A Review on Control Schemes for Grid Connected and Islanded Microgrid

B. E. Sedhom[1], M. M. El-Saadawi[1], A. Y. Hatata[1,2] and E. E. Abd-Raboh[1]

[1]Faculty of engineering, Mansoura University, Egypt, eng_bishoy90@mans.edu.eg

[2]Elect. Eng. Dept., College of Eng., Shaqra University, KSA, ahmed_hatata@su.edu.sa,

Abstract

A Microgrid (MG) is a part of the power system that consists of loads, distributed generations (DGs), and energy storage units. It operates in On-grid or Off-grid modes. When a microgrid operates in an Off-grid mode, its voltage and frequency must be adjusted to prescribed acceptable limits. This paper introduces a comprehensive review of research studies related to the available control schemes used in microgrids. The control methods are divided into three categories. The first category includes classical control methods that apply a conventional control method to adjust MG parameters. The second category is adaptive control methods to control the system parameters. The last category is the intelligent control methods that modify the classical control methods by applying one of the intelligent control methods. This paper presents a brief comparison between these control methods based on the method description, merits and demerits of each method and it gives a brief description of the main contribution of the researches containing these control methods.

Keywords

Microgrid, Droop control, *H*∞ control, Classical Control, Model Predictive Control, Intelligent control, Adaptive control

1. Introduction

A MG is a part of a low voltage network that usually located at the consumer's side. It can improve the system reliability, consumer confident and system power quality [1-2]. When MGs are connected to the utility grid, they operate in On-grid mode. When they are isolated from the grid, they operate in Off-grid mode. In case that they are operating in conjunction with the utility grid, they can exchange power from or to the grid through Points of Common Coupling (PCC). Nowadays, MGs become the main trend in distribution systems as they reduce the transmission losses, gas emissions, total cost, and hence increase the system efficiency [3-4]. However, MGs control under different operating conditions has become a great challenge, as they must be controlled under different operating modes. When MGs operate in On-grid mode, the MG voltage, *V*, and frequency, *F*, must be adjusted according to the utility grid specifications. In this mode, the DG units integrated with a MG must be controlled to deliver the adequate active power, *P*, and reactive power, *Q*, needed by the system loads. Under severe disturbances, the control system has to disconnect the MG from the utility and turn it to operate in Off-grid mode [5-6]. There are various control techniques that can be used to adjust MGs under different operating conditions.

This paper introduces a review of the MG control methods in both On-grid and Off-grid operational modes. These control methods can be categorized as classical control methods, intelligent control methods, and adaptive control methods. The classical control methods apply the conventional control systems to control *V*, *F*, *P* and *Q* during either grid connected mode or islanded mode. The intelligent methods apply optimization approaches to obtain optimal points to the controllers. The adaptive methods are used to control the MG in the two modes of operation and they can be used to control various parameters simultaneously.

The reset of the paper is organized as follow; section 2 introduces the MG operating modes, section 3 presents a brief summary of MG control schemes, section 4 discusses classical control methods, section 5 reviews the intelligent control methods, section 6 reviews the adaptive control methods, and section 7 compares between the different control methods. Finally, section 8 concludes the paper.

2. MG Modes of Operation

MGs can be operated in On-grid or Off-grid modes. When a MG operates in an On-grid mode, they can exchange power from or to the grid through PCCs. In the Off-grid mode, the MG operates isolated from the grid to supply its own load.

2.1. On-Grid Mode of Operation

In the On-grid mode of operation, the MG is coupled with the utility grid through PCC. In this mode, the MG is synchronized with the utility grid and hence, its *V* and *F* must be related to the utility grid voltage and frequency. In this case, the P and Q outputs from the DGs are changed according to the load profile and the system conditions. Control techniques are required to adjust the power output from the DGs connected to the MG and consequently from the MG to/from the utility grid [7-8].

2.2. Off-Grid Mode of Operation

In the Off-grid mode, the MG operates separately whenever it is disconnected from the grid. The MG enters the islanded (Off-grid) mode due to scheduled maintenance, grid outage, or economic reasons. In this mode, control methods are required in order to adjust *V* and *F*. They are also required to properly reconnect the MG to the utility grid [7-8]. Several control techniques can be used to regulate the MG under this operating mode.

Following are a summarized description of the main control schemes used for these two operation modes.

3. MG Control Schemes

The secure operation and easy switch between On-grid and Off-grid modes depend upon the MG controls. The main function of the controller is to provide a seamless operation and ensure that the system operates in the specified operating points. The MG control schemes are classified in various categories. According to the MG mode of operation, control schemes can be classified into three categories: islanded mode control, grid-connected control for AC MG and grid-connected control for DC MG [7-9]. Huang et al. [10] have classified the MG control strategies into three categories: isolated MG, grid-connected MG, and seamless transfer between the two operation modes. According to the communication system used Vandoorn et al. [11] have classified the MG control as communication control schemes, communication fewer control schemes, and hybrid control schemes. The control schemes were also classified according to control location as centralized control schemes, and distributed control schemes [12, 13]. According to the control levels, the MG control strategies were classified into three levels: primary, secondary, and tertiary, where the first two levels are related to the MG operation process, and the third level is applied to ensure an appropriate coordination between the MG and the main grid [14, 15]

In this paper, MG control methods are categorized according to the evolution of AI techniques in control schemes. The control schemes are classified as classical control methods, intelligent control methods, and adaptive control methods. The classical control methods depend on using the conventional control schemes to appropriately control MG V and F in grid connected and in islanded mode. The intelligent control methods are based on applying an AI technique to optimally regulate the MG control parameters. While the adaptive control methods based on applying an AI technique with a conventional control method to obtain an adaptive control to MG. Figure 1 shows the MG control methods presented in this paper.

4. Classical Control Methods

Classical control methods are applied to control the MG parameters during different modes of operation. In On-grid mode, the control methods are used to adjust *P* and *Q* output from the DGs. In the Off-grid mode, the control methods are used to adjust the *V* and *F*. These control methods are divided into communication-based control methods and non-communication control methods.

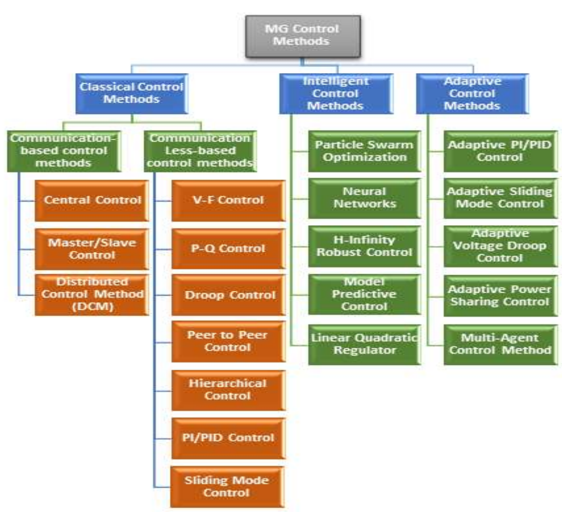

Fig. 1. MG Control Methods

The first one includes; central control distributed control and master-slave control method. The second one includes; V/F control, P/Q control, droop control, peer to peer control, hierarchical control, PI/PID control, and sliding mode control.

4.1. Communication-Based Control Methods

These control methods can be applied to ensure an appropriate power sharing, improve the system power quality, enhance the transient response, and minimizing the power circulated between the connected inverters. However, these methods require a convenient communication link with a high band-width. The use of communication lines among the inverters increases the cost of the system. Also, these methods don't have the ability to expand as the number of the connected inverters and the load current measurement must be determined previously. As a result, these methods have a low reliability and hence it isn't truly redundant and distributed. These methods include; central control, master-slave control, and distributed control methods (DCM). Table 1 shows the contribution of some selected studies on communication-based control methods.

4.1.1. Central Control

In this control method, a central controller communicates with all DGs in the MG to adjust the balance of *P* and *Q* between load and generation. In these methods, communication links between the DGs and the central controllers are required. This method is simple but it mainly depends on the quality of the communication links between the controller and the DGs. A supervisory control center is required. It has a large expense for both communication lines and control center. One of the main disadvantages of this control method is that it is cannot be implemented with large systems as it is difficult to expand the control system [11, 16-17]. Figure 2 illustrates the block diagram of the MG with the central controller.

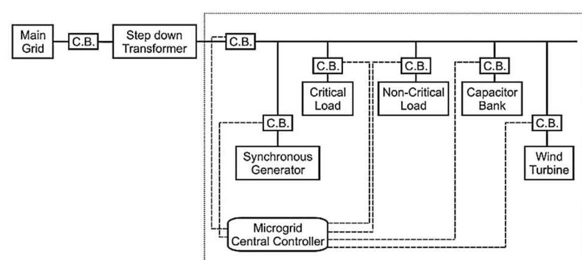

Fig. 2. Block diagram of the MG with the central controller

4.1.2. Master – Slave Control

Under grid connected mode, MG including all DGs follows the utility grid *V* and *F*. In this mode, the controller is applied to maintain the power for each DG. However, under the islanded condition, the *V* and *F* of MG must be controlled. One of the DGs is defined as the master unit and the others are defined as slave units. The master unit can regulate the *V* and *F* references to the DGs and hence the load is redistributed among various connected DGs. There are different strategies for assigning the master unit. It can be chosen as a fixed unit or as the unit with maximum r.m.s or crest current [11]. The master-slave control method can be applied in either a centralized or decentralized structure. The centralized control technique requires a communication link between the slave and the master units. Under this technique, MG can be controlled for a long time under the islanded operation [16]. However, the failure of the master control unit leads to whole system shutdown which represents a great drawback of this technique. Also, the failure of the communication links between the slave and the master units affects the reliability of this control technique.

4.1.3. Distributed Control Method (DCM)

This method can be used for the parallel converters. It has the ability to decrease the communication links between the DGs in MG and hence, improve the control system reliability [11, 16]. In this method, the information required is not global but adjacent to any unit [22]. Low band-width is required to preserve the instantaneous power sharing and high quality with different loads [25]. It is a flexible and reliable control method as it can divide the control task among different units.

Table 1. The contribution of selected studies on communication-based control methods

Category	Ref.	Contribution
Central Control	[18]	- Manage the MG stability by the operation coordination between DGs, main grid and loads using MGCC. - Detect islanding in MG by monitoring the PCC and analyzing the power quality on it.
	[19]	- Compensate the voltage unbalance using MGCC. - Restoring V and F using MGCC.
	[20]	- Manage the performance of MG applied in the transportation system. - Improve the power management system in MG using MGCC.
Master – Slave Control	[21]	- Don't use any communication links between the loads and the DGs during control system load sharing. - Master and slave DGs are controlled in indirect current control in On-grid mode and it operates with the PWM switching mode to present the voltage source in Off-grid mode.
	[22]	- Control the MG in grid connected and the islanded modes using the master-slave method. - The master unit behaves as a central controller for MG and it adjusts MG operation according to the voltage stabilization, ride through condition, power delivery on demand, power loss minimization, peak power shaving, a day ahead planning and black start.
	[23]	- Control distributed energy resources in MG using a master slave control method and regulate the power flow between the main grid and the MGs. - Manage the voltage constraints at the grid nodes.
	[24]	- Control MGs and to achieve an appropriate load sharing among DGs using master slave control method. - Investigate the maximum time delay that ensures the system stability.
Distributed Control Method	[26]	- Control MG using DCM by applying central controller to obtain the proper voltage regulation and the power sharing between different DGs and hence, the commands are distributed to the DGs through a low bandwidth communication links.
	[27]	- Propose a DCM for inverter based DGs. - The inverter controls the system V and F when it operates as voltage-controlled VSI. - The inverter regulates the generated P and Q output when it operates as current - controlled VSI.
	[28]	- Use DCM for restoring system *V* and *F* for MG in Off-grid mode. - Use DCM for optimum load sharing between DGs.
	[29]	- Achieve voltage recovery and current sharing using DCM for MG considering the effect of communication delay which may affect the system stability.

4.2. Communication Less-Based Control Methods

These control techniques operate without communications for power sharing so they enhance the system reliability of the network and decrease the investment cost. These methods have some advantages such as; flexibility, expandability, modularity, and redundancy. On another hand, these methods suffer from some limitations such as, slow transient response, the deviation in *V* and *F* amplitude and circulating current between the connected inverters due to the line impedance. Table 2 illustrates the contribution of some selected studies on communication less-based control methods.

4.2.1. V-F Control

This control technique is applied to control the MG parameters under the islanded mode of operation only. In this mode, it is required to control *V* and *F* of the MG within their acceptable limits to meet all load requirements. This control scheme is very important during synchronization from Off-grid to On-grid modes. [7, 11, 16].

4.2.2. P-Q Control

The main objective of this control is to control the *P* and *Q* output of the inverter to meet the economic operation of MG. At this mode, the *V* and *F* of MG are adjusted and stabilized according to the utility grid. The reference voltage is determined by the reactive power controller and the reference phase angle is determined by the real power controller. Figure 3 shows a block diagram of the P-Q control scheme. Active and reactive powers delivered by the inverters depends upon reference *V* and *F* [7, 33].

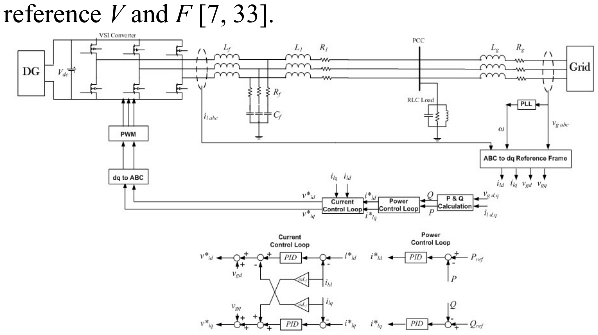

Fig. 3. P-Q block diagram

4.2.3. Droop Control

This control method depends upon the relationship between *P* with *F* and *Q* with *V*. According to droop characteristics, an increase in active power output leads to a decrease in load angle and hence a decrease in the frequency. Similarly, any increase in reactive power output leads to a reduction in terminal voltage. This control is a decentralized one as it uses only the local information of the DG. In addition to its low cost, the main advantage of this method is that it doesn't need any communication links between DG units. However, this method causes system instability when the slop of the droop characteristics is too small. Moreover, the deviation in the system *V* and *F* from their specified values and hence, it can't perform a proper power sharing in the MG. A secondary controller is required as it can't make a zero change in *F* and *V*. Figure 4 illustrates the block diagram of the droop control method.

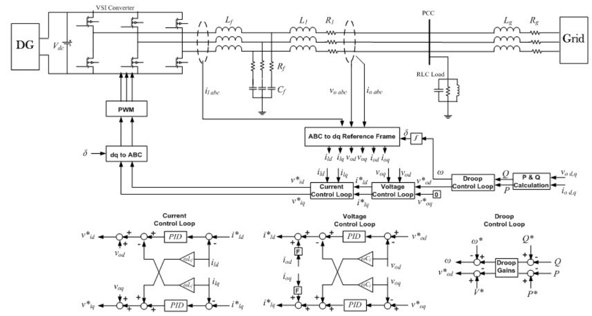

Fig. 4. Droop control block diagram

4.2.4. Peer to Peer Control

This type of control is characterized by the complete absence of a central controller. All DG units in the MG system have the same role within the MG. Each DG can be connected or disconnected from the MG without any changes to the control and protection of other connected units. Each DG performs its local control that depends on droop controller to automatically regulate its active and reactive output power to match the system load. Each DG can efficiently respond to the system load changes and can adjust its droop coefficients to reach the new balance point. This control method improves reliability and reduces the system cost [10, 39].

4.2.5. Hierarchical Control

This controller can be applied to decompose the complex control problem into smaller subproblems and reassembling their solutions into a "functioning" hierarchical structure. The hierarchical control structure contains three main levels, namely primary, secondary, and tertiary control levels. These control levels are responsible for processing, sensing, adjusting, supervising, and optimizing the operation of the MG [7]. The primary control maintains the *V* and *F* of the MG within their acceptable ranges under the variations of system generation or loads. The secondary control regulates the *V* and *F* deviations caused by the primary controls and retains *F* and *V* synchronization [16, 39]. This control level can be centralized or decentralized. The centralized one is applied to control small MGs and it depends on the principles of current control and voltage control loops. The decentralized control depends on specifying the maximum power generated from a MG and the load requirements to ensure a zero change in system *V* and *F* under any variations in generation and load [43, 44]. The tertiary control manages the power flow between the MG and the main grid and facilitates an economically optimal operation. The control is used to obtain the control system references during the islanded mode of operation and prepare the MG to reconnect with the main grid. However, this control method is suitable for large-scale MGs as it is not economic to apply multi-level control for small standalone MGs [45].

4.2.6. PI/PID Control

This method is a simple structured one. Due to its simplicity, it is extensively used in the power systems and the industrial fields. The technique is robust, reliable and can be appropriately tuned to provide the optimal performance. However, the main disadvantage of this controller is the difficulty to optimize the PID controller gain in nonlinear and complex systems. Also, it hasn't the ability to control Multi-Input Multi-Output (MIMO) and very large systems [49].

4.2.7. Sliding Mode Control (SMC)

The SMC method is used to ensure the stability of the constrained parameters for non-linear robust control. This method has a low computational burden. It has a robustness versus the disturbance and the model uncertainties. It has suffered from the chattering problem and in general, it has some of the drawbacks such as the proper transient and the zero steady state errors. However, the chattering can be eliminated by selecting the suitable design of the feedforward controller and sliding surface. Moreover, the bounds of the external disturbances and the uncertainty are desired to be known usually and merely guarantees complete robustness to external disturbances and uncertainties which satisfy the matching conditions [49].

Table 2. The contribution of selected studies on communication less-based control methods

Category	Ref.	Contribution
V-F Control and P-Q Control	[30]	- Adjust the system *V* and *F* during Off-grid MG using V-F control. - Coordinate the V-F control method with the maximum power point tracking (MPPT) method of PV. - Control the P and Q during grid connected MG using P-Q control coordinated with MPPT.
	[31]	- Adjust the MG *V* and *F* in an Off-grid mode using V-F control with MPPT applied to the DGs. - Control the *P* and *Q* of the MG in an islanded mode using P-Q control with V-F control via controlling MG voltage and frequency.
	[32]	- Control the MG *V* and *F* in Off-grid MG using V-F control. - Prepare the MG to swap between On-grid and Off-grid modes. - Control the MG *P* and *Q* output using P-Q control. - Improve the power balance between DGs and connected loads.
Droop Control	[34]	- Analyze the impact of droop coefficients on the MG stability and on the reverse equipment. - Evaluate the impact of the droop coefficients using bifurcation theory.
	[35]	- Apply both droop control, virtual impedance loop, current and voltage control and unbalance compensator to improve the system voltage unbalance in islanded MG.
	[36]	- Achieve frequency stability around the nominal values depending on tuning the coefficients of droop controller in islanded MG.
	[37]	- Control standalone multi-MG with one converter connected to enable renewable energy resources using droop control method to enhance MGs power sharing.
	[38]	- Modify droop controller using dynamic phasor to improve the transient performance compared to the classical droop control method.
Peer to Peer Control	[40]	- Control MG power flow by applying peer to peer control method and information communication technology. - Perform energy management system to allow each household to request or response to energy requirement with neighbors without using any wide control system.

	[41]	- Apply the peer to peer control method to enable customers to generate their own energy from MG renewable energy resources and share their energy with each other locally. - Balance local generation and demand using peer to peer control method and enable large penetrations of the renewable energy resources in the electric grid.
	[42]	- Control MG under both On-grid and Off-grid modes using peer to peer control method - Enhance the system swapping between Off-grid and On-grid modes.
Hierarchical Control	[46]	- Control MG using a hierarchical control scheme that depends on droop control as a primary control to achieve an appropriate sharing of power according to droop gains of DGs. - Retain the system *V* and *F* to their nominal values using secondary control. - Optimal generation scheduling and real-time adjustment of power generation using tertiary control.
	[47]	- Improve the power sharing and power quality in AC-MG using hierarchical control scheme depending on an internal control - Obtain appropriate power sharing between DGs using droop control as the primary control. - Adjust the system frequency to its nominal value using secondary control. - Select the proper droop gain to achieve the required output power from DGs using tertiary control.
	[48]	- Control the local power, voltage and current as a primary control using a hierarchical control scheme. - Control the power quality and retain the system *V* and *F* using a primary control - Enhance the synchronization between the MG and the grid using a secondary control. - Control power flow and apply energy management using a tertiary control.
	[49]	- Control flexible MGs using hierarchical control method depending on the inner control method to adjust the output voltage of the inverter - Regulate the system *V* and *F* using droop control as a primary control. - Compensate for the system *V* and *F* to retain their nominal values using secondary control.
PI/PID Control	[51]	- Apply PI controller to optimize P and Q for doubly fed induction generators - Investigate the wind turbine performance.
	[52]	- Compare between using fuzzy logic and conventional PID controllers for frequency control of an isolated MG.
	[53]	- Compare between applying PID controller and fuzzy logic PID controller to control the voltage of a DC MG.
Sliding Mode Control	[54]	- Improve the SMC method by applying a fixed switching frequency integral resonant SMC based on PWM for grid connected inverters - Eliminate the tracking error and THD of the grid current.
	[55]	- Analyze the SMC method for large scale variable speed wind turbine depending on using quasi-continuous SMC to ensure speed and power tracking.

	[56]	- Control second order harmonic ripples in DC MG using the SMC method based on the output impedance shaping of the DC source to resist the propagation of the ripple to the input.
	[57]	- Apply SMC to control MG voltage and current. in using the SMC method to - Control the terminal V and F of the DGs and enhance the protection of DGs from external faults.

5. Intelligent Control Methods

The intelligent methods use one of the optimization techniques in order to determine an optimal control solution of MG under the different operating conditions. This control method includes; particle swarm optimization, fuzzy logic controller, neural network, H-infinity, model predictive control, and linear quadratic regulator. Table 3 shows the contribution of some selected studies on intelligent control methods.

5.1. Particle Swarm Optimization (PSO)

This method of optimization is used to optimize uncertain parameters for vast optimization problems. In PSO, the velocity can be computed for each particle to extract the individual position. Then the position is updated in each iteration in terms of individual's behavior. The first step in the PSO technique is to initialize the individuals, velocity vector and position vector. The second step is to compute the velocity and the position respectively and hence update the velocity vector. PSO can solve non-linear, non-differential and multi-model function optimization. It is a simple implemented and an efficient technique. However, it has a difficulty of containing many parameters to adjust. It gives a near optimal solution and it requires a computing time to select the parameters of PSO [50].

5.2. Fuzzy Logic Control (FLC)

This method can be applied in MG control in combination with a distributed control method to obtain the optimum control parameters. It can be used in load frequency control, voltage control, and power sharing within the MG. It can be handled to achieve more capability for expert systems. The method can deal with non-linear models; fast varying systems and it is very efficient in small scale systems. As PSO method, it has the difficulty of containing many parameters to adjust. It is also very sensitive to the distribution of the memberships. For large scale systems, it takes a very long time in the computing process [61].

5.3. Neural Networks (NNs)

An Artificial Neural Network (ANN) is an information processing paradigm that is inspired by the way biological nervous systems, such as the brain, process information. This method is more effective for identifying, controlling, and optimizing the system parameters in offline or online or real-time application. It can solve non-linear and large-scale systems. It has similar advantages and disadvantages as FLC method [68].

5.4. H – Infinity Robust Control

This control method can be applied to synthesize the system stability and to improve the system performance in presence of parameters uncertainty and external disturbances. The method uses a linear matrix inequalities (LMI) method to handle the control problem. LMI is a useful tool used directly to find feasible and optimum solutions. This controller can be applied to minimize the effect of the uncertainties and disturbances. Also, it is more effective in improving the transient stability under the presence of uncertainties. The method is a repetitive control one as it includes an inner voltage control loop and an outer current control loop to improve the system power quality. It can maintain MG flexibility during altering between different control modes. This method is used for MIMO models and it can minimize the effect of perturbations on the control system. It can be used to compensate the effect of resonance due to the connection of power factor correction capacitance. However, this technique may be impractical for large system dimensions and with no constraints handling [71].

5.5. Model Predictive Control (MPC)

This control technique is applied to forecast the reference signals. The method can reduce the tracking error. MPC is the most popular control method in the industry. It can make an interaction between different variables and select the optimal strategy to control the constrains. It is a fast computing and economical method and can be used for predicting a dynamic system on a finite horizon. It can deal with the states and the control constraints with non-minimum phase. However, it cannot deal with unknown parameters and cannot correctly recognize the process model. It is difficult to make performance analysis using this control method [50].

5.6. Linear Quadratic Regulator (LQR)

This method is applied to obtain the optimal control policy. It can be used to reduce or increase the utility cost function. The main purpose is the selection of the weighting matrices to obtain the required response. It is a simple, stable and robust method. However, this method assumes that all the system states are measurable and it can't work under problem constraints. Also, the analytical solutions for the Ricatti equations are quite difficult. One of the major drawbacks of this method is that it cannot take into consideration the system disturbances [50].

Table 3. The contribution of selected studies on intelligent control methods

Category	Ref.	Contribution
PSO	[58]	- Apply a power frequency droop based PSO technique to optimize the ramp rate parameters and the P-F droop characteristics simultaneously in automatic generation control.
	[59]	- Optimize the droop control gains using PSO based on the line parameters between DGs and loads - Control the DGs in MG and analyze the impact of P and Q violations on the MG voltage and frequency.
	[60]	- Maintain a proper power flow of P and Q between the MG and the main grid and share the power between DGs with the desired ratio using PSO method.
FLC	[62]	- Apply a primary control consisting of a power control loop, voltage control loop, and the current control loop to adjust voltage and frequency. - Apply FLC as a secondary control to adjust V and F in order to achieve a power flow control between generation and consumption in MG
	[63]	- Control the system V and F in AC MG by using droop controller based on FLC - Ensure the stability of MGs with large load variations and imbalance between generation and loads.
	[64]	- Control the power flow between DGs in isolated MG by an improving the droop controller - Control DGs output voltage and current using proportional resonant voltage and current controllers.
	[65]	- Apply FLC to control load frequency and hence, control any mismatch between the generation and loads. - Maintain the system V and F constant against any changes in system loads
	[66]	- Control voltage in islanded MG using FLC method to improve the performance of the system voltage under system load variations - Compare between both FLC and traditional PI controllers.
NNs	[68]	- Apply an adaptive neural based supervisory controller to control PV-MG system including linear and nonlinear processes ignoring the large change in external environments.
	[69]	- Control inverter interfaced DGs in MG using NN based control method - Control DGs in MG without using any synchronizing control technique.
	[70]	- Apply NN based control method to track the MPP of the DGs and control the power exchange between the DGs and the main grid.
H∞	[72]	- Obtain the balanced neutral point in three-phase four wires inverters integrated with a MG - Eliminate the current flowing through the split capacitors for DC link using H∞ current controller.
	[73]	- Employ power management control in MG, ensure a power balance, select the battery capacity, and reduce the frequency fluctuations during the operation in MG using H∞ control method.
	[74]	- Apply H∞ control method with droop controller and V-I droop controller for inverter-based DG in islanded MG, - Obtain the reference for the voltage and current using H∞ with PI regulation strategy - Tune the PI controller parameters using H∞ controller.
	[75]	- Use the H∞ control method to control the current output controller for MG connected to inverters taking into consideration the impedance variation in MG.

	[76]	- Control the frequency fluctuations in MG based on H∞ controller - Use μ synthesis analysis to identify the range of change in system uncertainties parameters.
	[77]	- Apply H∞ controller to reduce frequency fluctuations caused by integrating DGs with MG - Use the PSO technique to optimize the weighting function in order to improve the system performance.
	[78]	- Describe a mixed H2/ H∞ control method to control MGs under uncertainties of load changes based on LMI method.
MPC	[79]	- Control MG in both On-grid and Off-grid modes using the MPC method - Provide reference signals for the local controller to ensure high power quality.
	[80]	- Apply MPC method as a multi-loop feedback control to improve traditional droop controller for multiple DG inverters in islanded MG
	[81]	- Obtain optimal power flow between the battery storage systems in the AC MG using the MPC method taking into consideration the line losses, the voltage constraints, the converter current constraints, and the nonlinear variations in batteries charging and discharging processes
	[83]	- Control multi-string PV systems in a DC MG using the MPC method by tracking the MPP of the PV arrays. - Control the bidirectional DC-DC converter for charging and discharging the battery energy storage. - Ensure delivering the required power to load using battery storage in case of lacking the generated power by the PV system. - Stabilize the bus voltage of the battery storage and evaluate the direction of power flow from the battery to the DC bus.
	[82]	- Apply MPC for optimal operation in grid connected and islanded MG tacking into account demand response, uncertainty power generated from DGs, load demand, and the real-time electricity price.
LQR	[84]	- Implement the PI controllers to damp the frequency oscillations. - Analyze the application of optimal state feedback LQR control for a smart MG. - Optimally design the Q and R in LQR to minimize the frequency oscillations in PSO for transient analysis. - Compare between the use of PI controllers and LQR control based PSO in damping the frequency oscillations in MG sources. - Minimize the frequency oscillations due to disturbances in MG and obtain an efficient energy management strategy using MGCC.
	[85]	- Apply LQR control algorithm with the integral controller to ensure fast dynamic response and to restore system voltage after any deviations from the reference grid voltage and to minimize the cost function of the system
	[86]	- Control the system frequency in MG under normal and abnormal operating conditions using LQR based FLC algorithm and hence improve the system dynamic performance

6. Adaptive control methods

These methods can use any control techniques to control a MG in both On-grid and Off-grid modes as it can adapt the MG operation and hence, obtain the required set points to the controller. This control method includes; adaptive PI/PID, adaptive SMC, adaptive voltage droop control, adaptive power sharing control, and multi-agents control. Table 4 shows the contribution of some selected studies on adaptive control methods.

6.1. Adaptive PI/PID Control

In the conventional PID control method, the PID controller parameters are selected by trial and error. However, the changing in system conditions may need to change these parameters. So, it needs an efficient method to adapt the parameters with the system parameter violations. To adapt the system parameters variation, an NN-based control method can be used to optimally select the PID control gain.

6.2. Adaptive Sliding Mode Control

The main obstacles for application of Sliding Mode Control (SMC) are two interconnected phenomena: chattering and high activity of control action. It provides a strong robustness to parameter uncertainties as well as unmatched model uncertainties and external disturbances. Moreover, this method avoids knowing the bounds of uncertainties. The adaptive SMC control method considers parameter uncertainties while SMC method usually only have the strong robustness to matched uncertainties.

6.3. Adaptive Voltage Droop Control

This control method depends on integrating two terms with the conventional reactive power control. The first of them is used to regulate the voltage drop across the transmission lines and the other is used to adjust the system stability and to enhance the reactive power sharing. The advantages of this technique include high reliability and no restriction on the physical location of the DG units. Thus, the control algorithms of each individual DG unit should use only locally measured variables. To achieve this special kind of autonomous MG operation, the frequency/voltage droop technique is often adopted. Nevertheless, this method requires a good knowledge of the power line parameters. Small errors may result in a positive feedback, and thus may cause system instability [16].

6.4. Adaptive Power Sharing Control

This method is used to improve the stability of multiple paralleled DGs in MG at different load sharing. The method is based on combining the static droop control method with an adaptive transient droop function for damping the fluctuations of power sharing controller in DG units [99]. The method is used to accurately improve the DC bus voltage control with an accurate power sharing between AC bus and DC bus in MG. However, it cannot be applied when the load is variable as the variation of the line voltage drop leads to inaccurate load power sharing [100].

6.5. Multi-Agent Control Method

This control method can be applied by representing each DG and load to be as an agent. Each agent can exchange information with other agents. This technique makes the system simpler and it improves the system reliability [9]. Each agent can take its decision according to its conditions without any external commands. An agent can be defined as a software or hardware that can receive data from the sensors, sends a command to the environment and negotiates with other agents [103]. It decides whether a MG connected load has to consume power from an agent or not. The controller can be centralized as a single agent, decentralized as several agents, or hierarchical that consists of different layers of agents. This method suffers from both the complexity in design and the requirement for a communication system to exchange information between agents [104-106].

Table 4. The contribution of selected studies on adaptive control methods

Category	Ref.	Contribution
Adaptive PI/PID Control	[87]	- Optimize the PI controller gains using the NN system - Apply NN system to improve the operation of the PI controller and make it more adaptive.
	[88]	- Apply FL algorithm to adapt the PI controller gains and hence improve the dynamic performance of the inverter interfaced islanded MG. - Enhance the dynamic performance of MG during the disturbances.
	[89]	- Apply adaptive PI controller to improve power quality and economic issues of MG. - Ensure stability of MG and render better realization for MG in islanded mode regardless of load constraints changing - Facilitate the load variation, voltage variation, and load disproportion.
Adaptive Sliding Mode Control	[90]	- Improve MG power control loop using adaptive SMC. - Mitigate control interactions between voltage and PI voltage controller error signal.
	[91]	- Apply adaptive SMC to control fuel cell energy generation system and interleaved boost power converters and to estimate DC bus impedance seen by the converter - Enhance system stability, uncertainties of bus impedance on the output voltage regulation, and equal current sharing between DG.
	[92]	- Apply adaptive SMC as a pump displacement controller and back stepping stroke piston controller, - Adapt the output pitch angle with adaptive SMC desired values under external disturbances and uncertainties.

	[93]	- Improve control performance of islanded MG during any disturbances using adaptive SMC - Maintain global robustness of the inverter control system by observing external disturbances and internal perturbations.
	[94]	- Apply adaptive SMC to improve MG power quality - Estimate the reference source current that controls the voltage source converter and regulates the *V* and *F* of MG to mitigate current harmonics. - Adapt the load fluctuations by determining real and reactive power references.
Adaptive Voltage Droop Control	[95]	- Control the voltage source converters in Off-grid MG using adaptive voltage droop control - Adapting conventional voltage droop control coefficients as a nonlinear function of its *P* and *Q* outputs. - Ensure commonly reactive power sharing by voltage source converters regardless of both active power control, unbalanced connecting and line impedances.
	[96]	- Apply an adaptive voltage droop control in grid connected DC MG - Combine adaptive voltage droop control with SMC to identify converter current reference based on its droop characteristics.
	[98]	- Apply adaptive voltage droop control to achieve accurate reactive power sharing - Tune voltage droop slope to compensate the mismatch in the voltage drops across feeders by using communication links. - Modify the net control action of the adaptive droop terms to have a negligible effect on the MG bus voltage.
	[97]	- Improve droop controller and achieve a good system performance using an adaptive voltage droop control method - Adaptively update output voltage reference for each converter.
	[100]	- Apply a distributed control method to ensure the proportional load sharing in MG tacking into account the line impedances - Control the output voltage of DG using a power controller to maintain the desired operating point on the droop curve in order to ensure the proportional load sharing.
Adaptive Power Sharing Control	[101]	- Apply a proposed distributed control scheme to solve the power sharing problem for a grid-connected AC MG consisting of multiple dispatchable DGs. - Model a MG as a multi-agent system (MAS) to provide reference signals to each DG. - Design a local tracking controller for each DG to obtain the local reference power output tracking.
	[102]	- Apply adaptive power sharing control to improve the DC bus voltage control with accurate power sharing between both AC and DC buses. - Design an AC dynamic local voltage compensator based on energy storage system.
Multi-Agent Control Method	[107]	- Achieve power balance in MG and resolve the dispatch of real and reactive power among agents in MG to determine real and reactive power mismatches using MAS control method. - Maintain the voltage at any point in the system within the acceptable limits to ensure system stability.

	[108]	- Select the appropriate operation modal of MG intelligently. - Apply MAS control method for self-controlling the optimal operation of a MG. - Apply MAS control method for monitoring the real-time data and autonomy of MG local protection
	[109]	- Present a novel regional control scheme by applying MAS control for islanded MGs - Three agents are used including an organizational agent, coordination agent and implementation agent.
	[110]	- Implement a hierarchical MAS to manage a MG cluster and to maintain the power balance between generation and consumption. - Reduce power exchange with the grid by applying a hierarchical multi-agent energy management system and performing power dispatch with the objective of minimizing power exchange with the grid.

7. Conclusion

This paper presented a review of MG control methods. There are various MG control methods and each method has its definite usage. Classical control methods are used to control V and F of MGs in Off-grid mode. These methods can control MGs under On-grid mode to some extent, but they cannot retain the MG parameters to their acceptable values. On another hand, intelligent control methods apply optimization methods to optimally control the MGs in different modes. Unfortunately, there are some difficulties in applying these methods as they require a long time for implementation. Adaptive methods are used to control MG in different modes and under different condition simultaneously, but these methods are complex in performing and implementation. The compound adaptive and intelligent control methods can overcome most of the difficulties facing the implementation of each method.

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