and learning schemes like ANN. In addition, the study performed a review of commercial control software for IBMG such as HOMER (hybrid optimization model for electric renewables), HOGA (hybrid optimization by genetic algorithms), SOMES (simulation and optimization model for renewable energy systems), among others.

The papers described above cover particular control objectives such as voltage and frequency stability, robustness against load changes, or fast transient response. All these features are partially covered by one objective function subjected to constraints of different variables and this method does not take in advantage more characteristics to increase efficiency in the energy production process. On the contrary, there is scarce research in multi-objective control algorithms. These schemes introduce several grid regulation requirements from their mathematical formulation based on various objective functions. This concern takes into account several aspects to optimize IBMG under the following characteristics:

- Seamless change in transient state for VSI-MG interactions;
- Steady-state stability for voltage, frequency and power variables;
- Power flow control injected or absorbed by the interactions between VSI and MG;
- Generation of an optimal law of control under constraints;
- Robustness against model uncertainties and disturbances in the MG.

On the other hand, multi-objective control algorithms have certain disadvantages such as mathematical complexity for control law formulation or a large computational load in on-line implementation. The challenges of multi-objective controllers are broader than those presented in conventional control because of their approach for specific regulatory targets in IBMG. There are topics such as mathematical complexity or computational load that present a challenge for implementing these control schemes. To apply these schemes, different alternatives are needed to reduce models in simple expressions and versatile implementation in hardware systems with good performance. These challenges must be adequately addressed by IBMG researchers and energy consumers.

The aim of this paper is to review various multi-objective algorithms focused on IBMG. The applications and forthcoming trends have also been reviewed. With this review, it is expected that researchers who are working on this topic could comprehend the state of the art and provide some insights into research gaps for future works. The rest of this paper is organized as follows: Section 2 reviews concepts on inverter-based MGs definitions, Section 3 shows the multi-objective functions approach on IBMGs, Section 4 presents the future trends with the aim of possible lines of research, and Section 5 highlights the conclusions of this work.

2. Inverted-Based Microgrids Definitions

2.1. Inverter Structure

The voltage source inverter (VSI) is an electronic power converter that transforms energy from DC to AC. For a single-phase system, the typical topology of a VSI is the full H-bridge [35]. The circuit consists of a combination of 4 transistors and 4 anti-parallel thyristors to control reverse voltage conversion from load to source. Output voltage generation v_o is performed through PWM or SPWM signals through the transistors. The massive implementation of DER requires storage systems to improve stability and resiliency on energy conversion in the VSI. Variable solar radiation and fluctuations in wind speed require devices for power storage to enhance the performance of IBMGs. For example, the last advances in electric batteries have made possible to integrate into the grid the energy of electrical vehicles' batteries to support non-conventional electricity generation [9]. The closed-loop scheme considers a cascade control for voltage and current because of measurements of output power. At the end of the VSI, a low-pass LC filter is located. This filter generates a sinusoidal voltage waveform for system loads (Figure 1).

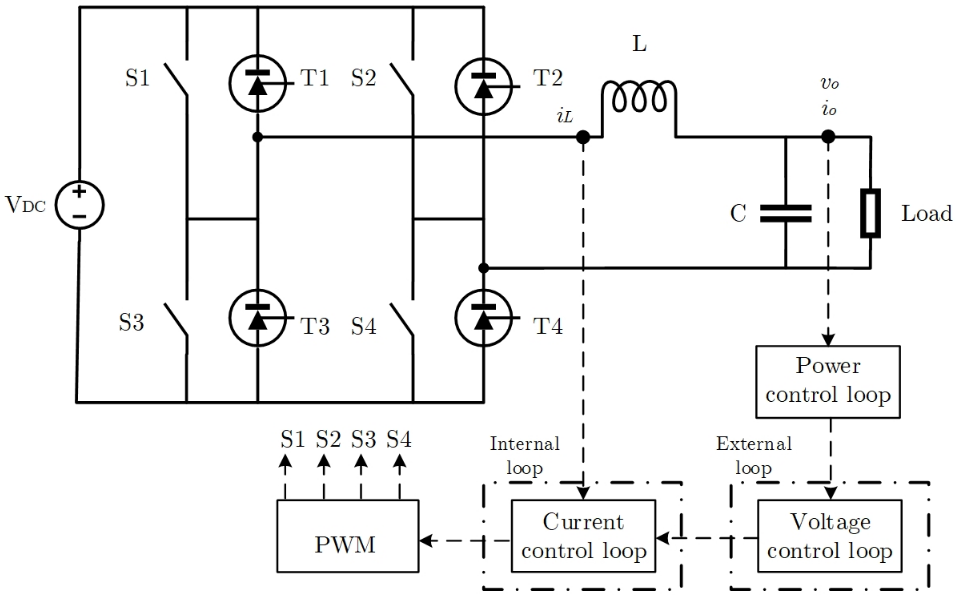

Figure 1. Single-phase inverter in islanding operation [35].

Typically, the VSI control is performed through cascade schemes [36]. The internal loop regulates the current i_o and external loop regulates the voltage v_o in the VSI. At every stage controllers from classic to advanced algorithms are needed. In Figure 2, the scheme of power control on VSI is observed. The measurements of voltage v_o and current i_o of the LC filter output are needed. The power supplied to the load through the output connector impedance (R_c, L_c) is calculated. These power values pass through a filter (L_f, C_f) to reach a droop control. This algorithm considers active P_i and reactive Q_i power values to modify the frequency and output voltage on the VSI. The droop control receives references for voltage V_o and frequency ω_o to calculate voltage reference v_i for the outer loop of the cascade control; the inner loop receives the reference of current $i_{li}*$ from the outer loop to control VSI current i_{li} through a PWM signal at the input of the inverter.

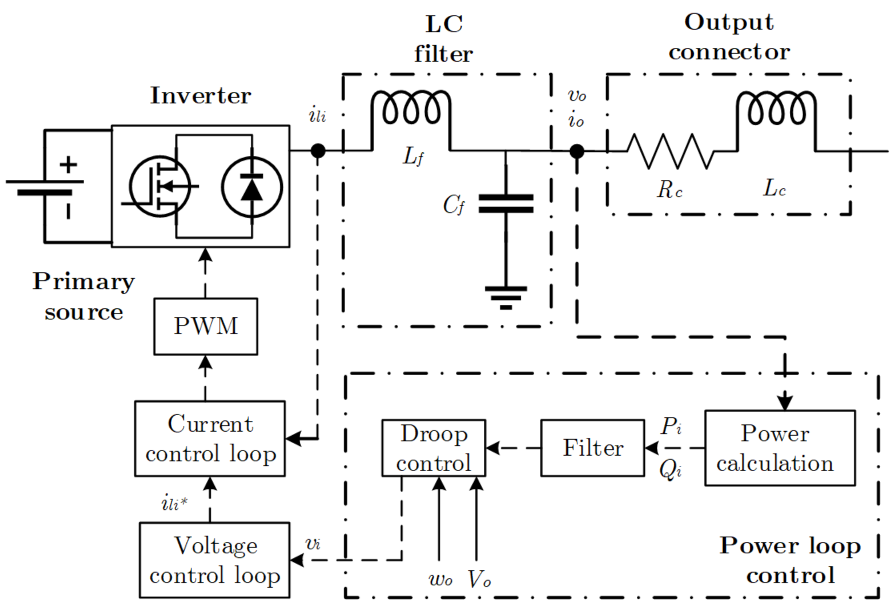

Figure 2. Single-phase inverter in islanding operation [36].

2.2. Microgrid Structure and Control

Microgrids (MG) are smaller power generation systems compared to traditional generation that associates diverse energy resources in parallel providing reliable and efficient electrical energy. The growth of MGs benefits many countries with competitive investment costs, scalability, and flexible operation [6]. In this context, issues such as energy management, electrical connectivity, and fossil fuels utilization are overcomed. The challenge of adding renewable resources in the traditional grid is addressed in MGs resulting in a massive trend of implementation with constant research on protection schemes and robust closed loop control. MGs are made up of several power sources like batteries, renewable, or non-renewable energy sources [32] as seen in Figure 3. MG can operate collectively when they are connected to the grid or in island mode when they work independently. MG constitutes one more source of generation that can supply power to loads, linear, and non-linear [37,38].

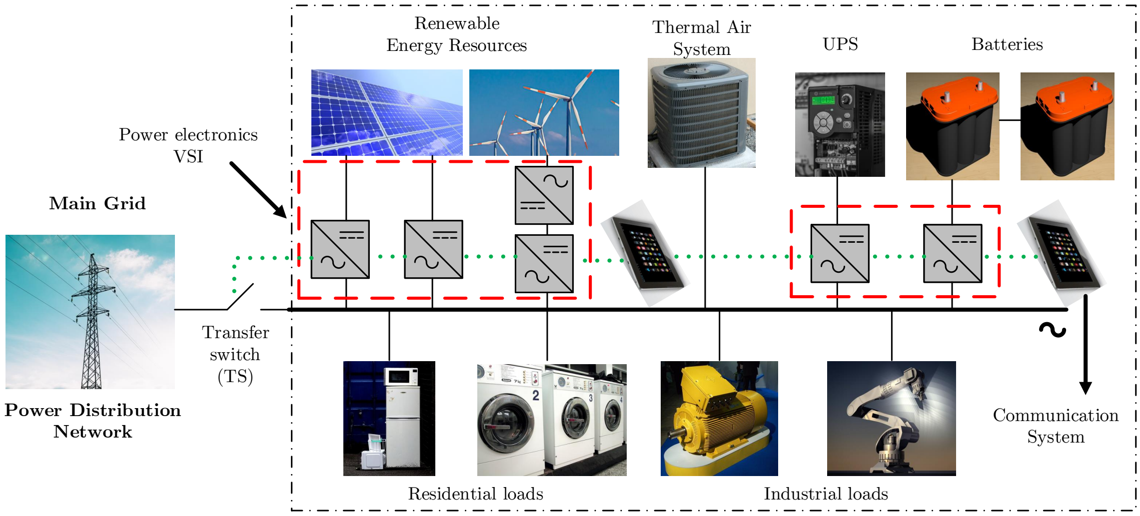

Figure 3. Microgrid scheme from inverter-based sources [32].

The link interfaces between the MG and the conventional electrical grid are the electronic power converters (EPC). MG links PES to absorb or inject electrical energy. In this state, the grid frequency and voltage are standardized values according to the distribution system. However, when the MG is disconnected to operate in island mode, voltage, frequency, and harmonic content present variable values due to its low inertia [39,40]. These parameters lose their stability and need to re-calibrate the EPC specifications to preserve the operation of equipment and systems [27,33,41].

This field has led science and technology to the development of research to improve the stability of MG in island mode. The alternatives are automatic control methods applied on EPC. These methods improve the energy exchange in situations of shared load, generation of harmonics by non-linear loads, or the slow dynamic response due to the implementation of low-pass filters to obtain voltage, current, or power values [42–44].

At the EPC level, inverter typologies are studied to develop a proper control law that satisfies the specifications of reliability in a PES. Therefore, research has been searching for objectives like improving a hierarchical control structure [23,45] or developing intelligent-inverter systems considering networks of inverters communicated in an array [37,46,47]. In the case of the low inertia of the MG, [19,48,49] present regulation schemes that carry on the stability of voltage and frequency.

The stability concept has a key importance in MGs where electricity production have to maintain a range of secure operations. This approach is essential in massive MGs implementation due to existing differences with traditional grid production, for example line impedances. The operational steady-state variables must satisfy system's constraints in voltage, currents, and frequency even if the MG is sharing power or reaching islanding under strong disturbances in the grid [50].

To manage efficiently an IBMG, control systems consider alternatives to overcome the challenges in DG. These goals with constant development ensure system stability and reliability. The most relevant trends are shown below [51–54]:

- *Control of output variables*. The output voltage and current variables in the IBMG must accurately follow their setpoints. In the event of disturbances, the oscillations of these variables must be damped to prevent critical deviations that affect the performance of the loads;
- *Power flow control and protections*. Over the years, MG was incorporated as support schemes for electrical generation shared with the utility grid. This scenario shows systems not prepared to incorporate more electrical generation due to the load capacity of their wires. For this reason, there are algorithms that limit the passage of high line currents due to voltage variations in the utility grid. In addition, the IBMG controller must maintain a balance between the power supply and demand in the event of any sudden load change. The controller aims to stabilize the IBMG regardless of the disconnection of equipment, increase of RES units, or the activation of electrical protections;
- *Cost-benefit*. The efficient control of IBMG must generate energy and economic benefits for its consumers. These advantages are recognized frequently in isolated areas that purchase IBMG equipment, and the investment will pay off in a short time. Benefits will be seen in lower electricity payments and the appropriate use of natural resources;
- *Transition between operating modes*. The IBMG is an independent generation system that supports the conventional grid in power-sharing activities or can work independently in island mode. The transitions between these two states must be carried out maintaining a smooth change among the voltage and frequency variables, ensuring their transient stability;
- *Controller tuning*. Controllers' performance is reduced by the variability of process behavior in situations of major changes in the generation system. This event causes the need to re-tune the controller if the background conditions change dramatically. Tuning works appropriately for certain performance ranges but does not respond to regulation conditions when DG leaves its linearity zone. Problems caused by the high incorporation of nonlinear loads, the low ability to reject disturbances, and communication delays in hierarchical MG control systems are also studied.

2.3. Hierarchical Control Structure

Hierarchical control in a MG represents a defined term to characterize a standard on DG. In this structure, three different control levels are represented with different objectives and time scales. In this way: Primary, secondary, and tertiary control structures have been defined [55]. This structure coordinates the different control levels necessary to manage electricity production. In each level, a control algorithm to manage voltage, frequency, power, among others is implemented. A typical hierarchical control is seen in Figure 4, where authors of [56] implemented a control scheme on a PV-battery-diesel MG.

This scheme presents the importance of adopting a controller appropriate to the generation objectives in the MG. This structure presents algorithms from classic controllers such as PID to inertia regulation techniques from VSG. In that field, there is more work to be done to achieve the reliability goals required by MGs.

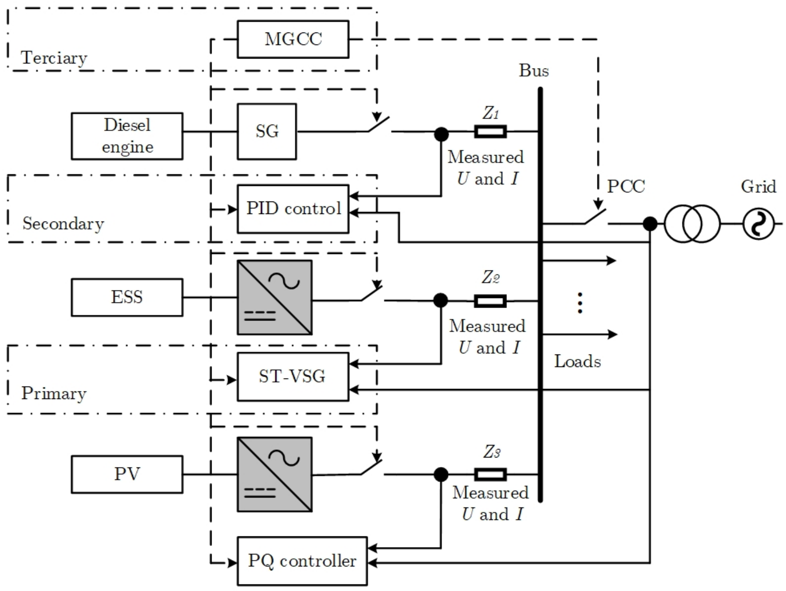

Figure 4. Hierarchical scheme for control of Photovoltaic (PV)-battery-diesel microgrids (MGs) [56].

2.3.1. Primary Control

The primary control is responsible for adjusting the voltage and frequency values to the specific rates in the MG. In that manner, it maintains the reliability of the system, improving the performance and the stability of the voltage locally. DG takes advantage of this feature to perform power-sharing activities appropriately [57]. The primary control structures possess the following characteristics:

- Regulation on internal voltage and current loops is done from linear and non-linear controllers. The objective is to measure and monitor the current in inductors and capacitors at the output of a filter. In this manner, the controller must maintain a fast and stable response to these values;
- The generation of a virtual impedance to emulate a physical impedance connected to the output of the system;
- The regulation of external control loops for active and reactive power variables, these values regulate the output voltage at the primary level. At this stage, droop power control is used.

At this stage, droop power control is used. This algorithm introduces the voltage and frequency variations in the inverter as expressed in the following equation:

$$\begin{aligned} \omega &= \omega^* - m(P - P^*) \\ E &= E^* - n(Q - Q^*) \end{aligned} \tag{1}$$

where ω^* is the angular frequency, E^* represent the amplitude of the no-load output voltage, and m and n are the coefficients that define the slope for frequency and voltage, respectively. Finally, P^* and Q^* are the reference values for active and reactive power [33]. The droop control is extensively studied and presents variants that enhance primary control performance. The versatility of mathematical expressions adopted by droop control approach has generated various proposals such us P-F/Q-U droop control, Modification of P-F/Q-U droop control, and P-U/Q-F droop control encountered at [33]. In addition, it is possible to find works based on DQ coordinates that solves the problem on susceptible systems to voltage and frequency distortion that must comply with the fixed-frequency operation [58].

2.3.2. Secondary Control

The secondary control performs the MG and main grid connection. The goal is to switch from island mode to conventional generation system. In this transition, the regulators are responsible for returning to stable values the frequency and amplitude variables, that have changed during the synchronization process. Consequently, the MG must measure the frequency and amplitude values required to perform the feedback control. At that time, these values can be restored in the event that there is a notable difference [59,60].

2.3.3. Tertiary Control

At this level of control, the MG accomplishes energy flow exchange with the main grid. In other words, the MG can inject or absorb power according to the needs of the environment. The variables manipulated at this level are the active P and reactive Q powers [59].

2.4. Microgrid Management Policies

Some countries have applied guidelines to manage MG efficiently. These policies assure fulfilment of power quality standards, avoiding failures that minimize generation capacity and caring electrical appliances under stable energy values. The results of these dispositions enhance electrical energy development on a big scale to comply consumption deficiencies because of the large population growth in the last years. The main MG policies are seen in Table 1; countries that have not established guidelines for MG have adopted policies from societies with similar electrical characteristics on the grid.

Table 1. Main energy polices for MG development from 2010 [61].

Country	Title	Year
USA	State-level Renewable Portfolio Standards (RPS)	Multiple years
USA	IEEE 1547-2018	2018
Poland	Renewable Energy Law of Poland	2015
Germany	2014 Amendment of the Renewable Energy Sources Act -EEG-	2014
China	Renewable electricity generation bonus	2013
China	The Notice of further improvement of New Energy Demonstration implementation	2013
Slovakia	Act on Energy and amendments to certain acts (No. 251/2012)	2013
Spain	Royal Decree Law on urgent measures to guarantee financial stability in the electricity system	2013
UK	Electricity Market Reform (EMR)	2013
Italy	National Energy Strategy	2013
China	China Energy White Paper 2012	2012
China	The Notice on New Energy Demonstration City and Industrial Park	2012
Croatia	Energy Act 2012	2012
Denmark	Regulation on Net-metering for the Producers of Electricity for Own Needs	2012
Luxembourg	Energy performance requirements for residential buildings 2012-2020	2012
Slovakia	Act on Regulatory Office for Network Industries (Act No. 250/2012)	2012
Lithuania	Law on Energy from Renewable Sources	2011
Spain	Regulation of small power plants connection to the electricity grid (Royal Decree 1699/2011)	2011
Slovakia	National Renewable Energy Action Plan (NREAP)	2010
Germany	Energy Concept	2010

VSI devices in DG are the power interface for the MG to consume or inject power into the conventional grid. They also perform other functions such as power flow control, fault sensing, connection or disconnection according to load demands, among others. For these reasons, the IEEE suggested specifications for IBMG with the standard (Std) IEEE 1547 series [37]. This standard covers the topics of: Power quality, voltage regulation, or MG islanding detection. For power VSIs, Std IEEE 1457-2018 [62] implemented a chapter for smart VSI associated with generating facilities of interconnections based on California Electric Tariff Rule 21 [63]. Table 2 shows power quality requirements for IBMGs.

Table 2. Power quality requirements on IEEE Std 1547-2018.

DC injection	Distributed energy resources (DER) will not inject more than 0.5% of DC current compared to full rated output. current at the reference point of applicability
Voltage fluctuation	*Rapid voltage changes:* DER in PCC at medium voltage must not exceed 3% of nominal voltage and 3% over a period of one second. DER in PCC at low voltage must not exceed 5% of nominal voltage and 5% over a period of one second.
	Flicker: Short-term flicker severity evaluated in a time of 600 s = 0.35. Long-term flicker severity evaluated in a time of 2 h = 0.25.
Current distortion	*Odd harmonics:* 4% for $h < 11$, 2% for $11 \leq h < 17$, 1.5% for $17 \leq h < 23$, 0.6 for $23 \leq h < 35$, 0.3% for $35 \leq h < 50$.
	Even harmonics: 1% for $h = 2$, 2% for $h = 4$, 3% for $h = 6$.
Overvoltage contribution	*Over one fundamental frequency period:* DER must not exceed 138% of nominal frequency value for a duration of one fundamental frequency period. Applicable to the line-to-ground or line-to-line voltage systems.
	On cumulative instantaneous overvoltage: DER instantaneous and cumulative voltage must not exceed acceptable region defined on Std Section 7.4.2.

3. Multi-Objective Functions Approach on IBMG

The traditional control approach in IBMG solve certain objectives based on one objective function. Aside from considering diverse variables in the process under constraints, the control law is determined on the minimization of a single objective function. Results so far have shown the performance optimization in energy production and costs, but other characteristics are not analyzed because the limitations of control algorithms or conflicts between objectives. For instance, the change of power references might lead to dispute between fast response to track new setpoints and oscillations of voltage and frequency variables on IBMGs; regulations on fast response and stability are desirable but under a consensus that keep balance in the system.

The existing multi-objective algorithms approaches need optimal solutions to avoid conflicts between goals. The application of a certain optimization method will depend on its advantages and a criterion of preserving moderate computational cost. This antecedents led research to various proposals on multi-objective optimization as seen in Figure 5.

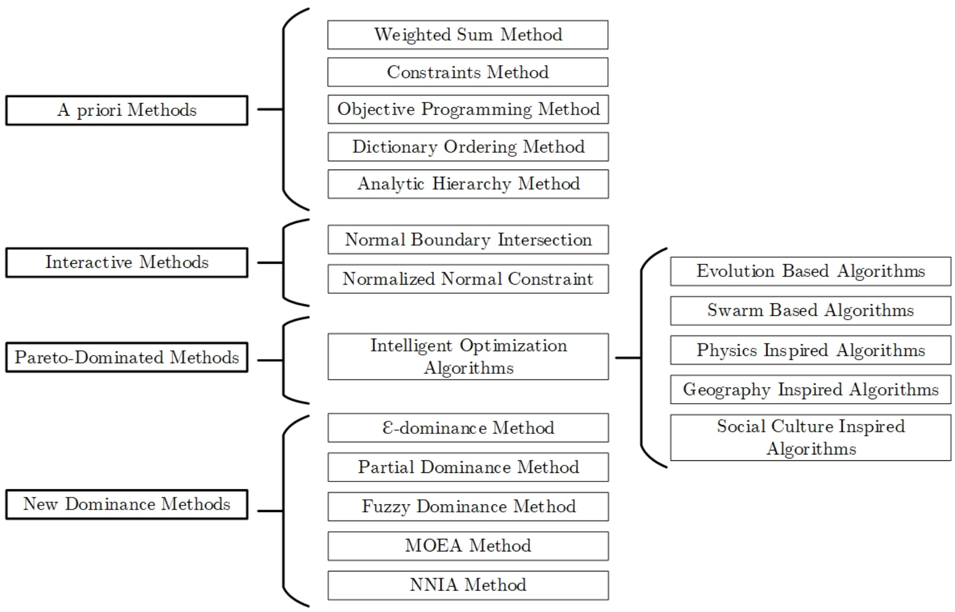

Figure 5. Multi-objective trade-off optimization methods [64].

The broad spectrum of multi-objective methods shows the alternatives to minimize a problem with various objectives depending on factors such us: Computational cost, achievements, and algorithms intrinsic concepts. This advantage represents an important source for new proposals non-used methods on IBMGs.

Constant research on MG have been leading to obtaining better efficiency results. The predominant AC consumption in residential and industrial applications has highlighted the VSI technology with improvements year after year. Main objectives and trends in the massive introductions of IBMGs consider the following aspects [1,65,66]:

- Energy-cost reduction;
- Reliability of the service;
- Minimizing power fluctuations;
- Reduction on peak loading;
- Mitigation on CO_2 emissions;
- Multi-objective optimization;
- Tuning algorithms.

The optimal solution of two or more conflicting objectives will not lead to a single solution instead, an optimal solution set with a trade-off of objectives looks for IBMG optimization. If an objective has value in IBMG performance, this aspect can be quantified as a mathematical function. The resolution for whole expressions are complex and advanced methods are required such as Pareto-optimal front.

The following concepts describe the main multi-objective approaches with their specific features reached for different controllers. The goals have been classified according to the requirements of main characteristics and means of achievement through advanced algorithms. Multi-objective optimization approach is also addressed where essential works in this area have been revised.

3.1. Energy-Cost Reduction

Effective operation and maintenance of MGs achieve reduced energy losses and increase system efficiency. This feature is a common approach in objective functions under constraints. Objective functions that describe the average cost of energy to the loads in MGs is given as follows [1]:

$$v_C(x(t), t) = \sum_{\forall y \in DER} (\pi_y(P_y(t), t) P_y(t) \Delta t) \tag{2}$$

where π_y is the kilowatt-hour cost of P_y kilowatts from DER y measured in hours.

Particular features compromise of transient and steady-state stability. Changes in output IBMG variables can be achieved properly with controllers with a fast and accurate response. However, an inadequate control law might create oscillations that lead to grid instability. On a permanent operation, events of connection and disconnection of loads and sources into the grid produce disturbances that affect the performance of MG in steady-state. With the major introduction of RES, the grid is susceptible to reaching instability due to RES low inertia. Variables of grid voltage and frequency are the most sensitive in AC energy production. The next concepts are essential features to keep stability and producing effective cost functions.

3.1.1. Fast Response

To acquire a fast response, controllers act aggressively to reach new setpoint values. This performance produce undesired oscillations in regulated variables. In [67], a VSI was regulated by a SMC. Despite the fast transient state and robustness in the steady-state, there is a major problem on the SMC that affects the control law. This issue is known as chattering and this dilemma is represented by high-frequency oscillations [68]. In most cases, the final control elements cannot respond to these changes so quickly. Another issue is that the mathematical formulation of the SMC can produce the resolution of singular functions which represent a problem in generating an adequate control law. To solve this problem, an ANFIS structure was employed. This method considered a neuro-diffuse system of inference rules. Therefore, the VSI achieved a fast transient response, steady-state stability, and avoided the generation of singular functions. The ANFIS algorithm guided the SMC for rejecting unknown disturbances. Similar work was found in [36], where the SMC and ANN algorithms were merged to eliminate voltage deviation at the primary control of a MG. The reduction of chattering was performed with the ANN.

In [69], a LQR was implemented for a seamless transition of a MG. The study analyzed the MG leaving the main grid to operate in island mode. This scenario typically presented severe transient changes. In this manner, the LQR reduced the transients generated in the voltage and current variables. The controller described fast dynamics in three different scenarios: Direct connection to the grid for reference variations of P and Q powers, alterations in wind speed and response to faults that contain immediate islanding of the MG.

3.1.2. Ramps for Power Setpoints Tracking

Ramps for the power rate on DGs have been properly introduced to change smoothly the power setpoints on MGs. However, some cases do not control appropriately the ramp rate and peak values generated. In [70] the peak power ramp minimization is introduced. Authors utilized the Nash bargain theory to maximize the social welfare problem. Results showed an efficient consumption of power from different sources of storage and generation with possibilities of reimbursement depending on local power generation policies. Other works like [71] presented a flat tie-line power scheduling control on MG. The MG was implemented between PVs, wind turbines, and energy storage units PV/WT/ESU. The power ramp is implemented to reach different energy values with precision and smoothness. Despite the complexity of the system, the objective was achieved by a central control algorithm that considered the fluctuations from the different sources.

3.1.3. Voltage and Frequency Regulation

It is a synthesis controller for the robustness of the process variables in a steady-state. To formulate this algorithm, the optimization of a mathematical function is needed. The key feature is the disturbance rejection through a mathematical approach that considers the measurable disturbances on the system. In [72], the controller was implemented in a MG for tracking the output voltage references. The rejection of disturbances in nonlinear loads was equally considered as a plus of this system.

In addition, the environmental conditions model was carried out to predict demand parameters in the load. On the other hand, [73] controlled a power converter through a MPC. The goal was to keep output voltage tracking. Advantages of this control method is the use of a different optimization function that presented a single prediction horizon. With this approach, the problem of the computational cost by the MPC implementation is minimized.

Many of the control algorithms in MG are based on the droop controller. This type of regulator is employed at primary control levels to stabilize voltage and frequency variables. The controller considered the relationship of frequency and voltage with active and reactive powers, respectively. In [74], the droop controller was used with the ANN to get better performance on the inverter. The system measures voltage and current values of the inverter to calculate the output power. This allowed the droop controller to obtain voltage and frequency reference values for a cascade control. The ANN was used to prepare the inverter for a sudden change where the MG needed to leave island mode to get connected to the traditional grid.

3.1.4. Virtual Impedance

The virtual impedance is an important concept to keep stability in the grid, especially when VSI are involved. The power flow can change significantly when there is a variable impedance at the VSI output.The target of virtual impedance is keeping the VSI operation through a virtual stable value of line impedances. In [75], a shaped control method was used to resolve PCC voltage issues to variable impedances. This method showed how important it is to consider a wide range of impedance values based on different frequency bands. Another paper like [76], improved energy quality for voltage and current in IBMG. This research used a cascade control to set local load voltage and current injection into the grid. The results showed an achieved seamless transition between grid connection and island mode due to the action of the H_∞ as inner control.

3.1.5. Virtual Inertia

In [19], the integration of a virtual inertia algorithm and the MPC was observed to stabilize the frequency of the MG. The scenario was a high penetration of renewable energy. As mentioned in the previous sections, renewable energies have low inertia compared to the conventional grid. When these generation sources are integrated, instability occurs in the voltage and frequency of the MG. Through the MPC applied with the virtual inertia algorithm, a time-stable and reliable system was achieved to face uncertainties generated by renewable energies integration. In this context, the improvement of stability was observed in frequency by comparing the results obtained by the MPC with a fuzzy algorithm.

The authors in [77] merged a virtual inertial algorithm with an adaptive controller. Virtual inertia is a practical algorithm to increase the inertia of MGs but there are problems: The strong electrical coupling and low accuracy to keep constant MG variables. To improve accuracy over the system from storage devices, the AC signal frequency response was analyzed. The system combined a cascade PI algorithm with the droop controller and virtual inertia. Results showed that the controller can withstand load variations in the MG with minimal changes in an operating frequency.

3.2. Reliability of the Service

Non-delivered energy (NDE) is quantified to show the reliability of the MG. The nature of the loads generate high or low cost depending if the load is critical or non-critical [78]. This objective function is calculated as follows:

$$v_R(x(t), t) = \pi_{NDE,noncrit} dP_L(t)\Delta t + \pi_{NDE,crit}(1 - u_{L,crit})P_{L,crit}(t)\Delta t \quad (3)$$

where dP_L is the total of non-critical load, $u_{L,crit}$ is a binary factor that express critical load connection or disconnection, and $P_{L,crit}$ is the critical load in kilowatts.

This feature is desired in many applications because of fluctuating conditions on the system's environment. Typical events are disturbances and uncertainties. In the IBMG case, common situations of disturbances were discussed in changes for voltage and frequency. Uncertainties are frequent too because of weather conditions, load unbalance, and unknown load profiles.

3.2.1. Uncertainties

In the case of robust control algorithms like H_2/H_∞, there are a few proposals in recent years. In [28], the authors used a cascade structure to perform current and voltage control. The internal current loop was adapted with a SMC controller, while the external voltage loop was integrated with a H_2/H_∞ algorithm. This hybrid structure did not need an accurate inverter model. In addition, inverter performance could be improved for system uncertainties, maintaining constant frequency values, low harmonic distortion, robustness for parameter variations, and fast transient response. Other objectives related were objectives like not depending on the process model, steady-state stability analysis, robustness against disturbances, and optimal tuning.

In [79], a H_∞ controller was implemented to improve robustness in a MG. The problem of low inertia in the MG was reviewed and the H_∞ algorithm was implemented as a method of tuning the parameters of virtual inertia. Different scenarios were considered such as: Step changes of load, effect of disturbances, and the system uncertainties. At long last, the voltage and frequency values of the MG were kept constant.

3.2.2. Adaptive Schemes

An adaptive controller in [80] was implemented between a MPC and ANN. The objective was to regulate voltage and frequency values in an inverter-based MG. The MPC analyzed the inverter model to establish a control law based on the dynamics of the power controller. Lyapunov's criterion is also incorporated to analyze system stability. Due to possible errors in the mathematical expression, ANNs were responsible for improving the model to avoid uncertainties. The controller managed an adaptive schema about the process conditions. To compare the effectiveness of this proposal, the authors explored various cases such as: Sudden load changes, different types of loads, gain variations, and communication delays.

3.3. Minimizing Power Fluctuations

Continuous changes in production and demand cause power fluctuations that are quantified by the difference in firm and variable generation in the electrical power system (EPS) aare s follows [81]:

$$v_D(x(t),t) = \pi_{\Delta P} \frac{|P_{EPS}(t) - P_{EPS}(t)(t-\Delta t)|}{\Delta t}. \tag{4}$$

In this context there are several advantages utilizing advanced controllers. The SMC is identified by two phases: The first in which the reference is reached as quickly as possible and the second, where it is to be ensured with robust tracking of the set-point over time. Consequently, this mathematical method is widely used to stabilize voltage and frequency variables in a MG. In [82], the SMC was applied to improve voltage regulation and active-reactive power transfer. This work led to robust design due to the stability analysis performed by the Lyapunov function. Hence, the advantages are observed in a hierarchical management system.

In addition, [83] addressed the problem of power tracking with robuster transient response.

3.3.1. Active and Reactive Power Sharing

It is important to establish an equilibrium between generation and demand. Different interactions from sources and loads generate active and reactive power flow. In [84], the power generation was performed on IBMG. The key scheme used was a voltage control mode and current control mode under the regulation of droop control. This decentralized scheme considered the capacity of VSI to perform the active and reactive power flow between different sources in island mode. In certain cases where reactive power is needed, the droop control is modified as seen in [85]. The IBMG shared accurately reactive power calculating the error of this variable when a disturbance was added. This process overcome power-sharing issues produced by mismatched line impedances.

3.4. Reduction on Peak Loading

This feature is characterized by the peak power on the PCC. The reduction of peak power yields a financial benefit to the grid [81]. The quantified objective is given as follows:

$$v_P(x(t),t) = \pi_p P^2_{EPS}(t) \tag{5}$$

where π_p is the cost per kilowatt squared of power P_{EPS} to the PCC.

The massive introduction of power converters have produced degradation of power quality in the grid. This aspect is traduced in increments of total harmonic distortion (THD) of current that produce abnormal heat in power wires and decrease the life cycle of electrical machines.

This concept seeks an optimal control law to regulate IBMG variables. The optimal value is the best option that minimize a criteria such us error of output values. Some control methods use an objective function to empathize one or various objectives to accomplish in closed-loop regulation.

3.4.1. Performance Index Minimization

The linear quadratic regulator (LQR) is an optimal control algorithm. It minimizes the law of control based on objectives defined in its optimization function.

It is essential to measure the state variables of the system, so that the optimization of the cost function reaches the approach of generating a global minimum value. In [86], the authors used this algorithm in a non-communication environment. This method was performed on hierarchical control. The LQR acted as a secondary controller to regulate the frequency in an autonomous MG. The results showed an optimal frequency regulation values near the system reference. These results provided stability at the second level of control. In this work, the dynamics of the MG output filter were considered as system state variables.

Fuzzy control is based on the experience of the process by an operator. This approach considers fuzzy inferences or rules. This criterion sets the output control law according to the process inputs and states. In [87], a fuzzy control was applied to a MG. The parameters considered were renewable generation and local load demand. The primary advantage of the fuzzy controller was the reduced number of inference rules for this type of process. However, in this work, optimization was performed to generate only 25 rules. These directions analyzed the power-sharing performance from the environmental conditions.

3.4.2. State Estimations

Otherwise, in [88] ANNs functioned as a mathematical estimation technique to observe the dynamics of distributed generation sources. This method indicated the benefits of using an advanced computing approach for predictions. This process is complex to perform with classic control algorithms.

Lastly, [89] presented a robust cascade control scheme by merging two optimal algorithms. The H_2/H_∞ was the external voltage loop controller and the LQR was the internal current loop controller. A full-state observer was also incorporated to have non-measurable system variables. The results indicated high stability and robustness in the presence of uncertainty parameters in the output filter and variable load changes.

3.4.3. Constraints

MPC has been very prominent in recent years. This feature is related to produce anticipatory control actions with prior knowledge of the system model. This algorithm is also optimal because of the minimization of a cost function. It is characterized because its mathematical formulation is in discrete time. The most relevant characteristic of MPC is the use of constraints. Many controllers use saturators to define a range for the control signal. However, the constraints in the MPC look for an optimal control law based on optimization criterion. In [90], power control was performed on a MG in island mode through MPC. The problem of the mathematical model considered a strategic power management system. The constraints taken into consideration were the storage system, battery, generation, and loads.

3.4.4. Harmonic Mitigation

The artificial neural networks (ANNs) are a mathematical algorithm emulating the functioning of brain neurons. ANNs have inputs, mathematical functions for activation, and outputs. Like any neuron, ANN can be grouped with others to resolve complex problems. This algorithm needs a training process, the ANN will acquire a knowledge of the desired output from certain input data through learning actions. In [91], shared power control was performed on a MG including nonlinear loads. The effect of nonlinear loads is the generation of harmonics at voltage output in the point of common coupling (PCC). ANNs mitigated voltage harmonics to make active and reactive power flow more efficient.

In [92], the SMC mitigated harmonics of output voltage on a MG. This controller is specified by robustness, fast response, and a zero error in steady-state. In addition, it performed tracking of the maximum power transfer point through the electronic converter.

3.5. Mitigation on CO_2 Emissions

The cost function that describes CO_2 mitigation can be determined through the carbon cap-and-trade market [93].

$$v_G(x(t),t) = \pi_{GHG} \sum_{\forall y \in DER} (G_y(P_y(t)\Delta t) \quad (6)$$

where the objective function is described as the sum of the carbon emissions G_y that produce P_y kilowatts of power by the price of carbon per ton of CO_2 (π_{GHG}).

3.6. Multi-Objective Proposals And Optimization

In this section, information is provided about trends on formulation and optimization of multi-objective approach. There are different proposals that seek power management control from advanced regulation structures and machine learning techniques such as genetic algorithms.

The multi-objective problem consists of minimizing various objectives that are important with each other. The objectives are considered in function of mathematical expressions of error or sensibility of the process's performance. This idea represents a problem because there is not a unique solution in this approach. All calculations represent optimum solutions that differ with other results about the degree of commitment between objectives. In this context, it is critical to find a collection of solutions that achieves regulation goals without the detriment of objectives among them.

The optimization of multi-objective problems is based on Pareto optimization. Figure 6 shows the concept of Pareto front for two objectives where the points in dashed lines are called non-dominated. These points are the best set of solutions compared to the other points called dominated points. The dominated points are also optimum solutions but improves one objective and affect adversely the other one.

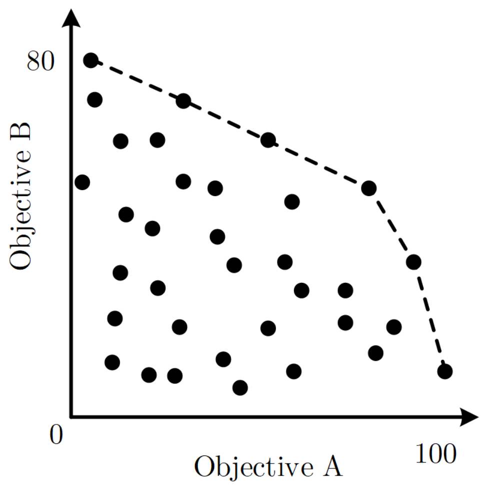

Figure 6. Pareto front for two objectives [94].

A multi-objective control proposal to improve MG power quality in island mode is found in [95]. Authors applied cascade voltage and current scheme to regulate voltage and frequency in the three-leg IBMG. The hybrid multi-objective symbiotic organism search (MOSOS) optimized specific objectives such as voltage overshoot and undershoot, rise time, settling time, and ITAE and PI parameters tuning were also considered. Results showed robustness in the applied controller under scenarios of harmonics and fluctuating sources as disturbances in the grid. Figure 7 presents a flow diagram of the proposed method over the control signal on VSI. The Figure 7 presents a flow diagram of the proposed method over the control signal on VSI.

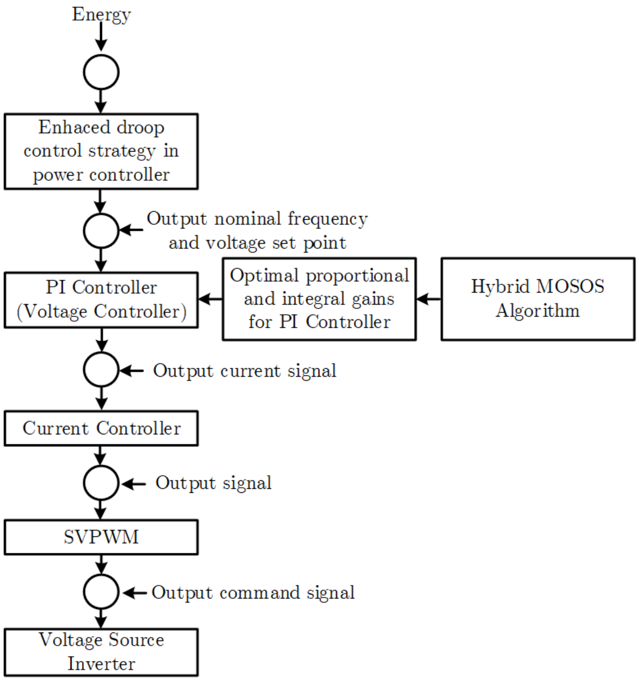

Figure 7. Flow diagram of multi-objective symbiotic organism search (MOSOS) multi-objective control [95].

The key objective is to generate a smooth response under the requirements of voltage overshoot and undershoot, rise time, settling time, and integral time absolute error. The cascade regulation structure couples a PI controller to develop the control signal of SVPWM on a VSI. The MOSOS scheme provides a numerical solution for the group of objectives presented in this analysis and the regulation of voltage and frequency in the MG is guaranteed.

Authors in [96], proposed a multi-objective control algorithm to improve the performance of multi-functional grid-connected inverters. These devices present limited capacity when trying to satisfy requirements for interactions of renewables in utility and providing ancillary power-quality services. The proposed method displayed a cooperative scheme with communication support between VSI to handle the requirements of power quality needed on distribution feeders. Figure 8 shows the interaction between comprehensive power quality evaluation objectives and hierarchical control to adjust the electrical power demand in a MG. The management of each DG system is accomplished by calculations of coefficients needed by local controllers to perform optimal compensation. In addition, based on measurements of voltage and current at PCC, the control scheme computed the THD on the utility grid. The tertiary control solved the Pareto's front solution to meet the requirements of the system operator.

The control scheme approach solved the energy management challenge optimizing a comprehensive power quality evaluation index. This performance index was based on catastrophe decision theory in order to quantify the parameters that enhance power quality on MGs. Results showed an effective utilization of the limited capacity of multi-functional grid-connected inverters to cover the specifications of optimal power quality on MGs.

As seen in previous sections, MGs supply energy into the utility grid or function independently in island mode. The commutations between these two operations modes generate transient jumps that compromise reliability in the utility grid. This antecedent encouraged authors in [97] to develop a multi-objective control structure based on a linear quadratic-based optimal bumpless controller with two degrees of freedom. Figure 9 shows the control scheme that covers the two operation modes in the MG.

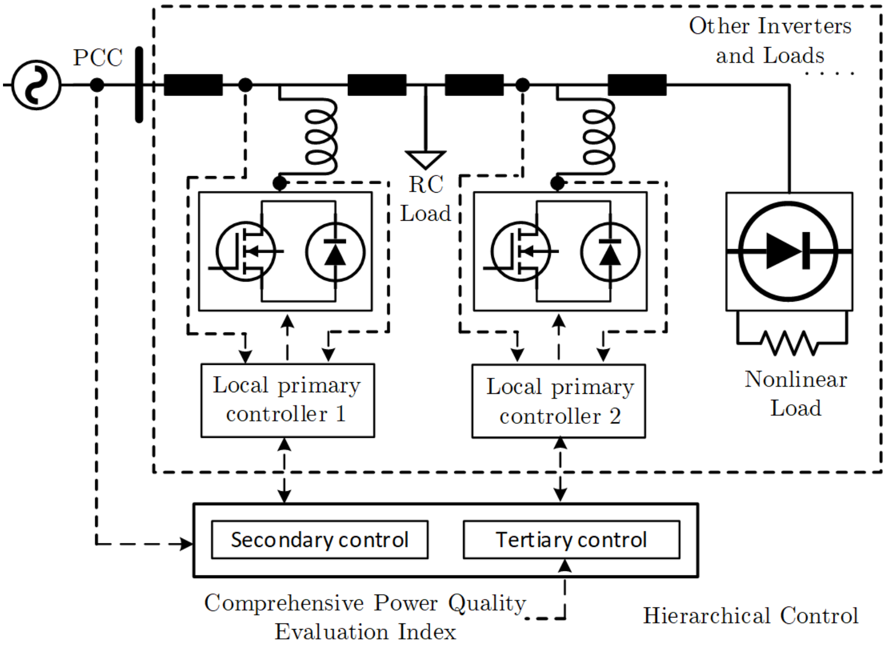

Figure 8. Multi-objective control on hierarchical-based micro-grid application [96].

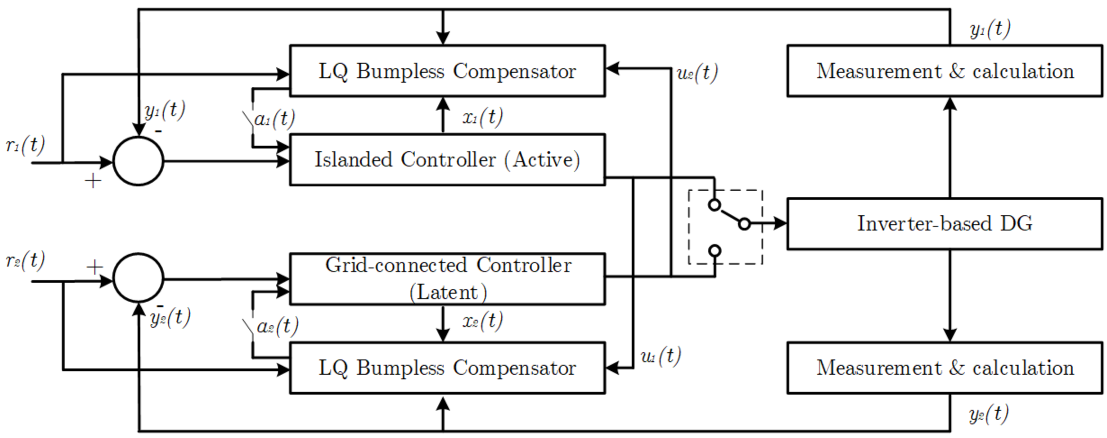

Figure 9. Bumpless control structure of MGs with two mode controllers [97].

This strategy measured MG's parameters such us voltage and current. The feedback measurements and the bumpless method improve the reference tracking error and controller tracking error. Although this is a novel regulation method on MGs, the proposal is based on conventional optimum schemes such us linear quadratic controllers. The mathematical structures are more fundamental compared to advanced controllers and the computing calculation is solved quickly. The approach covered the island-mode requirements such us power sharing and suppression of circulating current, and the grid-connected requirements such us active/reactive power flow and voltage/frequency synchronization with the conventional grid.

Some authors emphasized the concept of multi-objective control to achieve more efficiency on IBMG control. The existing research include complex algorithms to perform multi-objective optimization to achieve control goals.

In [98], the main idea was the control of power, voltage, and current values in an island IBMG. Particular objectives considered were overshoot/undershoot, settling time, rise time, and integral time absolute error (ITAE) in the output voltage. The main advantage in this context was the fuzzy membership functions used to determine objective functions. The complex mathematical expression was resolved by hybrid big bang-big crunch algorithm that tuned PI regulators under different changes in load consumption.

The advantage of multivariable MPC was seen in [65] where authors named to their research a smart branch method aimed for IBMG. The structure contemplated the voltage and current at PCC to perform distinct control objectives addressed in MPC performance index such as adjusting output transformer impedance, improvement of power quality, and keeping minimum deviations on current values to set a reduced harmonics on the grid. To solve this complex problem, multi-objective optimization was used; a key characteristic is found on droop control to tune MPC weights according to the measurement of variables.

A methodology for restoration sequences in distribution MG was addressed by [66]. The study studied the island mode case where a common issue of unbalanced load was compensated by controlled PQ inverters. The control strategy considered simultaneously energy optimization and dynamic stability, where MG transient behavior was previously analyzed with electromagnetic transient simulations. The multi-objective function subjected to constraints was optimized to achieve restored load and total restoration time approach to an IEEE 123 node test feeder.

Multi-objective coordinated control for MG inverters are addressed by [99], where issues of unbalanced conditions are presented. The grid-connected inverter operation was improved for issues of power oscillations and current harmonic suppression. The multi-objective coordinated control strategy decoupled grid voltage in positive and negative sequences to apply a simplified Fourier transform and mathematical complexity reduction achieved less computational load to improve power quality on IBMG under unbalanced grid voltages.

Table 3 shows the current trends on multi-objective optimization on MG and a comparison of methods.

Table 3. Multi-objective optimization approaches.

Method	Advantages	Disadvantages	Sources
Pareto optimality	Incorporates scalarization methods and provide flexible framework for algorithm design	Require priori knowledge of the Pareto front in objective space, the number of weight vectors grow exponentially with the objective space size	[1,100,101]
Global criterion	Simplicity and effectiveness because a Pareto ranking procedure is not required	The definition of desired goals requires extra computational effort; a solution might be non-dominated if the goals are chosen in a feasible domain and such conditions can limit their applicability	[2,102]
Linear combination of weights	Simplicity in implementation, use and computational efficiency	Difficult to determine appropriate weight coefficients when scare information of the problem is available	[103]
The ϵ-constraint method	Simple approach, it has been applied in many areas of engineering	High computational cost, encoding of objective functions limited for a few objectives	[104–106]
Multi-objective genetic algorithm (MOGA)	Versatility to find several members of the Pareto optimal set in a single performance of the algorithm	High computational cost	[107,108]
Non-dominated sorting genetic algorithm II (NSGA-II)	No extra diversity control is needed, elitism preserve pareto-optimal solutions	More members in the first non-dominated set lead place to other pareto-optimal solutions	[109–111]
Multi-objective evolutionary algorithm (MOEA)	The performance index are integrated as environmental selection, guided search and continuous optimization of the entire population	Slow convergence, poor performance and unknown convergence behavior of each non-dominated solution in the the Pareto optimal set	[112–114]

3.7. Tuning Algorithms

In [110], the problem of low-frequency instability in a MG for active and passive loads was analyzed. MG in island mode can suffer stability problems by small-signal changes. This issue was related to the low inertia and how DG becomes vulnerable to small changes in system operating conditions. Therefore, a LQR-based controller was designed. Authors also considered a Kalman filter to estimate system states. Kalman's technique is very useful as long as the mathematical function of the process is obtained. The Kalman filter can predict variable changes in a system, with no need of physical implementation of sensors or transmitters. In this work, the Kalman filter functioned as a state estimator that eased the communications system in hierarchical control. The LQR control and Kalman method contained diagonal matrixes that need calibration. The genetic algorithms (GA) technique was used for constant tuning. The type of GA used was the fast and elitist multi-objective non-dominated sorting genetic algorithm (NSGA-II).

In [115], the robust stability analysis was performed on a MG for inverters with droop controller. Some situations were analyzed when oscillating phenomena are generated in MG. The following reasons are presented: Large load changes, MG reconfiguration, high energy demand, low frequency from dominant electrical elements. Therefore, a two-degree freedom droop controller was implemented with the combination of a conventional droop control, and a robust transient function. For tuning, the authors implemented a mathematical method known as Kharitonov's theorem to minimize the oscillations of system variables. The rejection of disturbances, stability in equilibrium points, and uncertainties. Kharitonov's theorem has been used in several works to study the stability of MG. The algorithm provided a margin in which the gains of the droop control can be changed and maintain the reliability of the system.

In the case of collective behavior algorithms, [116] used the PSO to tune into a fuzzy PD+I method for reducing frequency fluctuations to the connection of renewable energy units. The PSO tuned the PD+I gains and fuzzy control parameters.

The controllers reviewed in this section look for common objectives such as: Improving transient response, tracking voltage and frequency references, disturbance rejection, voltage stabilization in non-linear loads, and efficient active and reactive power transfer. However, the following section will look at advantages that hybrid algorithms possess by joining diverse mathematical methods that accomplish robustness, fast response, or a broad range of performance with better performance. Table 4 shows a list of common objectives reached for control structures.

Table 4. Resume of advanced controllers objectives.

Control	Objective	Source
PID	Voltage and frequency control, grid stabilization, improvement of power quality	[117–119]
LQR	Seamless transition, current control in island mode, frequency regulation, power sharing, mitigation of small signal instability	[69,86,89,110]
MPC	Voltage and frequency control, virtual inertia, dynamic stabilization, power sharing, primary control	[39,73,90,120–123]
Fuzzy	Voltage and frequency control, power AC/DC control, virtual inertia, online tuning, power-sharing, voltage, current control	[39,87,98,124,125]
ANN	Faults detections, adaptive voltage and frequency control, islanding detection, prediction of load demand	[80,88,91,126–128]
SMC	Power flow control, disturbances rejection, voltage and frequency control, robust control for unbalanced load	[26,82,92,129–131]
H_2/H_∞	Robust and optimal control, voltage and frequency control, cascade scheme	[28,72,83]

These proposals have generated results that improved a specific objective that is the cost of energy reduction. The control algorithm approach could be extended to achieve other objectives related to the power quality. In this context, complex structures have been developed to accomplish better results compared to their predecessors. This structure merges different control methods, taking advantage of their inner capabilities. Table 5 presents an analysis of different controllers and objectives reached in their respective papers. The proposals presented show the high research potential for the design of the IBMG algorithms on VSI that overcome conventional regulators.

Table 5. Particular objectives on inverter-based MG (IBMG).

Method	V/f Control	Inertia Stability	Fast Transient Response	Power Flow Control	THD Reduction	Uncertainty Rejection	Tuning	Sources
ANN + droop control	✓	✓	✓	✓	—	✓	—	[74,132,133]
MPC + ANN	✓	—	—	✓	—	✓	—	[80,134]
MPC + VI	✓	✓	✓	✓	—	—	—	[39]
PI + VI + droop control	✓	✓	✓	✓	—	—	—	[77]
SMC + H_2/H_∞	✓	—	✓	—	✓	✓	✓	[28]
H_∞ + VSG	✓	✓	✓	✓	—	✓	✓	[79]
LQR + H_2/H_∞	✓	—	✓	—	✓	✓	—	[89,135]
SMC + ANFIS	✓	—	✓	—	✓	✓	—	[67,136]
SMC + ANN	✓	—	✓	✓	—	—	—	[36,137]
PSO + droop control	✓	✓	—	✓	—	—	✓	[138]
LQR + Kalman + GA	✓	—	✓	✓	—	✓	✓	[74]
Droop control + Kharitonov	✓	—	—	✓	—	✓	✓	[115]
Fuzzy PD + I + PSO	✓	—	—	✓	—	—	✓	[116]

The given information indicates the benefits of multi-objective control on IBMGs. General tasks are voltage, frequency, and power regulation. The objectives of fast response, rejection of disturbances, and uncertainties are also highlighted. Subsequent challenges are focused on generating stability through virtual inertia and impedance algorithms, the harmonic reduction due to the connection of nonlinear loads, and optimal tuning. Some cases will benefit from self-tuning to generate smarter algorithms.

4. Future Trends

This section presents future challenges in the field of control of IBMGs emphasizing multi-objective approach. These challenges include other control theories that have been unexplored or have had little implementation on DG. Current issues on multi-objective implementation have been addressed with the aim of future improvements by researchers. Other strategies to be reviewed below represent methods that fit into the multi-objective proposals to improve the performance of VSI in MGs. The targets of multi-objective control include features such us improving the robustness of voltage and frequency variables in steady-state, fast transient response, monitoring of energy references, lower harmonic generation, and stability for energy consumption of non-linear loads. In addition, the delay in closed-loop structures that incorporate a communication delay is considered.

4.1. Convergence of Solutions

Multi-objective approach presents a set of optimal solutions that converge according to the nature of the applied algorithm. The different techniques present distinct features that need to be improved to adapt the problem to a suitable way of resolution. The diversity of solutions offers selection alternatives that present local optimums. These values have to be avoided to perform a global optimum control. Additionally, the non-used multi-objective methods on IBMGs represent an alternative to achieve solutions with different perspectives compared to actual works on this area.

4.2. Computational Cost Administration

This feature is under constant improvement because of the efficiency of the control is compromised. Alternatives such us a stop criterion is under research due to its complex interaction between the number of iterations and objective functions. To reduce computational cost, the real-time applications seek for solutions based on discrete controller formulations, and parallel computing. Schemes with more than three objectives represent complex high-dimensional problems that can be decoupled to find solutions without losses of alternatives.

4.3. Mathematical Model Accuracy

Internal model control (IMC) requires the mathematical model of the process. In theory, the mathematical expression of the process should be a faithful representation of the physical components of the system. Therefore, the responses of these two approaches must be identical. However, there are differences between a mathematical model and the real dynamics of the process. These differences manifest as uncertainties. In this way, the controller aims to overcome the problem of uncertainties by mathematical modeling. Plus, it can reject disturbances with corrective actions based on the knowledge of the process. Ref. [139] utilized the capabilities of the IMC to tune two regulation algorithms: a PI controller and a fractional-order PI (FOPI) controller. The tuning process used the internal model approach to get adequate frequency regulation in MG.

4.4. Communication Delays

The Smith predictor is a technique used in delayed systems. Although the dynamics of electrical schemes are significantly fast, the delay comes from sensors or communication systems. In the hierarchical control of MGs, Ref. [140–142] communication delays are presented. Bandwidth represents a parameter that is decisive in the generation of delays. At that point, Ref. [142] incorporated the Smith predictor for delay compensation in voltage regulation of an inverter system. In addition, there are algorithms like Dahlin that have been unapplied to inverters in MG. This method vastly simplifies the design of delayed compensators, where the system is considered to be an equivalent first-order model. The design is versatile and effective for decreasing the effects of feedback delay.

4.5. Optimal Tuning/Self-Tuning

For tuning controllers, structures incorporating fuzzy models, ANNs, GA, among others have been observed. Collective intelligence systems like PSO optimize controllers from targets such as reducing performance index. Other collective intelligence optimization algorithms such as: artificial bee colony (ABC), ant colony optimization (ACO), and optimize grey wolf (GWO) can equally be considered to optimize IBMGs performance. Other mathematical algorithms can be extensively studied for MGs tuning. Algorithms such as: Inner point method, Kharitonov, linear programming, quadratic programming, Kalman filter, among others, can be mentioned. These resources represent also options for tuning control parameters that require extensive study. Their application will depend on several factors like complexity, hardware performance, or adaptability.

5. Conclusions

MGs are key components of a new era of electricity generation. These systems have proven its capability to deal with power flow efficiency and mitigation of reduction of greenhouse gases. Besides DC generations have simpler structures and present better efficiency over AC systems, the high residential and industrial consumption need VSI; these devices perform certain activities to manage electrical energy on MG. In some cases, IBMG performance is not exploited because of conflicting problems between two or more regulation objectives. The multi-objective approach overcome these issues providing a balanced solution to many IBMG objectives and driving the system to optimal energy management results. This paper presented the main objectives in an IBMG and methods to achieve these goals through control methods and multi-objective optimization.

The massive introduction of renewable resources led to the creation of policies that maintain the quality of service. This work has shown the main trends in this area based on studies and analysis performed in countries with high integration of MGs.

The control structure of VSI is optimized in a energy-cost concept that requires the minimization of an objective function under constraints. This traditional method does not consider a broad regulation scheme due to possible conflicts between its variables. In this context, the multi-objective approach looks for a global control of a system overcoming the conflicts of objectives and improving performance.

The various works covered showed a broad range of control algorithms designed to accomplish objectives based on their capabilities, such us fast response in the case of SMC. This particular event solves the transient issues on IBMGs connection/disconnection of the grid, but it is not comparable with the multi-objective approach which has become a better alternative for researches that seek big improvement in energy dispatch.

Future trends show the possible lines of research in this area. The high interactions of objectives in MGs have guided to novel and innovative proposals to achieve better energy management on IBMGs.

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Abbreviations

The following abbreviations are used in this manuscript:

ANN	Artifitial neural network
CG	Centralized generation
CO_2	Carbon dioxide
DER	Distributed energy resources
DG	Distributed generation
LQR	Linear quadratic regulator
MC	Microsource controller
MG	Microgrid
MPC	Model predictive control
PCC	Point of common couplig
PID	Proportional-integral-derivative
PSO	Particle swarm optimization
SMC	Sliding mode controller
VSI	Voltage source inverter

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