Received: 18 July 2020 | Revised: 14 December 2020 | Accepted: 17 December 2020

DOI: 10.1049/rpg2.12111

IET Renewable Power Generation

The Institution of Engineering and Technology WILEY

ORIGINAL RESEARCH PAPER

Control and optimisation of networked microgrids: A review

Mojaharul Islam[1] | **Fuwen Yang**[1] | **Mohammad Amin**[2]

[1] School of Engineering and Built Environment, Griffith University, Gold Coast, Australia

[2] Department of Electric Power Engineering, Norwegian University of Science and Technology, Trondheim, Norway

Correspondence
Fuwen Yang, School of Engineering and Built Environment, Griffith University, Gold Coast, Australia.
Email: fuwen.yang@griffith.edu.au

Abstract

Microgrids (MGs) have become an integral part of smart grid initiatives for future power system networks. Networked microgrids consist of several neighbouring microgrids connected in a low/medium distribution network. The primary objective of a network is to share surplus/shortage power with neighbouring microgrids to achieve mutual cost-effective operation, utilising green energy from renewable energy resources in the network and increasing the reliability of customer service. This article classifies networked microgrids on the basis of network formation and provides an overview of recent research on control of networked microgrids. In addition, a state-of-the-art review of optimisation methods is provided to solve the energy optimisation problem in networked microgrids. Furthermore, the advantages and challenges of the networked operation of microgrids are presented as for possible research directions in the future.

1 | INTRODUCTION TO NETWORKED MICROGRIDS (MGs)

In the last decade, distributed energy resources (DERs) have been integrated into transmission and distribution power networks to reduce the amount of carbon emissions worldwide and to meet the increasing demands of power systems [1, 2]. An MG is one of the leading features of a smart grid power network for integrating DERs within a distribution network [3]. An MG can be defined as a low-voltage (LV)/medium-voltage (MV) power network that integrates DERs and energy storage systems (ESSs) to create a grid that feeds different loads in the network and can operate in either grid-connected or island mode [4]. A networked MG (NMG) is an advanced MG concept in which a network is formed using several adjacent MGs. Figure 1 illustrates a typical NMG in a distribution network. The goal of such a network is to provide mutual power sharing with neighbouring MGs to increase the reliability of an MG network and to reduce operational costs. The network also enables restoring service to customers after a fault/deficient power condition occurs, efficient use of renewable energy resources (RESs) in the network, providing mutual support in island operation and reducing the burden on the main grid in grid-connected operation. Several similar concepts for defining NMG exist in the literature. Multi-microgrid (MMG), MG cluster and interconnected MGs are the most frequently used terminologies in the literature to represent a network of MGs connected through an electrical power network to achieve power exchange amongst them.

However, energy sharing between MGs creates a new challenge because multi-level optimisation is essential in energy management systems (EMSs). Moreover, the parallel operation of multiple MGs will raise the issue of controlling voltage and frequency throughout an NMG. Furthermore, delays in the communication network significantly impact the stability and performance of an NMG [5, 6]. A feasibility study of NMGs was conducted in [7–9] by focusing on the potential benefits and challenges of a network. Moreover, a review of the classification of NMGs based on AC/DC, voltage and phase-sequence constitutional forms was provided in [10]. A summary of NMG projects worldwide was also provided in this article. A comprehensive review of the control of DC MGs and DC MG clusters was included in [11]. The operational feasibility of DC MG clusters was discussed in the literature without an extensive discussion of control methods. In addition, a review of NMGs architecture, control, communication and operation was conducted in [12]. However, control and optimisation methods for NMGs were not included in this review. Meanwhile, the operation and control of NMGs were reviewed in [13] without focusing on control and optimisation methodologies. In addition, a survey on the distributed control and communication strategies for NMGs was presented in [14]. Different types of distributed

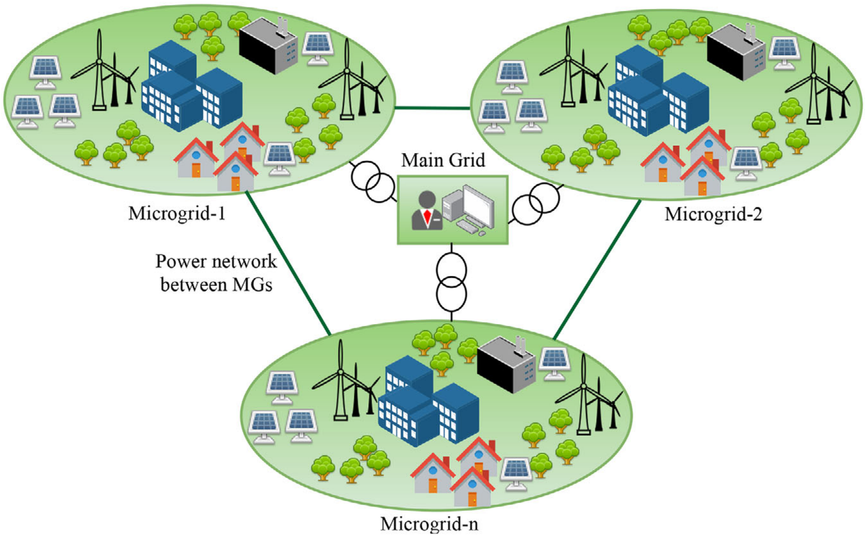

FIGURE 1 An NMG in a distribution network

control strategies and communication network reliability were discussed in this article. A survey on EMSs for NMGs based on EMS objectives, timescale and scheduling optimisation was also conducted in [15]. This research focused on optimisation methods under a distributed EMS structure. Hence, a review of methods for obtaining optimised control and energy sharing in NMGs remains lacking. Studies have applied different methods and algorithms for the control and optimisation of energy in NMGs. This article discusses a typical classification of NMGs based on network formation. Thereafter, a summary of control structures and methods in different networked operation scenarios is reviewed. Furthermore, different EMS structures used in the energy optimisation of NMGs are discussed. In addition, a review of applied algorithms for achieving optimal energy management in networked operation is presented. Lastly, the major advantages and challenges of the networked operation of MGs are described for future research suggestions regarding this highly potential concept.

2 | TYPES OF NMGs

MGs in a certain geographical area can form a physical network to achieve a local/global objective through cooperative interaction amongst MGs and with the main grid. Interconnection amongst MGs depends on the requirement and agreement amongst MGs in a network during the formation of that network. In practice, limiting interconnection types amongst MGs is extremely difficult. Thus, this article discusses the most common types of NMGs used in recent research. NMGs can be classified into three types based on network formation: star-connected, ring-connected and mesh-connected NMGs. Each MG in a network can be formed with dispatchable/non-dispatchable DERs, ESSs and controllable/uncontrollable loads. All MGs in the network can operate in both grid-connected and island mode. MGs in the network can use a common bus to connect with main grid or a separate electrical connection to connect themselves with main grid.

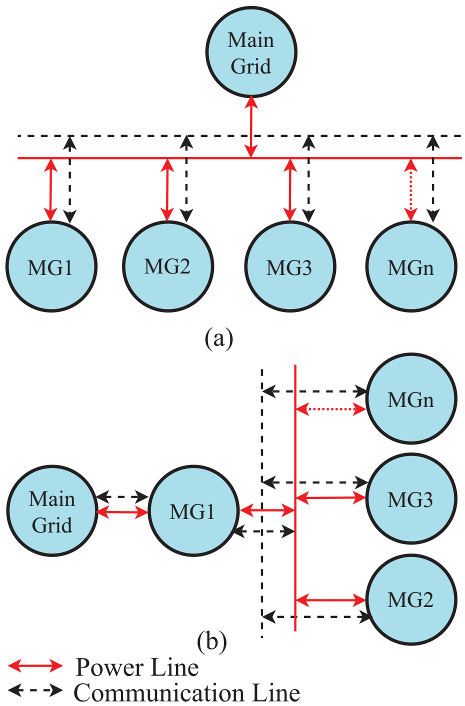

FIGURE 2 Star-connected NMG

2.1 | Star-connected NMG

The most common structure of NMGs is a star or radial structure. In a star structure, several MGs can be connected to a common bus to form a star network [16–19]. MGs in the network can connect to the main grid through the common bus. Figure 2(a) shows the typical architecture of a star-connected NMG connected to the main grid through a common bus. An MG in the network will exchange power/information with the main grid and with other MGs through the common bus to achieve economic optimisation. If an MG in the network experiences a shortage of power, then it will buy the required

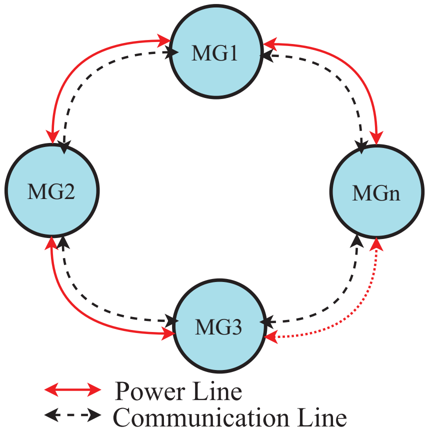

FIGURE 3 Ring-connected NMG

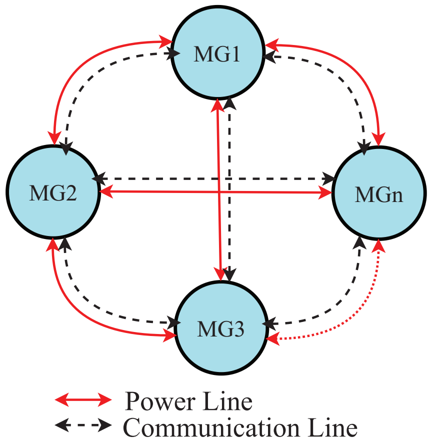

FIGURE 4 Mesh-connected NMG

power from other MGs in the network or from the main grid to realise power balance in the MG. By contrast, if an MG has surplus power during its operation, then it can sell the excess power to other MGs in the network or to the main grid. Power exchange amongst MGs is determined through information sharing between an MG's EMS and distributed network operator (DNO). In cooperative island mode, MGs in a network can also use the same electrical bus to exchange power amongst them. Thus, this structure eliminates the requirement for a private power network between two MGs. A radial network can be formed using another approach wherein a large MG in the network can only connect to the main grid through direct electrical connection, whilst small MGs in the network can connect to a large MG through a separate common bus with a radial structure to form a star network [20, 21]. Small MGs in the network can communicate with large MGs to share power amongst them. A large MG can be the dominant MG in a network. The dominant MG in a star-connected network should support neighbouring MGs in the network during power deficiencies. The dominant MG in the network is responsible for maintaining network power flow control in cooperative island operation. Figure 2(b) shows the typical architecture of a star-connected NMG connected in a separate common bus. The star network is easy to install and control because of existing radial power network in the distribution system to exchange power/information with other MGs in the network. However, a single point of failure and high-cost installation are the major drawbacks of a star-connected network.

2.2 | Ring-connected NMG

In a ring structure, several adjacent MGs can connect with one another to form a ring and share power with neighbouring MGs [22–27]. In this type of network, each MG can communicate with neighbouring MGs in the ring to share power amongst them. Figure 3 shows the typical architecture of a ring-connected NMG. Each MG in the ring network can connect to the main grid through separate electrical connections or only one MG in the network can connect to the main grid. Each MG in the ring structure is connected to another MG on each side, forming a continuous path for power and signal transmissions. Power and information can be exchanged in any direction in the network. The ring structure provides separate electrical connections to exchange power with other MGs in the network. Neighbouring MGs can directly communicate with one another to exchange power amongst them. Thus, this structure increases the redundancy and flexibility of the network compared with a star network. Moreover, the structure reduces the power transmission cost between MGs. A ring network is generally used in an LV residential network. The ring structure can be a highly suitable solution for NMGs because of secure fault isolation, high reliability, connection flexibility and improved voltage stability. The major drawbacks of the structure include its complex protection setting and the dependency on side cables for exchanging power and information with other MGs in the network.

2.3 | Mesh-connected NMG

In a mesh structure, several neighbouring MGs in a region can connect to form a mesh for sharing power with all the other MGs in the network [28–30]. Figure 4 shows the typical architecture of a mesh-connected NMG. A mesh structure follows the ring structure but has redundant additional lines to avoid failure in the main loop. A mesh structure is typically used in MV and high-voltage power networks. In a mesh structure, each MG in the network exhibits a redundant power or communication link with all the other MGs in the network. Thus, each MG can communicate or exchange power with another MG in the network through a redundant power or communication link. The mesh structure provides more privacy and flexibility for power exchange than the other types of structure. This network can easily maintain the voltage stability margin, is suitable for short-distance transmission and upgradable from two other structures. Moreover, redundancy in connection increases the reliability of the structure. It also reduces transmission loss in an NMG. However, the control and energy management of such

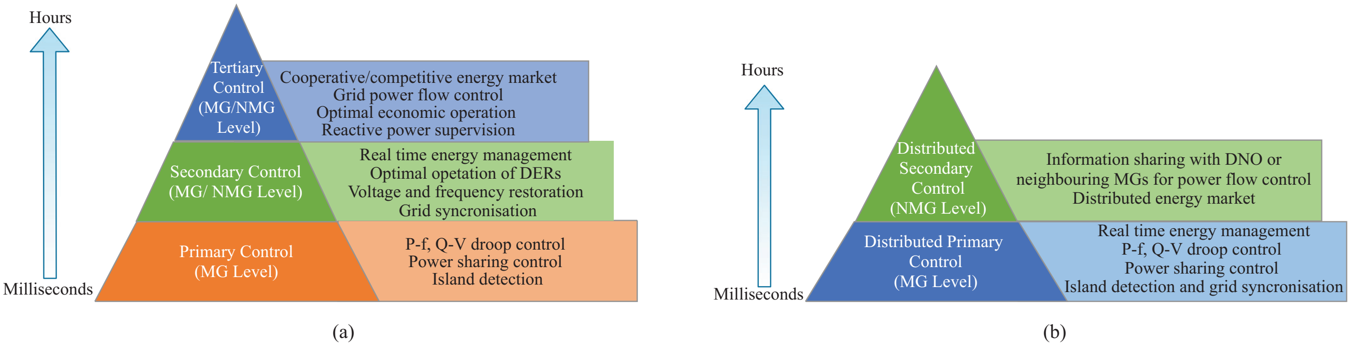

FIGURE 5 (a) Hierarchical and (b) distributed control structure of NMGs

network type are more challenging and complicated compared with those of the star and ring structures. In addition, the mesh structure exhibits a more complicated protection structure and reactive power sharing is difficult to maintain amongst MGs.

3 | CONTROL IN NMGs

NMGs control is a challenging issue in regulating the voltage and frequency of the network under different operating scenarios and system architecture. Optimal power sharing amongst DERs is another challenge in an NMG. The control of single MGs was discussed in several articles [31–36]. However, control in NMGs has recently become the focus because of the increasing interest in NMG research. Hierarchical and distributed control structures are used in research to achieve the control objectives of NMGs. The hierarchical control structure used in [37, 38] demonstrated the operational feasibility of NMGs in a distribution system. Meanwhile, a distributed control structure was presented in [19, 39] for a network of MGs operating in island mode. Figures 5(a) and 5(b) illustrate the control pyramids of NMGs that use hierarchical and distributed control structures. In a hierarchical control structure, primary-level control implements droop control, island detection and local protection in an MG. Meanwhile, the secondary-level control performs voltage and frequency regulation due to primary-level deviation, grid synchronisation, optimal operation of DERs in an MG/NMG and real-time energy management to maintain the power balance of individual MGs in the network. Tasks in secondary-level control can be performed using three controlling concepts: centralised, decentralised and distributed. In the centralised control approach, an MG central controller collects information from all the measurement units of the system through a communication link and performs optimal scheduling of DERs and load in an MG. The central controller also communicates with DNO or other MGs to implement tertiary-level control. Centralised control is the most applied approach to power systems due to its implementation flexibility. The major drawbacks of the central control approach are single point of failure, high bandwidth requirement and hindering of the plug-and-play functionality. Decentralised and distributed controls can be implemented using local information to eliminate the necessity of a central controller. Decentralised control does not consider information sharing with neighbouring nodes and uses only local information to accomplish an optimal decision. Droop control can be used to implement decentralised control. The major drawback of decentralised control is its poor system performance due to lack of communication. The distributed control approach uses information sharing with neighbouring DERs to overcome the downside of centralised and decentralised controls. DERs in an MG/NMG send/receive information with adjacent nodes to perform optimal operation and power sharing amongst DERs. Distributed control exhibits plug-and-play capability, low bandwidth requirement, high flexibility and system side performance enhancement. Tertiary-level control performs market operation with DNO. Each MG in the network shares its buy/sell information, such as price signal and reserve capacity, with DNO. On the basis of the information shared by individual MGs, DNO performs optimal market operation to facilitate network-wide power sharing. In cooperative island mode, MGs in the network can share information with a dominant MG instead of sharing information with DNO based on the previous consensus. The dominant MG performs market and system stability operations in island operation mode. Meanwhile, distributed control structure consists of two levels: distributed primary control and distributed secondary control. In distributed primary level control, each MG performs voltage, current and frequency regulation, island detection, grid synchronisation and load power management in an MG. In secondary-level control, MGs share the necessary information for power sharing or maintaining system-wide control to neighbouring MGs or DNO. On the basis of network information, each MG determines the necessary actions to achieve the individual/network objectives based on the previous consensus between MGs and the DNO. Table 1 summarises recent studies on NMG control based on the primary research objectives. Meanwhile, several methods have been applied to control NMGs under different operating conditions. The following subsections discuss the main control methods applied in recent studies.

3.1 | Droop control method

Droop control is a well-established method for load sharing in parallel connected inverters in an MG [54, 55]. The characteristics of conventional droop control, i.e. $P-\omega$ and

TABLE 1 Summary of recent studies on the control of NMGs

Main Research goal	Major Remarks	References
Voltage and frequency control	• Distributed secondary control • Pinning based PQ and droop control • ESS is not counted	[40]
	• Hierarchical control • Large signal model • Uncertainty of RES is not considered	[38]
	• Power exchange control • Model predictive control • Generation uncertainties has ignored	[22]
	• Distributed control • Adaptive neural network • ESS is not counted	[19]
	• Distributed control • Droop control • RES and ESS are not considered	[41, 42]
	• Distributed control • Cluster-oriented control • Double-layer communication network	[43]
	• Primary frequency control • Reinforcement learning • No experimental validation	[44]
Voltage stabilisation and generation cost minimisation	• Hierarchical control • Finite-time consensus algorithm • Uncertainty of RES is not considered	[45]
System stability margin	• Power exchange control • Adaptive fuzzy droop control • Uncertainty of RES is not considered	[46]
	• Dynamic assessment • Reachable scomputation • No real-time simulation	[47]
	• Genetic Algorithm • Dynamic Droop • No experimental validation	[48]
V-I controllability	• Design robustness • Probability index • No real-time simulation	[49]
Steady-state error	• Primary control • Feed-forward and robust feedback control • Uncertainty of RES is not considered	[18]
Active and reactive power control	• Virtual impedance • Genetic Algorithm • ESS is not counted	[50]
	• Tertiary control • Graph theory • ESS is not counted	[51]
	• Hierarchical communication graph • Building MG-community • EES is not counted	[52]
	• Distributed secondary control • MAS • Networked depended control	[53]

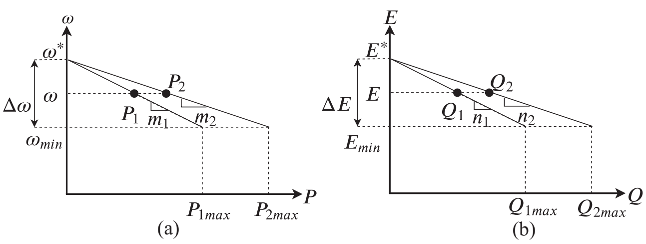

FIGURE 6 (a) P-ω and (b) Q-E droop

$Q - E$, can be represented using Equations (1) and (2) and Figure 6.

$$\omega_k = \omega^* - m_k P_k, \tag{1}$$

$$E_k = E^* - n_k Q_k, \tag{2}$$

where P_k, Q_k, m_k, n_k, ω and E are the output active power, output reactive power, frequency coefficient, voltage coefficient, rated frequency and rated voltage of the kth inverter, respectively.

Droop control techniques can be divided into three types:

1. conventional droop control,
2. virtual impedance droop control,
3. adaptive droop control.

Conventional droop control is useful for maintaining voltage and frequency in parallel connected inverters by avoiding critical communication links. The major drawback of conventional droop control is a slow transient response and poor harmonic load sharing amongst inverters under line impedance mismatch and non-linear load conditions. Virtual impedance-based droop control overcomes the line impedance mismatch problem through improved reactive power sharing amongst parallel-connected inverters. The major drawback of virtual impedance droop control is the degradation of voltage regulation. However, adaptive droop control is applied to address slow transient response and achieve accurate power sharing amongst inverters by maintaining system-wide voltage and frequency within an acceptable limit.

Droop control can also be used to control voltage and frequency in an NMG. A distributed secondary control was applied in [40] for achieving coordinate operation between droop-controlled and PQ-controlled DERs in an NMG. Coordination was realised on the basis of pinning control and a group consensus algorithm. Primary and secondary controls were implemented in [41] using a distributed control framework. At the primary control level a droop controller was used to facilitate proportional load sharing among DERs in the network. And, at the secondary control level voltage deviations due to load change and adjusting power generation of DERs to facilitate the power exchange among MGs. In [45], a droop function was modified by adding voltage deviation and average marginal cost in secondary and tertiary levels in a cluster of DC MGs. The objective of the control was to maintain a stabilised voltage throughout the network and reduce generation cost. A two-layer power flow model was introduced in [56] using a hierarchical control structure to regulate the critical bus voltage and frequency after a disturbance. Coordinate control of RES-dominant MGs was presented in [57] to achieve network operation in grid-connected and interconnected island modes. Droop control was used to realise network power sharing in interconnected operation mode. Moreover, an improved droop control strategy was implemented in [58] to reduce voltage and frequency fluctuations in MMG environment. In addition, pinning-based control method is highly suitable for MGs with a large number of DERs. A pinning-based DER cluster-oriented tertiary control was used in [42, 43] to generate a voltage/frequency reference based on power mismatch amongst MGs in a cluster. A distributed secondary droop control was implemented on the basis of the generated reference for maintaining the voltage and frequency of MGs in a cluster along with optimal power sharing. Virtual impedance control is an improved version of the droop control method that can increase reactive power sharing between parallel inverters by adding virtual impedance to the control loop. In [50, 59], a virtual impedance controller was designed to minimise global reactive power sharing between MGs in a network of MGs. An adaptive droop control-based coordinated control scheme was presented in [58] to achieve power-sharing amongst MGs and boost frequency and DC voltage stability in a DC/AC NMG.

3.2 | Model predictive control (MPC) method

MPC, also known as receding horizon control, is widely recognised as an optimal control strategy that exhibits high performance [60, 61]. Optimised control is achieved on the basis of future behaviour predicted by a linear model of the entire system [62]. The general equations for MPC are presented as Equations (3) and (4).

$$\Delta x(k+1) = A\Delta x(k) + B\Delta y(k) + C\Delta u(k), \tag{3}$$

$$0 = D\Delta x(k) + E\Delta y(k) + F\Delta P(k). \tag{4}$$

where x denotes the dynamic state variables, y denotes the algebraic variables outside each MG, u denotes the control variables (voltage, frequency or power) and P denotes the uncontrolled variable of the system (DERs/load). (A–F) are the system matrices of the linear system model. The ideal procedure to implement the MPC methods in an NMG is illustrated in Figure 7.

Step 1: Each MG in the network determines its linear model, measures the local states $x(k)$ and allows states of neighbouring MGs.

Step 2: Each MG determines the optimal control sequence for generating the first control effort.

Step 3: The control inputs are calculated, and the results are implemented in the local controllers.

Step 4: The sampling time index $k = k + 1$ is increased, and the preceding steps are repeated.

The major advantage of MPC is predicting system disturbance to perform an upcoming control action and improve the transient responses of a system. An accurate system model is a

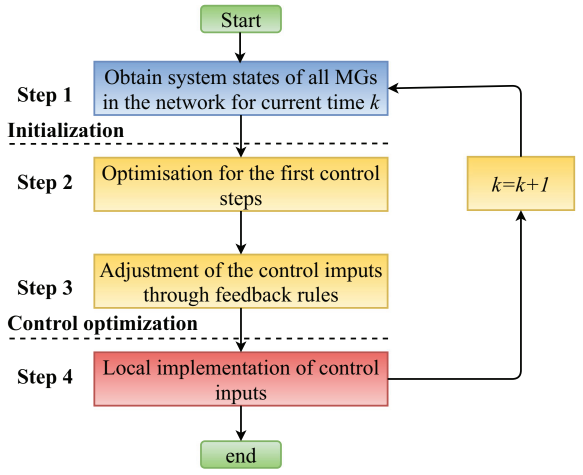

FIGURE 7 Procedure for implementing the MPC method in an NMG

prerequisite for implementing this control method. Moreover, the possible cost of the controller is another downside of the MPC method. MPC-based control is a prominent method for controlling voltage and frequency in a networked of MGs. In [47], an MPC method was used to regulate the voltage and frequency of DERs in an island MG connected to an adjacent grid-connected/fully island mode MG. An MPC method was also applied in [63] for controlling frequency in an NMG by adjusting the voltage of voltage-sensitive loads and maintaining voltage constraints. A distributed economic MPC was presented in [64] for coordinated stochastic power sharing amongst MGs.

3.3 | Graph theory-based control method

A graph is a set of nodes that are connected through a set of edges [51]. Graph theory–based distributed secondary and tertiary controls were mentioned in the research to reduce power mismatch between MGs and DERs in NMGs. A two-layer hierarchical communication graph was presented in [52] to utilise a thermostatic control load in a building MG community. The inner and intra building communication graph ensured that power regulation and dispatch orders are at satisfactory levels. A graph theory-based tertiary control was proposed in [51] to regulate power sharing in a DC MG cluster. Cooperation amongst MG agents determined the voltage set point for the proportional sharing of networked load within the MG cluster. A two-layer distributed control method was implemented in [53] by using two subgraphs. The first graph ensured demand–supply balance, and the second graph reassigned controllable DERs for optimal power dispatch.

3.4 | Artificial intelligence (AI) control method

AI control methods are widely used for controlling single MGs [65, 66]. AI control methods can be easily applied to solve the control problem in a complex power network, such as an NMG. Long processing time and excessive memory are the major drawbacks of implementing AI-based control methods in a real application. Several studies have also applied AI-based methods to control voltage, frequency and power in NMGs. Adaptive primary and secondary voltage and frequency controllers were developed in [19] for inverter-based DERs in an island NMG. The controllers were designed using neural networks and distributed cooperative control theory to reduce the dependency of the controllers on system dynamics and to achieve PQ power sharing amongst DERs in a network. An adaptive deep dynamic programming scheme consisting of three deep neural networks was applied in [67] to achieve integrated frequency control in a network of MGs. This control replaces conventional load frequency control and generation command dispatch to minimise frequency deviation and generation cost in an MG network. Meanwhile, an adaptive fuzzy interface system was implemented in [46] to regulate the droop coefficient in a network of DC MGs, increasing system stability margin and power allocation precision. In [68], a genetic algorithm-based control method was used to enhance system stability in photovoltaics (PV) MG clusters by addressing oscillation due to the dynamic nature of PV. The effect of a large transient due to inverter switching and end-user load on system dynamic stability was analysed in [44] for an RES-dominant NMG. A reinforcement learning-based trained controller was adopted to avoid considerable frequency deviation by reducing system voltage set point. Moreover, a reinforcement learning-based distributed secondary control was implemented in [21] via reward feedback pinning for the selected distributed generators in an MMG system. In [18], a robust feedback voltage control strategy was applied to suppress system disturbance caused by DER output in MMG. An alternating direction method of multipliers (ADMM)-based tertiary control was implemented in [69] to solve the optimal power flow problem and provide real and reactive power references for secondary control level in an NMG.

4 | OPTIMISATION OF ENERGY IN NMGs

Optimisation of energy sharing through an EMS is another challenging issue in NMGs. The EMS architecture of NMGs can be divided into three types: centralised, distributed and hierarchical EMSs.

In a centralised EMS, all MG resources in an NMG are scheduled by a central EMS for optimal energy sharing between MGs [70–72]. Figure 8(a) shows the centralised EMS structure of an NMG. In a centralised EMS, MGs do not have individual EMS and depend on a central EMS for energy optimisation. A centralised EMS aggregates information from all MGs and computes the optimal operating point for all the controlled resources of a network to achieve the global objective. High computational burden, dependency on a communication network, a single point of failure and sacrificing the privacy of individual MGs are the major drawbacks of a centralised EMS.

In a distributed EMS, each MG within an NMG has its own EMS with autonomous decision-making capabilities for achieving its objectives and energy sharing with adjacent MGs. Communication between MG EMSs is achieved in a distributed manner for cooperative interaction amongst them [64, 73, 74]. On the basis of information sharing amongst MG EMSs, each MG EMS makes an optimal decision about power sharing with other MGs. Figure 8(b) shows the distributed EMS structure of an NMG. In a distributed EMS, power sharing amongst MGs is accomplished by sharing minimal information with neighbouring MGs to maintain the privacy of individual MGs. Moreover, the requirement of a central entity is eliminated to obtain the network objective. A distributed EMS reduces computational burden and communication channel dependency compared with a centralised EMS. However, NMGs consisting of a large number of MGs can increase computational burden on individual EMSs. Moreover, a distributed EMS is difficult to apply if the MGs in a network do not want to share any information with their neighbouring pairs. Thus, the necessity of a central entity is arising to implement energy sharing amongst MGs without sacrificing the privacy of individual MGs. To address these issues, the concept of hierarchical EMS is implemented in NMGs.

In a hierarchical EMS, each MG EMS is responsible for optimising its resources to achieve the objectives of an MG. In parallel, a central EMS will communicate with all MG EMSs in the network to determine optimal energy power sharing amongst MGs [16, 75, 76]. Figure 8(c) shows the hierarchical EMS structure of an NMG. The central EMS in a hierarchical structure works as a market operator to facilitate power exchange amongst MGs or between MGs and the main grid. The central EMS achieves the network objectives by preserving the privacy of individual MGs. Moreover, a hierarchical EMS can be implemented with a low-bandwidth communication link because minimal information is flowing through the communication network. Thus, such EMS reduces the requirement for communication channel bandwidth compared with other EMS structures.

Optimisation of EMS in an NMG depends on local and global objectives of a network. Table 2 summarises the recent studies based on the objectives of the network formation in an NMG. Meanwhile, different methods and algorithms are used to solve the optimisation problem in an NMG with different EMS architectures. The next subsections summarise the methods and algorithms used in recent studies to solve the optimisation problem in an NMG.

4.1 | Optimisation using multi-agent framework

A multi-agent system (MAS) is a computational system composed of multiple interactive intelligent agents working together to achieve a global goal. The function of each agent is defined using a set of behaviour. Each agent performs different autonomous behaviour on the basis of their goal [77]. The autonomous behaviour of agents makes integrating MAS into the energy optimisation of NMGs feasible and even easy. The dependency of high-speed communication links to interact amongst different agents is the major drawback of agent-based optimisation. An MAS is used in different EMS architectures

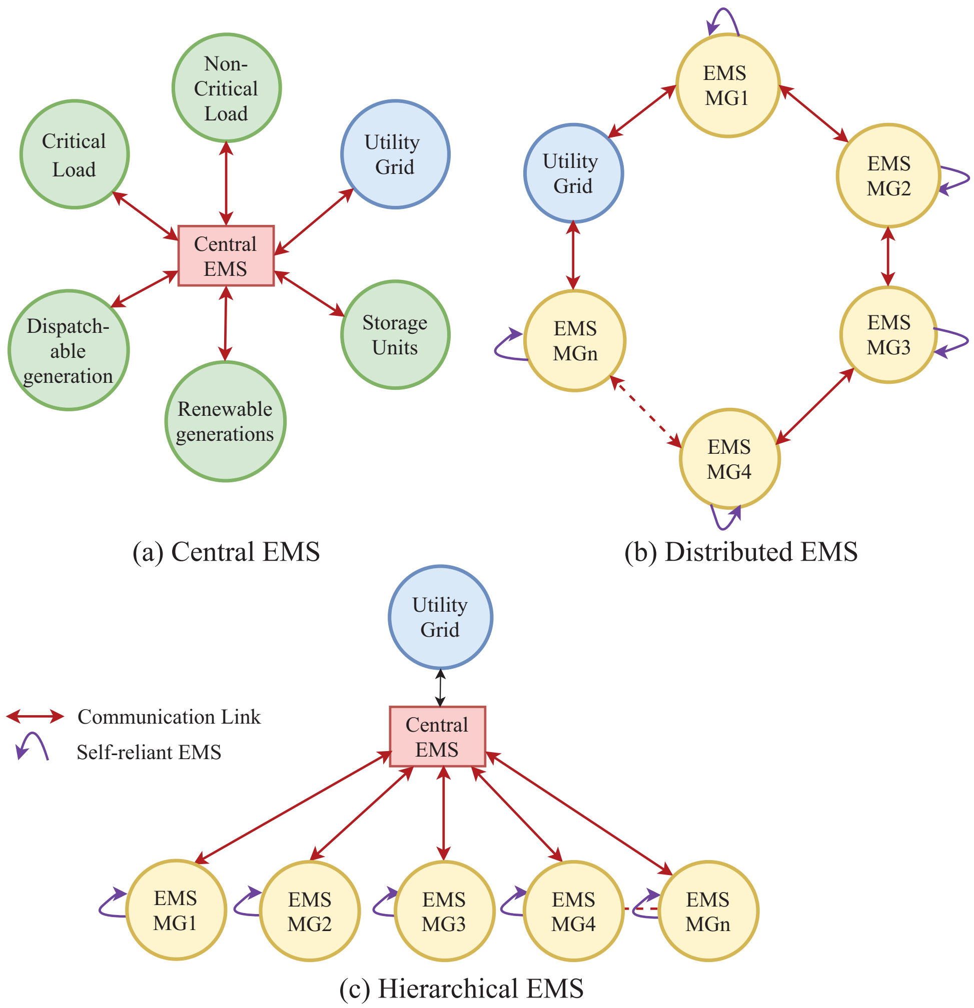

FIGURE 8 EMS structures of an NMG

to solve the optimisation problem in an NMG. Figure 9 shows the multi-agent market trading framework of an NMG for energy optimisation. Several field-level agents are monitored and controlled by a designated market interactive agent to gain the benefits in a competitive/cooperative market structure. In [78, 79], two virtual markets were considered in an EMS under MAS frameworks, and an incentive mechanism based on a priority index is introduced to reduce system peak in addition to providing cost benefits for high-priority index customers. MAS technology was also applied in [27] by assigning one agent for each power link between adjacent MGs to decide power exchange in different network topology. In [80], an MAS-based distributed control framework was used to describe energy management amongst MGs, and a gossip algorithm was applied to solve the optimisation problem. Moreover, an MAS was used in [81] for the energy resource scheduling of an island network consisting of MGs and lumped loads. MGs compete with one another in the wholesale market to provide power for lumping loads. Furthermore, an MAS was also applied to a bi-level decentralised market structure wherein each MG intelligent agent performs as a generator or load agent in the upper level for efficient resource management between connected MGs [82]. In [83], an MAS framework was used to reduce the operating cost of an NMG by informing the central EMS of the amount of adjustable power in addition to the amount of surplus/shortage power of individual MGs. A multi-agent–based robust energy scheduling was proposed in [84] for optimal tie-line power flow control in NMGs. Peer-to-peer communication and distributed sensors were utilised for scheduling DERs in the network by using a cyber–physical system.

4.2 | Optimisation using linear/quadratic programming

Linear/quadratic programming is a method for solving the optimisation problem of an objective function, which is the linear/quadratic function of decision variables. Optimisation problems in an NMG can be illustrated using a multi-objective optimisation problem. A typical multi-objective optimisation problem in an NMG system is expressed as

$$\min_{x} F(x) = [F_1(x), F_2(x), \ldots, F_k(x)]^T, \quad (5)$$

TABLE 2 Summary of recent studies on optimisation of NMGs

Main research goal	Major remarks	References
Increase supply reliability	• Adjustable generation control • Mixed integer linear programming • Increase the installation cost.	[83]
	• Self-healing to faults • Consensus algorithm • Dynamic stability is not considered	[73]
	• Supply to critical load • Spanning tree algorithm • ESS is not considered	[102]
	• Maximising the number of served loads and minimizing the restoration time •MILP • No real field data	[88]
	• Maximise power restoration • decentralised EMS • Scenario based testing	[24]
	• Probabilistic modeling • ICA • No real field data	[25]
Peak to average ratio minimisation	• Scholastic model of scheduling • Numerical simulation • No real field data	[103]
Reducing system peak	• Demand response • MASframework • ESS is not counted	[78]
Reactive power sharing	• Power exchange control • Genetic algorithm • PV, Wind & ESS is not considered	[50]
Individual MGs benefit	• Distributed coordinated control • Game theory • ESS is not considered	[39]
	• Convex linear/quadratic program • Price regime for buy/sell • Uncertainlity of demand is not considered	[85]
	• Stochastic and probabilistic modeling • PSO • No real field data	[104]
	• Stochastic bi-level optimisation algorithm • Scenarios based modeling • Ess is not considered	[105]
	• Reserve scheduling • Game theory • Conservativeness of robust optimisation	[94]
Optimal control of storage	• Central energy management • Linear/quadratic optimisation model • Single point of failure due to central control	[85, 86, 106]
Generation cost minimisation	• Distributed EMS • Online ADMM • Based on past generation information	[107]
Power exchange minimisation	• Distributed EMS • Convex optimisation • No real field data	[27]
Power loss minimisation	• Power flow management • Coalition game theory • ESS is not considered	[96]
Operational cost minimisation	• Power flow management • Coalition game theory • No real field data	[93]
	• Hierarchical energy management • Non-linearity and non-convexity is not considered	[75]
	• Stochastic EMS • Model predictive control • Forecasting based study	[64]
	• Power flow management • Stochastic bi-level problem • ESS is not considered	[108]
	• Energy resource scheduling • MAS framework • ESS is not considered	[81]
	• Distributed EMS • Game theory • Applicable for large scale RESs	[74]
	• Energy trading • Iterative distributed algorithm • PV, Wind & ESS is not considered	[29]
	• Both AC and DC power exchange network • ADMM algorithm • ESS is not considered	[23]
	• Multi-time-scale EMS • MILP • Privacy of individual MGs is not considered	[90]
	• Incentive mechanism • ADMM • Nash bargaining theory	[109]
Efficient resource management	• Real-time bidding • MAS • DERs uncertainity is not considered	[82]

subject to

$$g_i(x) \leq 0, i = (1, 2, \ldots, n), \tag{6}$$

$$h_j(x) = 0, j = (1, 2, \ldots, m). \tag{7}$$

where, $F(x)$ is the object vector that should be minimised. The object vector contains k scalar objectives. $g_i(x)$ and $h_j(x)$ are the inequality and equality constraints, respectively. The decision vector is x.

The goal of the optimisation is to minimise the objective function. In contrast with a single-objective problem, a multi-objective problem has no single solution. Thus, the latter should be converted into a single-objective optimisation problem by using scalarisation and linearisation methods before applying linear/quadratic programming [85, 86]. Linear/quadratic programming has been used in centralised and hierarchical EMSs for the optimal energy management of NMGs. The major drawback of this optimisation method is its inability to cope with large-scale problems. In [85, 86], an equivalent integer-free linear/quadratic programming model was derived from an original non-linear optimisation model to minimise individual MGs cost in parallel with minimising the total cost of a network through the coordinated dispatching of ESSs in the network. Meanwhile, mixed-integer linear/quadratic programming was used in [87–89] to model and solve the optimal power dispatch problem. A mixed-integer linear programming (MILP) algorithm was integrated into an MPC framework for the appropriate scheduling of ESSs, DGs and controllable loads to minimise the running cost of grid-isolated NMGs [87]. In [88], the interaction amongst grid-connected MGs under a central EMS was modelled and solved using MILP to minimise service restoration time and maximise the number of served loads. To minimise thermal wastage in an NMG, MILP was used in [89] to share the thermal load demand from neighbouring MGs whilst

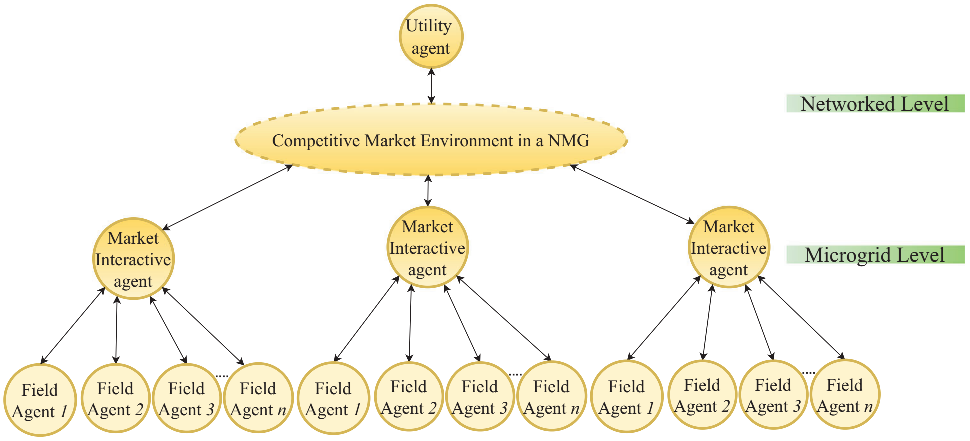

FIGURE 9 Multi-agent framework for the energy optimization of an NMG

electrical load demand was met by purchasing from a utility grid. In [17], an energy management model for an urban NMG with a shared resource was presented in an MPC framework, and MILP was used to solve the optimisation problem. A two-level EMS that comprised day-ahead integrated optimisation and real-time distributed compensation was proposed in [90] to minimise the operation cost of an MG community. An MILP-based method was used to select the charging/discharging of batteries to avoid overcharging/overdischarging of batteries in the MG community. A stochastic MILP problem was formulated in [24] to maximise service restoration in an NMG environment. Centralised and decentralised approaches were considered to compare their performance. In [91], a cost-aware smart MG cluster was formed to reduce the operating cost of an MG network. An MILP-based optimisation method was applied to facilitate power exchange amongst MGs in the network. In [92], an integrated energy exchange scheduling strategy was implemented on an MMG network under a central control centre and MILP was used to solve the energy scheduling problem.

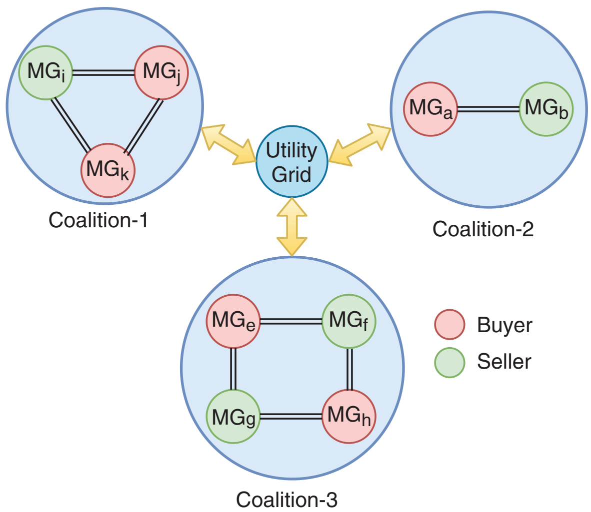

FIGURE 10 Game theory model of an NMG

4.3 | Optimisation using game theory

Game theory is a collection of mathematical models formulated to study situations of conflict and cooperation. In an NMG, collisions amongst MGs are formed on the basis of a previous agreement to fulfil network objectives. Figure 10 shows the coalition formation scenario for applying the game theory model to an NMG. In addition, the total payoff function of a coalition S in an NMG is as follows:

$$u(S,\Omega) = -\sum_{i\in S_s, j\in S_b} Cost^{pur} + \sum_{i\in S} Cost^{loss} + \sum_{i\in S} Cost^{com} + \sum_{i\in S} Cost^{shed}, \quad (8)$$

where Ω is the joining order of the buyers in the coalition S. $Cost^{pur}$ is the cost of electricity purchase amongst MGs and the main grid for each buyer MG_i. $Cost^{loss}$ is the expenditure for transmission of each MG_i in the coalition. $Cost^{com}$ represents the communication costs of MG_i to transfer information within the coalition. $Cost^{shed}$ is the expenditure for MG_i to compensate for the loads that are cut off.

The value function $v(S)$ can be defined for MG N coalition game,

$$v(S) = \min_{\Omega\in\Omega_S} u(S,\Omega), \quad (9)$$

where $\Omega \in \Omega_S$ is the set of all joining orders over buyers in S.

The game theory model is extremely useful in a competitive and bargaining environment wherein each element in a coalition exhibits independent decision capability. However, the complexity of the decision-making process increases with the number of players in the coalition. In NMGs, game theory can be applied to distributed and hierarchical EMS structures. The game theory model has been applied in several studies to solve the energy optimisation problem in an NMG by forming cooperative groups between MGs. A three-stage algorithm based on the cooperative game theory model was used in [93] to reduce the operating cost and load shedding compensation of MGs, enabling MGs in the coalition to exchange power directly by paying a transmission fee. Furthermore, cooperative game theory was adopted in a reserve scheduling model of EMS to minimise forecasting error in real-time operation [94]. A coalition game theory model was implemented in [95, 96] to optimise power loss over distribution power lines in NMGs. The additional profits (i.e. payoff) from coalitions will be distributed amongst MGs in the coalition by their Shapely value. Moreover, a comparison with the non-operative operation mode was performed to represent the benefits of the coalition. A multi-leader and multi-follower game theory model was applied in [97] to reduce the power unbalance and operation economy of a grid-connected three/single-phase hybrid MMG. Furthermore, a leader–follower bi-level structure was used in [98] under centralised and decentralised decision models. A Stackelberg game model was used to interact amongst MGs under a decentralised decision model. In [99], a peer-to-peer game theory model was adopted to realise energy trading amongst MGs in an MG community. A Stackelberg game approach was used in the model to represent the interaction between buyers and sellers. In [100], a comprehensive cost–benefit model of MGs with a surplus or shortage of power in real-time market trading was built and applied to a non-cooperative game model. A non-cooperative game theoretic method was also adopted in [101] to study power trading modes amongst MG systems. A priority mechanism was implemented in the trading process in which an MG in the network that experiences more power shortage will be given higher priority than the other MGs to purchase power from the network.

4.4 | Optimisation using heuristic algorithms

Heuristic algorithms have been well applied in several studies to solve optimisation problems in NMGs. Heuristic algorithms are highly efficient for solving the complex optimisation problem in NMGs. However, such expert systems require a high memory to be implemented in real applications. The tabu search method was applied in [72] to solve the day-ahead optimal energy management problem in an NMG under different scenarios. Moreover, a particle swarm optimisation (PSO) algorithm was applied to the EMS of NMGs to minimise the cost of individual MGs [104, 110]. Energy resources and loads are modelled via probabilistic modelling before applying the algorithm to the system. Considering the uncertainty of renewable generations and load demands, the optimal power dispatch problem in an NMG was solved using an imperialist competitive algorithm (ICA) and a PSO algorithm [111].

The result presented lower operating costs of MGs through optimal power sharing in a network. A gossip algorithm was applied in [80] to solve the hierarchical optimisation problem in an NMG, and thus, reducing operating cost and ensuring the resilience of MGs in grid-connected mode. In island mode, the objective of the EMS is to optimise economic performance by maintaining the safe operation of a network. In [25], an ICA was applied and compared with the Monte Carlo simulation method to maximise load support and network reliability in an NMG operating in grid-connected or island mode. Furthermore, a minimum spanning tree algorithm was applied in [102] to allocate critical loads to appropriate DGs in an isolated NMG without ESS. The non-critical load supply was determined by the MGs by using a linear matrix inequality approach. In [112], a direct search method was developed for the optimal scheduling of generations in a network and for reducing the total cost of a network by considering the inter-area power flow limit in an MMG network. In [113], the non-dominated sorting genetic algorithm-II (NSGA-II) was used to solve a multi-objective optimisation problem in an NMG. The objectives of NMGs are to minimise operating power and pollution emission to establish an environmentally friendly society for the future. A comparison with other heuristic algorithms such as PSO and ICA was performed to exhibit the optimal performance. In [74, 114], interaction amongst MGs was explained using an interactive energy game matrix in a bi-level multi-objective optimisation problem. Then a hybrid algorithm consisting of rough set theory, a hierarchical genetic algorithm and NSGA-II was applied to solve the model. A reinforcement learning algorithm with cooperative neural fitting iteration was proposed in [115] for the coordinated control of multiple controllers in an NMG environment. A diffusion strategy was incorporated into the algorithm to coordinate the actions of DER units and ESS devices by exchanging their evaluations and decisions via a wireless network. In [116], each entity in the decentralised EMS structure was formulated using second-order cone programming and then integrated into a two-stage robust optimisation structure. Thereafter, ADMM was applied to coordinate power exchange between MGs and the main grid. The energy management problem in an MMG interconnected by a DC and AC energy exchange network was studied in [23]. ADMM was applied to EMS to minimise the overall energy cost in a distribution network consisting of multiple MGs. In [107], an online EMS based on an online ADMM was implemented in an NMG to reduce scheduling inaccuracy due to the forecasting errors of DERs. A comparison with an off-line algorithm with inaccurate predictions was presented to demonstrate the robustness of the optimisation algorithm. An incentive-based distributed energy trading and social cost minimisation were discussed in [109]. An ADMM-based optimisation method was used to solve the optimisation problem amongst interconnected autonomous MGs.

4.5 | Optimisation using stochastic and robust algorithms

A stochastic energy management framework was presented in [117] to investigate the effect of correlated wind generations on EMS. A linear approximation of a bi-level distributed sequential computation algorithm was used to solve the optimisation problem. A two-stage stochastic optimisation algorithm was applied in [105] to minimise the operation cost of individual MGs in a network. In the first stage, scheduling of the generation set point was performed on the basis of forecasting, and the second stage revised the scheduling on the basis of real scenarios. In [118], optimal scheduling of DC-linked MMGs was implemented on the basis of stochastic programming to minimise the scheduling cost within the coalition. In [103], a multi-objective energy scheduling problem was formulated to achieve low-power generation cost and low peak-to-average ratio in an NMG. An adaptive scheduling approach with online stochastic iterations was implemented to solve the energy scheduling problem. A robust optimisation method was used in [30] for scheduling MMG systems by considering the uncertainty of RESs and forecast loads. A deterministic model was transformed into its non-linear robust counterpart to obtain a minimised daily operating cost of the entire system.

5 | ADVANTAGES AND CHALLENGES OF NETWORKED OPERATION OF MGs

The operation of an NMG has several advantages and challenges. This section presents the major advantages and challenges of NMGs.

5.1 | Advantages of networked operation

5.1.1 | Cost effectiveness of a network

One of the primary purposes of NMGs is to gain economic benefits via mutual energy sharing amongst MGs [75, 93]. In this concept, one or more MGs in a network exhibits excess generation or has a resource that can generate more power. By contrast, one or more MGs in the same network exhibits a shortage of power generation for a short/long period. In such a case, excess power or capacity can be sold to overcome the power shortage of a network. The additional income resulting from this power sharing will provide economic benefit for MGs with excess generation. Meanwhile, MGs with a power shortage may reduce operation cost if the power price of a neighbour MG is less than the power price of the main grid. The coordinated dispatching of ESSs/DERs can be cost-effective operation for an RES-dominant NMG [119]. A competitive bidding market amongst MGs is a highly attractive solution for energy trading amongst MGs to realise a cost-effective operation of individual MGs. A distributed or hierarchical EMS framework can be used to implement a market bidding facility amongst MGs. However, the cost-effectiveness of the entire network is occasionally more important than that of individual MGs in a community-based MG [64, 90]. In such cases, cooperative resource sharing amongst MGs is the most effective approach for obtaining a cost-effective network.

5.1.2 | Utilising resources in a network

The networked operation of MGs provides the opportunity to utilise the excess generation or capacity of an MG. MGs with excess generation/capacity can share power with MGs experiencing power shortage [83]. Such sharing will reduce the grid dependency of MGs. It will also help to utilise green energy from RESs. RESs in an MG are variable in nature and can generate excess power for a certain period. The excess generation in an MG is typically sold to the main grid with nearly zero economic benefits. If the excess generation from RESs in an MG can be sold to other MGs in the network through a cooperative power exchange amongst MGs, then that MG will gain economic benefits. Moreover, utility-owned RESs outside an NMG can supply power to an NMG at a competitive price to support the shortage of power in an NMG. Resource utilisation may be achieved via an NMG controller [74, 117]. Moreover, the previous consensus between MGs and an NMG controller will require to maximise the utilisation of resources in a network.

5.1.3 | Increasing reliability in a network

Reliability is one of the important issues in NMGs that should be assessed during the planning stage of NMGs [120]. Networked operation amongst MGs provides an opportunity to increase the supply reliability of MGs in a network [25, 110]. Cooperative operation amongst MGs can minimise system restoration time under a fault or power deficiency condition. It also ensures an efficient operation of demand response. The result increases customer satisfaction through economic benefits. Supply reliability also depends on the structure of NMGs. The mesh structure NMG is a more reliable network compared with other structures due to the redundant power link for power exchange amongst MGs. Besides that, networked operation of MGs in emergency/autonomous island mode can increase power supply reliability for the critical load of each MG by using DERs or battery storage [102]. The supply for critical load can be short/long term depending on the requirement and availability of resources in a network. The reliability of supply can be controlled by the NMG controller/dominant MG in the network though a common bus or a private power network between MGs. However, a previous agreement between MGs or a DNO is required to execute the emergency power sharing strategy.

5.1.4 | Operation of a distribution network as NMGs

A utility network operator can use the concept of an NMG to reduce the management complexity of a distribution network. A distribution network can be divided into several virtual MGs to operate as a network, increase the reliability of the system and simplify the management of large networks [8].

5.2 | Challenges of networked operation

5.2.1 | Privacy of individual MGs

The privacy of individually owned MGs is a challenging issue for the networked operation of MGs due to information sharing in such network. An NMG can be classified in accordance with the ownership of MGs: (1) utility-owned NMG, (2) privately owned NMG and (3) utility–private mixed-owned NMG. A utility-owned NMG is flexible in terms of operation and management because they can use the existing power network and are controlled by a central entity. Privately owned NMG consists of MGs with different ownerships. MGs in a mixed-owned NMG may not agree to share private information to other MGs. Information sharing is crucial during the cooperative island operation of MGs to reduce voltage/frequency deviation in a network. MGs in a network should establish an agreement to set the boundary of information sharing before operating in cooperative mode [20]. Meanwhile, a hierarchical EMS can be used to overcome the privacy problem amongst MGs in a mixed-owned NMG. Data handling during the control and optimisation of a network requires special consideration for these types of MGs. Moreover, an appropriate guideline/standard should be developed to overcome conflict of interest during the cooperative operation of MGs.

5.2.2 | Control and stability issues

Control and stability issues in an NMG are more complex than those in a single MG. Appropriate power electronics devices are important for power flow control amongst MGs in different operating modes. Networked operation in island mode is more challenging when two or more MGs operate in island mode but intend to resume cooperative mode. Voltage and frequency stability are difficult to achieve in such a network. Adaptive and robust power electronic devices should be developed to facilitate power exchange amongst MGs. A master–slave approach can be a suitable solution in which one MG will act as the master and will be responsible for setting voltage and frequency references. Other MGs in a network will work as slaves by following the master MG to minimise voltage and frequency deviations. In this approach, the master MG is responsible for maintaining the stability of the overall system. However, the privacy of MGs may be required to be sacrifice. Meanwhile, the NMG controller can send voltage, frequency and power references to individual MGs based on information from the network and each MG. However, this process may increase computational complexity. Thus, a robust control architecture should be developed to avoid control and stability issues in networked operation. Further quality research is anticipated in this area.

5.2.3 | Dependency on communication network

The networked operation of MGs depends on communication amongst MGs in a network of MGs. The power-sharing decision amongst MGs requires information from neighbouring nodes. Such information sharing is based on modern communication networks. Therefore, the requirement of a redundant communication network should be evaluated in the design stage by considering the amount and frequency of information and future extension [9]. Moreover, maintaining a secure communication network is a challenging task because of possible cyberattacks in a communication network. Communication networks based on different information and communication technologies (ICTs) may lead to possible cyberattacks in NMGs. A control structure based on a hierarchical or distributed framework should share information with neighbouring nodes for the optimal control of a network. Such networks typically connect to several ICT networks. Thus, a hierarchical or distributed control structure of NMGs is more vulnerable to possible cyberattacks. By contrast, in a central controller structure, all the nodes in a network send/receive information from/to the central controller to perform the desired control action. The central controller in an NMG broadcasts the control command to the all nodes through one-to-one communication protocol. Thus, the central control structure is less vulnerable and more resistant to cyberattacks. Cybersecurity in NMGs addressed in [121–123] because of the network dependency of the control structure in an NMG. A cyberattack-adoptive distributed control structure was incorporated in [124] wherein each node detects and isolates the defected nodes to exhibit optimal operation for other MGs in the network. Three types of possible attacks, namely, a communication link, a local controller and an MG controller, were considered to demonstrated the performance of the control strategy. Additional research is required in the future to avoid possible cyberattacks and communication failures in an NMG.

5.2.4 | Protection complexity

The protection scheme of NMGs differs from that of a single MG due to various possible system structures in a network [125–127]. The system structure in an NMG changes depending on the operation mode and optimal flow path in a network. A dynamic change of the system structure will change the current rating/direction of the breakers. Consequently, false tripping or malfunctioning of the breakers may occur at a certain point in the network. Accordingly, the setting of protection devices should be modified to respond to the revised structure of a network to maintain system reliability. An adaptive protection scheme should be developed to meet the protection requirements for an NMG. Additional contribution is necessary to develop adaptive protection schemes that can support various protection structures of NMGs. Moreover, fault analysis within private power networks between MGs should be addressed in the future.

6 | CONCLUSIONS

This article classifies NMGs into star, ring and mesh structures based on network formation. A summary of the control structures and methods for regulating voltage, frequency and power in NMGs under different operation scenarios is presented. A brief discussion of different EMS structures used in the energy optimisation of NMGs is also demonstrated. Moreover, methodologies and algorithms for solving the energy optimisation problem in NMGs are presented. In addition, the advantages and challenges of the networked operation of MGs are provided in this article. The summary of recent studies indicates that compared with dealing with the energy optimisation problem; minimal quality research has been conducted on power flow control in NMGs. The effect of MG cooperative operation on distribution network stability and quality should be addressed in the future. Moreover, the effects of communication networks and protection issues on NMGs performance should be the focus in future research to utilise the advantages of NMGs in a distribution network. Furthermore, suitable power electronic devices and energy trading guidelines should be developed to control power flow though power networks amongst MGs. In conclusion, this work intends to provide an extensive review of NMG research to direct interested researchers and professionals in developing suitable control and optimisation models of NMGs for promoting smart grid technologies in future power system networks.

ORCID

Mojaharul Islam https://orcid.org/0000-0002-3516-3745
Fuwen Yang https://orcid.org/0000-0002-2572-2259
Mohammad Amin https://orcid.org/0000-0003-0391-9322

REFERENCES

1. Yoldaş, Y., et al.: Enhancing smart grid with microgrids: challenges and opportunities. Renew. Sust. Energ. Rev. 72, 205–214 (2017)
2. Farrelly, M., Tawfik, S.: Engaging in disruption: a review of emerging microgrids in Victoria, Australia. Renew. Sust. Energ. Rev. 117, 109491 (2020)
3. Lidula, N., Rajapakse, A.: Microgrids research: a review of experimental microgrids and test systems. Renew. Sust. Energ. Rev. 15(1), 186–202 (2011)
4. Islam, M. et al.: Grid power fluctuation reduction by fuzzy control based energy management system in residential microgrids. Int. Trans. Electr. Energy Syst. 29(3), e2758
5. Arefifar, S.A., Mohamed, Y.A.R.I., El.Fouly, T.: Optimized multiple microgrid-based clustering of active distribution systems considering communication and control requirements. IEEE Trans. Ind. Electron. 62(2), 711–723 (2014)
6. Rua, D., et al.: Impact of multi-microgrid communication systems in islanded operation. In: 2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies. IEEE, pp. 1–6
7. Yuen, C., Oudalov, A.: The feasibility and profitability of ancillary services provision from multi-microgrids. In: Power Tech, 2007 IEEE Lausanne. IEEE, pp. 598–603
8. Li, Z., et al.: Networked microgrids for enhancing the power system resilience. Proc. IEEE 105(7), 1289–1310 (2017)
9. Marzal, S., et al.: Current challenges and future trends in the field of communication architectures for microgrids. Renew. Sust. Energ. Rev. 82, 3610–3622 (2018)
10. Xu, Z. et al.: Analysis on the organization and development of multi-microgrids. Renew. Sust. Energ. Rev. 81(2), 2204–2216 (2017)
11. Meng, L., et al.: Review on control of dc microgrids and multiple microgrid clusters. IEEE Trans. Emerg. Sel. Topics Power Electron 5(3), 928–948 (2017)
12. Alam, M.N., Chakrabarti, S., Ghosh, A.: Networked microgrids: state-of-the-art and future perspectives. IEEE Trans. Ind. Inf. 15(3), 1238–1250 (2018)
13. Chen, B. et al.: Networked microgrids for grid resilience, robustness, and efficiency: a review. IEEE Trans. Smart Grid 12(1), 18–32 (2020)
14. Zhou, Q. et al.: Distributed control and communication strategies in networked microgrids. IEEE Commun. Surv. Tutorials 22(4), 2586–2633 (2020)
15. Zou, H., et al.: A survey of energy management in interconnected multi-microgrids. IEEE Access 7, 72158–72169 (2019)
16. Xu, Z., et al.: Control devices development of multi-microgrids based on hierarchical structure. IET Gener. Transm. Distrib. 10(16), 4249–4256 (2016)
17. Parisio, A., et al.: Cooperative MPC-based energy management for networked microgrids. IEEE Trans. Smart Grid 8(6), 3066–3074 (2017)
18. Wang, C., et al.: Voltage control strategy for three/single phase hybrid multimicrogrid. IEEE Trans. Energy Convers. 31(4), 1498–1509 (2016)
19. Amoateng, D.O. et al.: Adaptive voltage and frequency control of islanded multi-microgrids. IEEE Trans. Power Syst. 33(4), 4454–4465 (2017)
20. Hussain, A., Bui, V.H., Kim, H.M.: A resilient and privacy-preserving energy management strategy for networked microgrids. IEEE Trans. Smart Grid 9(3), 2127–2139 (2016)
21. Liu, W. et al.: Reinforcement learning-based distributed secondary optimal control for multi-microgrids. In: 2017 IEEE Conference on Energy Internet and Energy System Integration (EI2). IEEE, pp. 1–4
22. John, T., Lam, S.P.: Voltage and frequency control during microgrid islanding in a multi-area multi-microgrid system. IET Gener. Transm. Distrib. 11(6), 1502–1512 (2017)
23. Liu, T., et al.: Energy management of cooperative microgrids: a distributed optimization approach. Int. J. Electr. Power Energy Syst. 96, 335–346 (2018)
24. Arif, A., Wang, Z.: Networked microgrids for service restoration in resilient distribution systems. IET Gener. Transm. Distrib. 11(14), 3612–3619 (2017)
25. Nikmehr, N., Ravadanegh, S.N.: Reliability evaluation of multi-microgrids considering optimal operation of small scale energy zones under load-generation uncertainties. Int. J. Electr. Power Energy Syst. 78, 80–87 (2016)
26. Xi, W. et al.: Economic operation of multi-microgrids containing energy storage system. In: 2014 International Conference on Power System Technology (POWERCON), IEEE, pp. 1712–1716
27. Dagdougui, H., Sacile, R.: Decentralized control of the power flows in a network of smart microgrids modeled as a team of cooperative agents. IEEE Trans. Control Syst. Technol. 22(2), 510–519 (2014)
28. Choobineh, M., Silva-Ortiz, D., Mohagheghi, S.: An automation scheme for emergency operation of a multi-microgrid industrial park. IEEE Trans. Ind. Appl. 54(6), 6450–6459 (2018)
29. Gregoratti, D., Matamoros, J.: Distributed energy trading: the multiple-microgrid case. IEEE Trans. Ind. Electron. 62(4), 2551–2559 (2015)
30. Hussain, A., Bui, V.H., Kim, H.M.: Robust optimization-based scheduling of multi-microgrids considering uncertainties. Energies 9(4), 278 (2016)
31. Rajesh, K., et al.: A review on control of AC microgrid. Renew. Sust. Energ. Rev. 71, 814–819 (2017)
32. Borazjani, P. et al.: A review on microgrid control techniques. In: Innovative Smart Grid Technologies-Asia (ISGT Asia), pp. 749–753.IEEE, (2014)
33. Yazdanian, M., Mehrizi-Sani, A.: Distributed control techniques in microgrids. IEEE Trans. Smart Grid 5(6), 2901–2909 (2014)
34. Miveh, M.R., et al.: Control techniques for three-phase four-leg voltage source inverters in autonomous microgrids: a review. Renew. Sust. Energ. Rev. 54, 1592–1610 (2016)
35. Raeispour, M. et al.: Robust sliding mode and mixed h_2/h_∞ output feedback primary control of AC microgrids. IEEE Syst. J. 1–12 (2020)
36. Gholami, S., Saha, S., Aldeen, M.: Robust multiobjective control method for power sharing among distributed energy resources in islanded microgrids with unbalanced and nonlinear loads. Int. J. Electr. Power Energy Syst. 94, 321–338 (2018)
37. Zhang, F., Zhao, H., Hong, M.: Operation of networked microgrids in a distribution system. CSEE J. Power Energy Syst. 1(4), 12–21 (2015)
38. Zamora, R., Srivastava, A.K.: Multi-layer architecture for voltage and frequency control in networked microgrids. IEEE Trans. Smart Grid 9(3), 2076–2085 (2018)
39. Liu, W., et al.: Game theoretic non-cooperative distributed coordination control for multi-microgrids. IEEE Trans. Smart Grid 9(6), 6986–6997 (2018)

40. Liu, W., et al.: General distributed secondary control for multi-microgrids with both PQ-controlled and droop-controlled distributed generators. IET Gener. Transm. Distrib. 11(3), 707–718 (2017)
41. Golsorkhi, M.S., Hill, D.J., Karshenas, H.R.: Distributed voltage control and power management of networked microgrids. IEEE Trans. Emerg. Sel. Topics Power Electron 6(4), 1892–1902 (2017)
42. Lu, X., et al.: Distributed coordination of islanded microgrid clusters using a two-layer intermittent communication network. IEEE Trans. Ind. Inf. 14(9), 3956–3969 (2017)
43. Lai, J., et al.: Cluster-oriented distributed cooperative control for multiple AC microgrids. IEEE Trans. Ind. Inf. 15(11), 5906–5918 (2019)
44. Radhakrishnan, N., et al.: Improving primary frequency response in networked microgrid operations using multilayer perceptron-driven reinforcement learning. IET Smart Grid 3(4), 500–507 (2020)
45. Li, Y., et al.: A distributed coordination control based on finite-time consensus algorithm for a cluster of dc microgrids. IEEE Trans. Power Syst. 34(3), 2205–2215 (2018)
46. Fu, Y. et al.: Droop control for dc multi-microgrids based on local adaptive fuzzy approach and global power allocation correction. IEEE Trans. Smart Grid 10(5), 5468–5478 (2018)
47. Li, Y., Zhang, P., Luh, P.B.: Formal analysis of networked microgrids dynamics. IEEE Trans. Power Syst. 33(3), 3418–3427 (2018)
48. Verma, A.K., Singh, B., Shahani, D.: Grid to vehicle and vehicle to grid energy transfer using single-phase bidirectional ac-dc converter and bidirectional dc-dc converter. In: 2011 International Conference on Energy, Automation, and Signal (ICEAS), IEEE, pp. 1–5
49. Arefifar, S.A., Ordonez, M., Mohamed, Y.A.R.I.: Voltage and current controllability in multi-microgrid smart distribution systems. IEEE Trans. Smart Grid 9(2), 817–826 (2018)
50. Zhu, Y., et al.: A virtual impedance optimization method for reactive power sharing in networked microgrid. IEEE Trans. Power Electron. 31(4), 2890–2904 (2016)
51. Moayedi, S., Davoudi, A.: Distributed tertiary control of DC microgrid clusters. IEEE Trans. Power Electron. 31(2), 1717–1733 (2015)
52. Wang, Y., et al.: A distributed control scheme of thermostatically controlled loads for the building-microgrid community. IEEE Trans Sustain Energy 11(1), 350–360 (2019)
53. Li, Q., et al.: Networked and distributed control method with optimal power dispatch for islanded microgrids. IEEE Trans. Ind. Electron. 64(1), 493–504 (2016)
54. Tayab, U.B., et al.: A review of droop control techniques for microgrid. Renew. Sust. Energ. Rev. 76, 717–727 (2017)
55. Planas, E., et al.: General aspects, hierarchical controls and droop methods in microgrids: a review. Renew. Sust. Energ. Rev. 17, 147–159 (2013)
56. Wu, X. et al.: A hierarchical control framework for islanded multi-microgrid systems. In: 2018 IEEE Power & Energy Society General Meeting (PESGM). IEEE, pp. 1–5
57. Sahoo, S.K., Kishore, N.: Coordinated control and operation of a multi-microgrid system. In: 2017 7th International Conference on Power Systems (ICPS). IEEE, pp. 283–288
58. Qingzhu, W., Chan, X.: Coordination control for multi-microgrid system with parallel structure based on improved droop control strategy. In: 2018 International Conference on Smart Grid and Electrical Automation (ICSGEA). IEEE, pp. 299–302
59. Zhu, Y. et al.: A virtual resistance based reactive power sharing strategy for networked microgrid. In: 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia), IEEE, pp. 1564–1572
60. Qiu, Q., Yang, F., Zhu, Y.: Distributed model predictive control with switching topology network. In: 2017 11th Asian on Control Conference (ASCC), IEEE, pp. 2364–2369
61. Yang, F., et al.: Cooperative model predictive control for distributed photovoltaic power generation systems. IEEE Trans. Emerg. Sel. Topics Power Electron 4(2), 414–420 (2016)
62. Lou, G., et al.: Distributed model predictive secondary voltage control of islanded microgrids with feedback linearization. IEEE Access 6, 50169–50178 (2018)
63. Liu, K. et al.: Distributed MPC-based frequency control in networked microgrids with voltage constraints. IEEE Trans. Smart Grid 10(6), 6343–6354 (2019)
64. Kou, P., Liang, D., Gao, L.: Distributed EMPC of multiple microgrids for coordinated stochastic energy management. Appl. Energy 185, 939–952 (2017)
65. Mahmoud, M.S., Alyazidi, N.M., Abouheaf, M.I.: Adaptive intelligent techniques for microgrid control systems: a survey. Int. J. Electr. Power Energy Syst. 90, 292–305 (2017)
66. Chettibi, N., et al.: Adaptive neural network-based control of a hybrid ac/dc microgrid. IEEE Trans. Smart Grid 9(3), 1667–1679 (2016)
67. Yin, L., et al.: Adaptive deep dynamic programming for integrated frequency control of multi-area multi-microgrid systems. Neurocomputing 344, 49–60 (2019)
68. Zhao, Z., et al.: Dynamic characteristics analysis and stabilization of pv-based multiple microgrid clusters. IEEE Trans. Smart Grid 10(1), 805–818 (2017)
69. Wang, Y. et al.: Peer-to-peer control for networked microgrids: Multi-layer and multi-agent architecture design. IEEE Trans. Smart Grid 11(6), 4688–4699 (2020)
70. Majumder, R., Bag, G.: Parallel operation of converter interfaced multiple microgrids. Int. J. Electr. Power Energy Syst. 55, 486–496 (2014)
71. Jose, J. et al.: Dynamic microgrid-based operations: a new operational paradigm for distribution networks. In: Innovative Smart Grid Technologies-Asia (ISGT-Asia), pp. 564–569.IEEE, (2016)
72. Arefifar, S.A., Ordonez, M., Mohamed, Y.A.R.I.: Energy management in multi-microgrid systems—development and assessment. IEEE Trans. Power Syst. 32(2), 910–922 (2016)
73. Wang, Z., et al.: Networked microgrids for self-healing power systems. IEEE Trans. Smart Grid 7(1), 310–319 (2016)
74. Lv, T., Ai, Q.: Interactive energy management of networked microgrids-based active distribution system considering large-scale integration of renewable energy resources. Appl. Energy 163, 408–422 (2016)
75. Tian, P., et al.: A hierarchical energy management system based on hierarchical optimization for microgrid community economic operation. IEEE Trans. Smart Grid 7(5), 2230–2241 (2016)
76. Wang, Y., Mao, S., Nelms, R.M.: On hierarchical power scheduling for the macrogrid and cooperative microgrids. IEEE Trans. Ind. Inf. 11(6), 1574–1584 (2015)
77. Islam, M., Lee, H.H.: Iec61850 based operation, control and management of utility connected microgrid using wireless technology. In: International Conference on Intelligent Computing. Springer, pp. 258–265 (2012)
78. Nunna, H.K., Doolla, S.: Demand response in smart distribution system with multiple microgrids. IEEE Trans. Smart Grid 3(4), 1641–1649 (2012)
79. Nunna, H.K., Doolla, S.: Energy management in microgrids using demand response and distributed storage—a multiagent approach. IEEE Trans. Power Delivery 28(2), 939–947 (2013)
80. Mao, M. et al.: Operation optimization for multi-microgrids based on centralized-decentralized hybrid hierarchical energy management. In: Energy Conversion Congress and Exposition (ECCE), pp. 4813–4820.IEEE (2017)
81. Logenthiran, T., Srinivasan, D., Khambadkone, A.M.: Multi-agent system for energy resource scheduling of integrated microgrids in a distributed system. Electr. Power Syst. Res. 81(1), 138–148 (2011)
82. Nunna, H.K., Doolla, S.: Multiagent-based distributed-energy-resource management for intelligent microgrids. IEEE Trans. Ind. Electron. 60(4), 1678–1687 (2013)
83. Bui, V.H., Hussain, A., Kim, H.M.: A multiagent-based hierarchical energy management strategy for multi-microgrids considering adjustable power and demand response. IEEE Trans. Smart Grid 9(2), 1323–1333 (2016)
84. Liu, Y., et al.: Distributed optimal tie-line power flow control for multiple interconnected ac microgrids. IEEE Trans. Power Syst. 34(3), 1869–1880 (2018)
85. Sandgani, M.R., Sirouspour, S.: Coordinated optimal dispatch of energy storage in a network of grid-connected microgrids. IEEE Trans. Sustain. Energy 8(3), 1166–1176 (2017)

86. Sandgani, M.R., Sirouspour, S.: Energy management in a network of grid-connected microgrids/nanogrids using compromise programming. IEEE Trans. Smart Grid 9(3), 2180–2191 (2017)
87. Zhang, Y. et al.: Dynamic dispatch of isolated neighboring multi-microgrids based on model predictive control. In: 2016 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), IEEE, pp. 50–55
88. Arif, A., Wang, Z.: Service restoration in resilient power distribution systems with networked microgrid. In: Power and Energy Society General Meeting (PESGM), pp. 1–5.IEEE, (2016)
89. Hussain, A., Lee, J.H., Kim, H.M.: An optimal energy management strategy for thermally networked microgrids in grid-connected mode. Int. J. Smart Home 10(3), 239–258 (2016)
90. Xing, X., et al.: Energy management strategy considering multi-time-scale operational modes of batteries for the grid-connected microgrids community. CSEE J. Power Energy Syst. 6(1), 111–121 (2019)
91. Erol-Kantarci, M., Kantarci, B., Mouftah, H.T.: Cost-aware smart microgrid network design for a sustainable smart grid. In: GLOBECOM Workshops (GC Wkshps), pp. 1178–1182.IEEE, (2011)
92. Li, P. et al.: An integrated energy exchange scheduling and pricing strategy for multi-microgrid system. In: TENCON 2013-2013 IEEE Region 10 Conference (31194). IEEE, pp. 1–5
93. Ni, J., Ai, Q.: Economic power transaction using coalitional game strategy in micro-grids. IET Gener. Transm. Distrib. 10(1), 10–18 (2016)
94. Li, Y. et al.: Optimal operation of multi-microgrids via cooperative energy and reserve scheduling. IEEE Trans. Ind. Inf. 14(8), 3459–3468 (2018)
95. Saad, W., Han, Z., Poor, H.V.: Coalitional game theory for cooperative micro-grid distribution networks. In: 2011 IEEE International Conference on Communications Workshops (ICC), IEEE, pp. 1–5
96. Wei, C., et al.: Gt-cfs: a game theoretic coalition formulation strategy for reducing power loss in micro grids. IEEE Trans. Parallel Distrib. Syst. 25(9), 2307–2317 (2014)
97. Wang, C. et al.: Optimal management for grid-connected three/single-phase hybrid multimicrogrids. IEEE Trans. Sustain. Energy 11(3), 1870–1882 (2019)
98. Asimakopoulou, G.E., Dimeas, A.L., Hatziargyriou, N.D.: Leader-follower strategies for energy management of multi-microgrids. IEEE Trans. Smart Grid 4(4), 1909–1916 (2013)
99. Paudel, A., et al.: Peer-to-peer energy trading in a prosumer-based community microgrid: a game-theoretic model. IEEE Trans. Ind. Electron. 66(8), 6087–6097 (2018)
100. Liu, Z., et al.: Operation mechanism and strategies for transactive electricity market with multi-microgrid in grid-connected mode. IEEE Access 8, 79594–79603 (2020)
101. Li, S. et al.: Power trading mode in multi-microgrids with controllable distributed generation: a game-theoretic approach. In: IEEE International Conference on Energy Internet (ICEI), IEEE, pp. 165–170
102. Fang, X., et al.: Coordinated dispatch in multiple cooperative autonomous islanded microgrids. Appl. Energy 162, 40–48 (2016)
103. Fathi, M., Bevrani, H.: Adaptive energy consumption scheduling for connected microgrids under demand uncertainty. IEEE Trans. Power Delivery 28(3), 1576–1583 (2013)
104. Nikmehr, N., Ravadanegh, S.N.: Optimal power dispatch of multi-microgrids at future smart distribution grids. IEEE Trans. Smart Grid 6(4), 1648–1657 (2015)
105. Wang, Z., Chen, B., Wang, J.: Decentralized energy management system for networked microgrids in grid-connected and islanded modes. IEEE Trans. Smart Grid 7(2), 1097–1105 (2016)
106. Ouammi, A., Dagdougui, H., Sacile, R.: Optimal control of power flows and energy local storages in a network of microgrids modeled as a system of systems. IEEE Trans. Control Syst. Technol. 23(1), 128–138 (2015)
107. Ma, W. et al.: Distributed energy management for networked microgrids using online ADMM with regret. IEEE Trans Smart Grid 9(2), 847–856 March, (2018)
108. Wang, Z., et al.: Coordinated energy management of networked microgrids in distribution systems. IEEE Trans. Smart Grid 6(1), 45–53 (2015)
109. Wang, H., Huang, J.: Incentivizing energy trading for interconnected microgrids. IEEE Trans. Smart Grid 9(4), 2647–2657 (2016)
110. Nikmehr, N., Najafi-Ravadanegh, S.: Reliability evaluation in multi-microgrids under probabilistic optimum operation using heuristic algorithm. In: Smart Grid Conference (SGC), pp. 92–98.IEEE, (2015)
111. Nikmehr, N., Najafi-Ravadanegh, S.: Probabilistic optimal power dispatch in multi-microgrids using heuristic algorithms. In: Smart Grid Conference (SGC), pp. 1–6.IEEE, (2014)
112. Yammani, C., Macha, V.K.: Fuel cost minimization with reserve capacity and inter-area flow limit for reliable and cost effective operation of multi microgrids. In: Region 10 Conference (TENCON), pp. 3189–3194.IEEE, (2016)
113. Pooranian, Z. et al.: Economical and environmental operation of smart networked microgrids under uncertainties using NSGA-II. In: 2016 24th International Conference on Software, Telecommunications and Computer Networks (SoftCOM), IEEE, pp. 1–6
114. Lv, T. et al.: An interactive operation model for distribution network with multi-microgrids to optimize wind power integration. International Conference on Renewable Power Generation (RPG 2015) (2015)
115. Liu, W. et al.: Cooperative neural fitted learning for distributed energy management in microgrids via wireless networks. In: Vehicular Technology Conference (VTC-Fall), pp. 1–5.IEEE, (2017)
116. Gao, H. et al.: Decentralized energy management for networked microgrids in future distribution systems. IEEE Trans. Power Syst. 33(4), 3599–3610 (2017)
117. Malekpour, A.R., Pahwa, A.: Stochastic networked microgrid energy management with correlated wind generators. IEEE Trans. Power Syst. 32(5), 3681–3693 (2017)
118. Guo, B., Liu, N.: Stochastic optimal scheduling for dc-linked multi-microgrids in distribution networks. In: IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society. IEEE, pp. 2707–2711
119. Zhou, Z., et al.: Game-theoretical energy management for energy internet with big data-based renewable power forecasting. IEEE Access 5, 5731–5746 (2017)
120. Cortes, C.A., Contreras, S.F., Shahidehpour, M.: Microgrid topology planning for enhancing the reliability of active distribution networks. IEEE Trans. Smart Grid 9(6), 6369–6377 (2017)
121. de Carvalho, R.S., Mohagheghi, S.: Analyzing impact of communication network topologies on reconfiguration of networked microgrids, impact of communication system on smart grid reliability, security and operation. In: 2016 North American Power Symposium (NAPS). IEEE, pp. 1–6
122. Venkataramanan, V., Zhou, Y., Srivastava, A.: Analyzing impact of communication network topologies on reconfiguration of networked microgrids. In: North American Power Symposium (NAPS), pp. 1–6.IEEE, (2016)
123. Abhinav, S., et al.: Synchrony in networked microgrids under attacks. IEEE Trans. Smart Grid 9(6), 6731–6741 (2017)
124. Zhou, Q. et al.: A cyber-attack resilient distributed control strategy in islanded microgrids. IEEE Trans. Smart Grid 11(5), 3690–3701 (2020)
125. Gopalan, S.A., Sreeram, V., Iu, H.H.: A review of coordination strategies and protection schemes for microgrids. Renew. Sust. Energ. Rev. 32, 222–228 (2014)
126. Alabdulwahab, A., Shahidehpour, M.: Microgrid networking for the monitoring, control and protection of modern power systems. Electr. J. 29(10), 1–7 (2016)
127. Brearley, B.J., Prabu, R.R.: A review on issues and approaches for microgrid protection. Renew. Sust. Energ. Rev. 67, 988–997 (2017)

How to cite this article: Islam M, Yang F, Amin M. Control and optimisation of networked microgrids: A review. *IET Renew Power Gener.* 2021;1–16. https://doi.org/10.1049/rpg2.12111