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Review

Optimized controller for renewable energy sources integration into microgrid: Functions, constraints and suggestions

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ABSTRACT

The generation and integration of renewable energy sources (RESs) into microgrid (MG) systems have recently demonstrated a significant increase due to the capability of RESs to meet the rising power demands and reduce environmental pollution. However, the fast expansion of MGs and their complex structures due to the wide integration area of distributed RESs and their intermittent behaviour may affect the power system stability and security. Thus, a properly optimised control method is important to guarantee an efficient, secure and high-quality power transfer. This paper highlights a comprehensive study of optimised controller approaches concerning the RES integration into MGs and their classification in terms of structure, characteristics, operation, constraints, functions, cost, pros and cons. This study focuses on the advanced and conventional optimisation algorithms used in MG applications. The rigorous review shows that current control optimisation strategies can enhance the operation and integration of RESs into MGs. However, further improvement of control optimisation is required to achieve sustainable energy operation and renewables integration in the future. The majority of the existing methods is restricted to simulation analysis; consequently, experimental validation is necessary. The standard requirements concerning the integration of RESs into MGs and their possible improvement and harmonisation are highlighted. This study also focuses on different issues, challenges and constraints related to the integration and control optimisation of RESs as well as recommendations for future research. Overall, this review will hopefully strengthen the efforts towards the development of a reliable renewable integration using efficient optimisation algorithms for future applications.

1. Introduction

The fast-growing global electricity demand, the depletion of conventional energy sources and the generation of electrical energy from non-renewable sources have led to environmental pollution (Juaidi et al., 2019). Consequently, the expansion of a distributed generation (DG) system that uses renewable energy sources (RESs) to generate electricity is important to cater to future energy needs. Thus, RESs, such as wind, photovoltaic, hydro, biomass and tidal energy, are vital sources of clean energy in modern power systems due to their efficient production of electrical energy with less environmental influences, increased system reliability and easy installation and expansion (Shayesteh et al., 2018). According to the International Energy Agency (International Energy Agency, 2019), renewable power capacity increases annually, accompanied by falling costs and growths in investment. For example, the power generation capacity of RESs revealed its largest annual growth in 2017, with approximately 178 GW of increase worldwide, raising the overall capacity by nearly 9% from that in 2016. Solar energy ranks first amongst the recently installed RESs at approximately 55%, which is higher than the combined generations from nuclear power and fossil fuels. Wind and hydropower systems provide large contributions, accounting for 29% and 11%, respectively. Fig. 1 shows the global share of RES usage in power generation during 2007–2017. Excluding hydropower sources, RESs produced 12.1% of the world's power generation (International Energy Agency, 2019; Renewable energy policy network, 2018).

Electrical power grids currently have a complex structure due to the wide area and fast expansion of distributed RESs (DRESs) interconnection. Thus, MGs could be regarded as the most intelligent solution for optimal operation (Avancini et al., 2019; Zarrabian et al., 2016). Recently, the interest in MG has significantly increased because of its potential advantages in providing efficient, secure, reliable, environmentally friendly and sustainable power from RESs (Zamora and Srivastava, 2010). An MG is a semi-autonomous system that combines a DRES, an energy storage system (ESS) and dispatchable loads to ensure the reliability of power supply to the local community. An MG can isolate and separate itself from the main grid disturbance to the load to improve grid security and efficiency (Yang, Lin et al., 2016).

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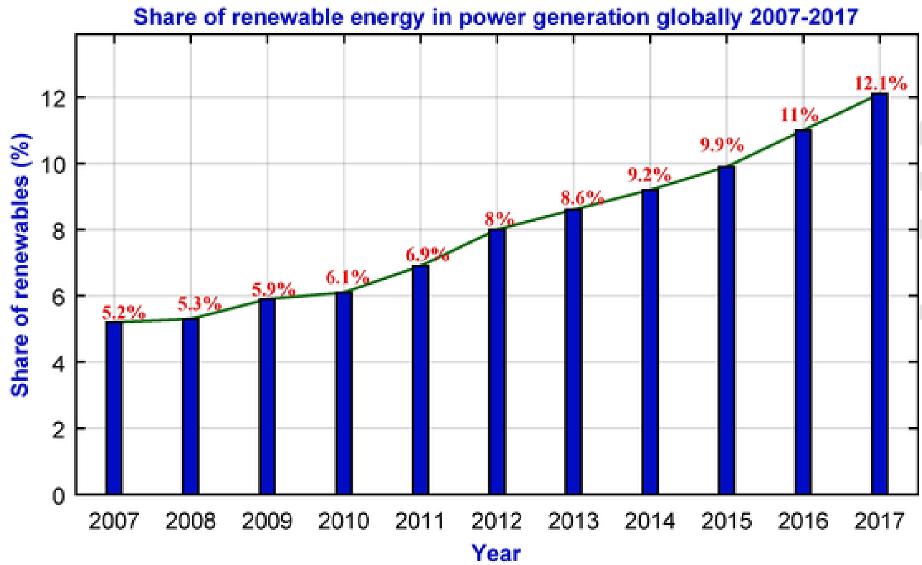

Fig. 1. Global share of RESs in power generation from 2007 to 2017.

The integration of distributed energy sources (DERs) into MGs is challenging, and many important considerations must be taken. The main concern of this integration is preserving stability after the start of a disturbance (Zarrabian et al., 2016). Electricity disturbance leads to major technical and economic issues; therefore, research works on MGs have been investigated to support grids and enhance their stability during disturbances (Tabar et al., 2018). MGs have more crucial problems than conventional power grids; these problems include inherent inertia, uncertainty and random penetration of distributed generation (Zarrabian et al., 2016). However, good mitigation and integration control of MGs would lead to reduced power losses and increased reliability (Gamarra and Guerrero, 2015).

The planning process is compulsory to ensure system stability due to the installation and integration of MGs. The MG planning process can be approached as a sequence of optimisation problems (Gamarra and Guerrero, 2015). Thus, several optimisation algorithms have been developed by researchers to solve MG issues at different planning levels. Consequently, many studies have been conducted to investigate the optimisation techniques applied to the integration of RESs into MGs. For example, Banos et al. (2011) reviewed various algorithms and comprehensively analysed the optimal sizing of RES-based hybrid systems. Their review concluded that the use of heuristic approach-based multi-objective optimisation and parallel processing is important. However, their review was conducted before the adoption and discovery of a new algorithm, which can achieve multi-objective solutions. A review study of computational optimisation techniques applied to MGs was introduced by Gamarra and Guerrero (2015). However, this review focused only on MG planning and discussed a few optimisation techniques. The power management strategies applied for MGs were also reviewed by Nanfang et al. (2013). However, their review only focused on particle swarm optimisation (PSO) and the Tabu search algorithm (TSA). The hierarchical controls and droop methods applied in MGs were compared by Planas et al. (2013). However, the optimised controller based on machine learning and heuristic optimisation methods was overlooked in this study. Sawle et al. (2017) introduced the genetic algorithm (GA) and PSO methods for a PV/wind/biomass hybrid energy system towards its optimal design. Although this study achieved optimal sizing to decrease the capital cost and the diversity of sources, other optimisation techniques with improved results were not considered. An optimisation approach was introduced by Niknam et al. (2012) to solve the cost minimisation problem. However, recent studies on heuristic optimisation methods, such as those by Chaouachi et al. (2013), Indragandhi et al. (2018) and Aghajani et al. (2015), have been applied with high efficiency. Other types of algorithms, such as fuzzy logic (FL), harmony search algorithm (HAS), adaptive neuro-fuzzy inference systems (ANFIS), TSA and artificial neural network (ANN), have been respectively used by Ambia et al. (2015), Arefifar and Mohamed (2014), Chaouachi et al. (2013), Chen et al. (2013) and Elena Dragomir et al. (2015) for optimisation during the advancement of MGs. These new optimisation approaches and strategies have been introduced in optimising controller problems. Consequently, although these individual methods have been well documented, a comparative overview of these methods increases the attractiveness of reviewing optimised controllers in MGs. Additionally, many reviews have been conducted in the area of MGs, particularly their applications, control techniques, protection devices, operating algorithms and energy management. However, existing reviews in this area that provide various detailed aspects of the optimised controller are limited. Therefore, an overview of the optimised controller of RESs incorporated with MGs would be beneficial. Overall, this review study aims to achieve the following objectives to bridge the knowledge gap.

(a) To discuss various existing optimised controller methods for RES integration into MGs, including their operation and characteristics.
(b) To present a comprehensive analysis with the current status of the optimisation algorithm used in RES integration and evaluate the issues and barriers to attaining sustainable MG development.
(c) To highlight the effective solutions to tackling the high integration constraints and challenges for the efficient integration and high productivity of MGs.
(d) To provide selected recommendations for further development of optimisation strategies for reliable RES integration by focusing on economic dispatch and environment issues.

The results of this review would be helpful for developers, engineers and power system operators in building a novel and efficient optimisation method/algorithm or improving the present technology. Accordingly, the key contribution of this review would hopefully help the future improvement of MG systems. This review is divided into eight sections. An explanation of how the literature review was conducted presented in Section 2. The overviews of MG systems and RES integration are provided in Sections 3 and 4, respectively. The MG optimised controller considerations and intelligent approaches, including advantages, disadvantages and constraints, are covered by Sections 5 and 6, respectively. The issues and challenges are comprehensively discussed in Section 7. Finally, the conclusion of this review and some selected proposals are presented in Section 8.

2. Literature review selection methods

This review was conducted according to the content analysis. The literature for this review was selected using Scopus scientific databases. Google Scholar, Scopus and Web of Science were selected for citation. Keywords, such as microgrid optimisation, renewable energy sources, optimised controller, renewables integration and distributed generation, were used to search for appropriate papers within the scope and target of this review study. Many papers were selected from this research. However, the appropriate literature was chosen on the basis of the title, keywords, abstract, contents of the paper and main topic of interest of the analysed journal. Finally, the authors selected the papers depending on the impact factor, review process and citation. This study identified and analysed 158 papers, which included journals (125), conference proceedings (24) and some certified webpages (9). Afterwards, the selected references were read carefully to extract valuable information related to optimised controllers of RES integration, operation methods and associated limitations. Fig. 2 illustrates the schematic of the review selection method.

The obtained results were structured into five groups. Firstly, overviews of the types of MG system and the integration of RES were provided. Secondly, the optimisation methods for RES integration and operation were comprehensively reviewed. The optimised controllers and approaches, as well as their characteristics, classifications and assessment procedures with cons and pros, were highlighted. Thirdly, the key issues, challenges and constraints were studied. Fourthly, the review explored different solutions to address the challenges and constraints. Finally, some significant recommendations and suggestions for future improvement of optimised controller methods for reliable and efficient RES integration into MGs were provided.

3. Overview of the MG system

In recent years, world energy demand has dramatically increased. Consequently, the trend towards MG development in power systems increased mainly in Europe, the United States, Australia and Japan (Zia et al., 2018). In this regard, based on the recent report of the MG development tracker (the 16th edition of the Navigant research global MG datab4ase), Asia Pacific has recently emerged as the global leader in MG capacity with 40% (led by China, Japan and Australia), followed by North America with 34% (led by USA). The worldwide regional MG capacity is shown in Fig. 3 (Navigant Research, 2019). MGs have various features that contribute to its increasing popularity. These features include the following: (*a*) capability to work easily in conjunction with the utility grid; (*b*) increases reliability; (*c*) reduces the demand on the main grid, thereby preventing grid failure; (*d*) cost-effectiveness; (*e*) considerably less complicated structure; (*f*) different steady-state and dynamic characteristics of RESs; (*g*) less specialised aptitude requirements for operation and depends on computerisation; (*h*) environmentally friendly due to the use of RES; (*i*) demonstrates a considerable degree of imbalance due to the existence of single-phase loads; and (*j*) a large part of the supply from 'uncontrollable' resources (Planas et al., 2013).

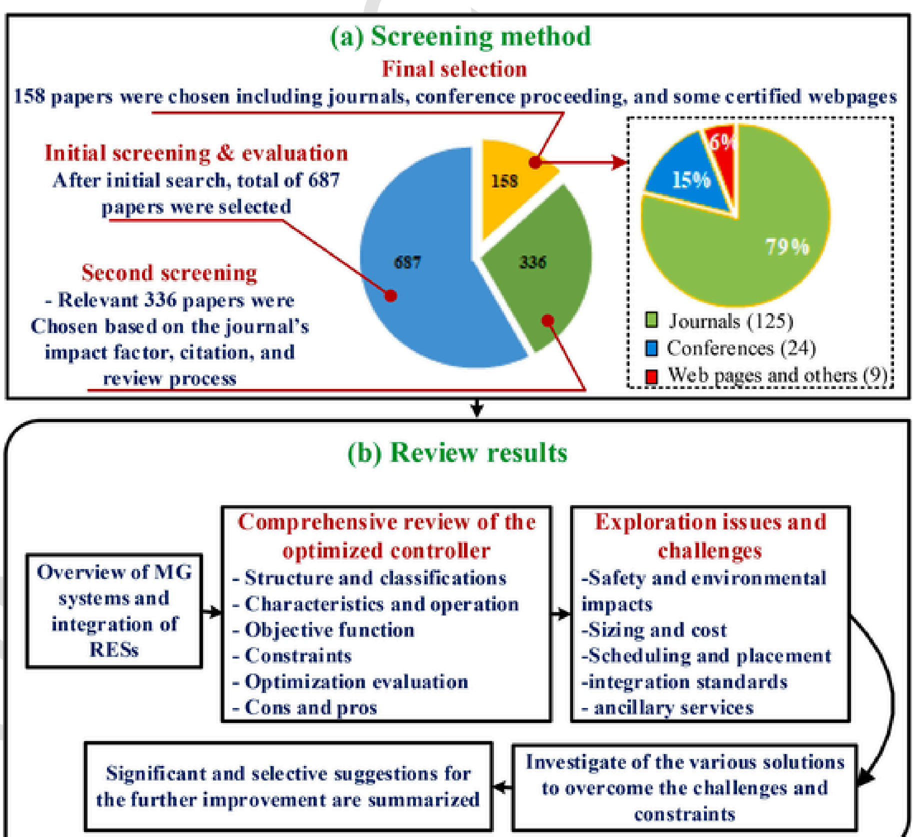

Fig. 2. Schematic of the review selection method.

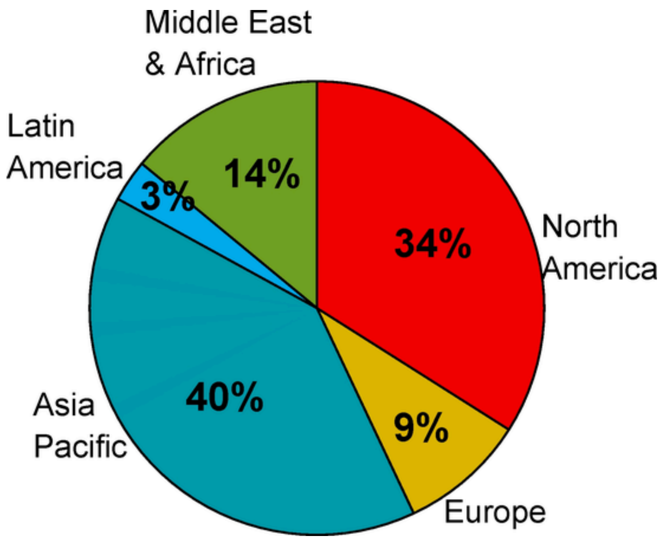

Fig. 3. Total MG power capacity share by region across the globe.

3.1. Structure of the MG

Overall, an MG is an independent electrical grid that comprises electrical generation, loads and an ESS, which can be linked to the main power grid or operate independently. The power generated in an MG is fundamentally produced by RESs, such as wind, solar PV, biomass and hydro energy (Zhang et al., 2013). The generated electrical power cannot be utilised due to the characteristic of energy formed by the MG. Therefore, the power must be converted using a power electronics interface, especially in the case of the main grid connection. This interface is necessary to provide the guideline of the local power and voltage (Justo et al., 2013). Notably, the intermittent behaviour of RESs affects MG operation. Consequently, an ESS is added to the MG to save extra power generated and deliver power into the utility grid when the grid cannot meet the load requirement. Two kinds of loads are available: critical and non-critical loads. Therefore, the critical load is supplied by continuous power in the event of faults or during maintenance. However, the load shedding system might be activated to achieve power balance for non-critical loads (Bakar et al., 2017).

An MG can be defined as a small electric power network that is responsible for the transmission, distribution and generation over a given region. MGs can achieve power balance and the ideal energy allocation. Fig. 4 illustrates the configuration and structure of an MG, which is divided into three layers (Li et al., 2015). The distribution network dispatch layers coordinate push the MG to provide the optimal economic and reliability of the distributed network. The centralised control layer ensures coordination between the load and the supply to ensure power balance. This layer depends on the forecasts of load demand and distribution generator (DG) output to guide the planning of the load, DG and ESS in real time. The local control layer (bottom layer) is used to facilitate the coordination of the DG and control the ESS and the load within the MG.

3.2. AC and DC MGs

MGs can be categorised as DC- and AC-MGs. In this type, the interconnection point, which is known as the point of common coupling (PCC), is presented as the electrical interface between the main utility grid and the MG. The PCC in the MG is commonly a three-phase AC bus. A fast switch is added in between the utility power grid and the PCC as the cut-off point (Planas et al., 2015).

During normal operation, RESs are responsible for supplying the load for the required power, whilst the extra power generated from RESs is supplied to the main grid. When the power generated from RESs cannot meet the load demand, the main electrical grid must regulate and send the required electricity into the AC-MG. The RES output power is mostly DC power, which must be converted into AC power to fit the existing AC network. In some AC-MGs, AC must be converted to DC because some equipment uses DC power to operate. Consequently, the DC-AC-DC energy conversion leads to low efficiency and power losses. By taking the operation of high DC voltage as a reference, a DC-MG is designed to solve the problem in AC-MGs. Fig. 5 shows the DC-MG design, in which the three-phase AC grid is equipped with a bidirectional DC/AC inverter (Veneri, 2017). Therefore, the conversion level is low in the DC-MG because it jumps to the AC stage in the middle of the process. In this type of MG, the voltage and frequency synchronisation and reactive power management issues are eliminated. Therefore, the DC transmission system is stable. Additionally, the phase and frequency control are not considered, making the operating system in the DC-MG substantially easier than that in the AC-MG (Salam et al., 2008).

An MG can operate in either stand-alone or grid-connected mode. MGs can use power from the electrical network to meet the load demand in the grid-connected mode. During maintenance or fault occurrence, the MG will operate in stand-alone mode and disconnect

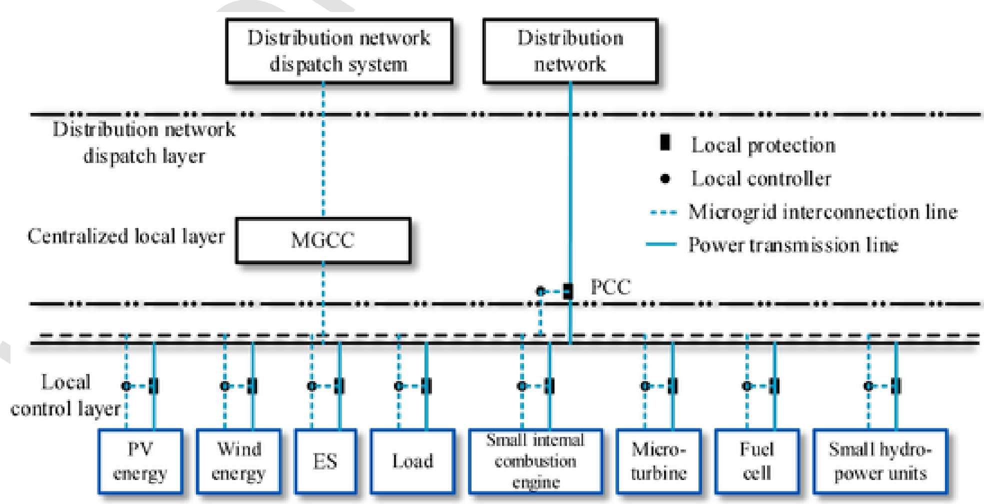

Fig. 4. Composition and structure of MG.

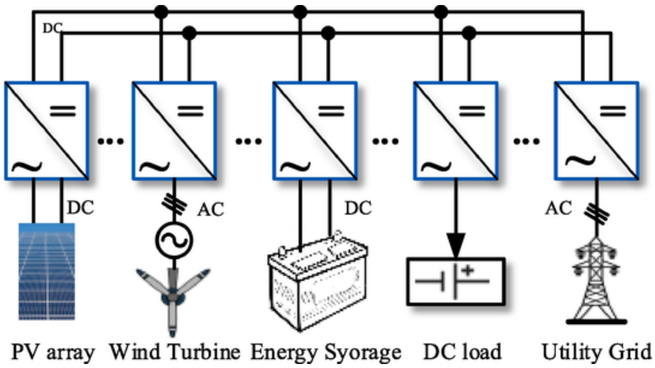

Fig. 5. DC-MG integrated with the bi-directional controller.

from the main grid. In the stand-alone mode, the MG must work flexibly to guarantee that the electricity supplied to the critical load is not influenced. Notably, proper regulation for the transient occurrence in the switching process is necessary to avoid equipment damage in the MG (Mehrizi-Sani and Iravani, 2010).

3.3. Hybrid energy system (HES)

The world has sufficient power generation sources to supply the rapid increase in electricity demand. However, power generation resources are either non-renewable or intermittent sources that reduce the reliability of the power system. Hence, renewable and conventional energy sources must be integrated to ensure green energy sources in the future and non-distractive power supply. RESs, such as solar, wind, geothermal, hydro, biomass and fossil fuels, must be integrated into a single unit to cover the demand area. A hybrid energy source (HES) combines different sources, including conventional and renewable sources, energy battery storage and load. A hybrid MG contains conventional resources (i.e. fossil fuel and diesel generator) and RESs, such as solar energy, wind energy, micro-turbine, tidal energy and biomass. Meanwhile, an ESS comprises a battery, hydrogen fuel, supercapacitor and flywheel storage, as illustrated in Fig. 6. Table 1 lists various ideal characteristics of widely used MG energy sources (Mariam et al., 2013).

The mitigation of greenhouse gas (GHG) emissions must be considered due to the increasing awareness of climate change and social responsibility. Therefore, renewable energies are integrated into the MG system to increase the energy efficiency of the MG. The energy system in the MG must also be optimised to ensure reliability and reduce energy wastage, cost, power loss and GHG emission (Baseer et al., 2019). Thus, in recent years, researchers have used hybrid energy systems to ensure the sustainable development of systems as listed in Table 2.

3.4. Energy storage system (ESS)

ESSs can effectively flatten the peak valley variance by optimising the charge and discharge behaviours. ESSs can be classified into large- and small-scale ESSs; the former requires a high initial cost and the latter may lead to intermittency (Cho et al., 2015). Several kinds of ESS are available: flywheel energy, gravity energy, compressed-air energy, electrochemical, battery energy, lithium-ion, hydrogen fuel cell and chemical fuel cell storage systems. The advantages, disadvantages, development, cost analysis and operation in the MGs of these ESSs have been reviewed and compared by many researchers (Faisal et al., 2018; Luo et al., 2015). Moreover, many applications of ESSs in MGs, such as peak shaving (Chen et al., 2012), optimal power follow (Mehrjerdi and Hemmati, 2019), reliability (Bahramirad et al., 2012), frequency regulation and power quality (Guerrero et al., 2013), have been investigated.

4. Integration of RESs

The integration of different RESs into the MG is a significant approach towards achieving secure, clean, reliable and efficient electrical power of advanced economies along with an improved level of electrical service reliability and quality. Many promising RESs and optimisation technologies have been developed and have entered into early commercialisation levels to form efficient MGs (Lorestani and Ardehali, 2018). RES integration gradually increased gradually by the end of 2017, and its contribution to the energy mix is shown in Fig. 7 (Renewable energy policy network, 2018). The integration of

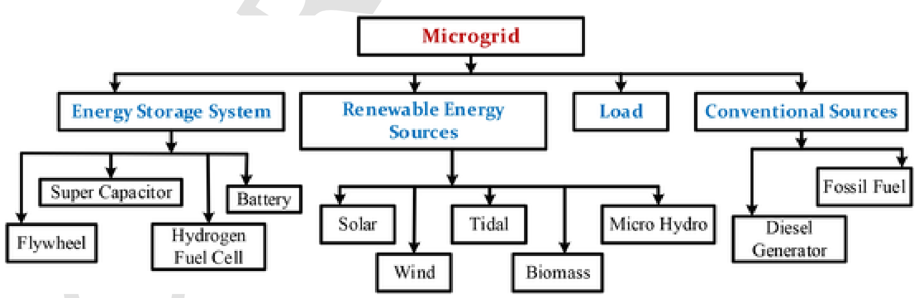

Fig. 6. Type of sources in hybrid MG.

Table 1
Typical features of widely used MG sources.

Features	Solar	Wind	Diesel	Biomass	Microhydro
Availability	Depends on the location	Depends on the location	Any time	Depends on the location	Depends on the location
GHG emission	No	No	Yes	Yes	No
Produced power	DC	AC	AC	AC	AC
Ideal interface	Converter (DC-DC-AC)	Converter (AC-DC-AC)	No	Synchronous generator	Synchronous generator
Control	Uncontrollable	Uncontrollable	Controllable	Uncontrollable	Uncontrollable
Power flow	MPPT & DC link voltage	MPPT, pitch & torque	Direct	Turban generator & governor	Direct via generator

Table 2
Sustainable system in MG.

Ref.	Grid	PV	WT	Tidal	Biomass	MT	DG	FC	BES	Hydrogen Tank	EV
Abdolrasol et al. (2018)	✓	✓	✓				✓	✓	✓		
Kaur et al. (2014)	✓						✓				
Jung and Villaran (2017)	✓	✓					✓		✓		
Moradi et al. (2015)	✓	✓									✓
Hasanien (2017)	✓	✓	✓	✓							
Kumar et al. (2017)	✓	✓	✓				✓		✓		
Malathi and Saravanan (2017)	✓	✓									
Alonso et al. (2012)	✓						✓		✓		
Indragandhi et al. (2018)		✓	✓				✓		✓		
Zhao et al. (2014)			✓			✓		✓	✓		
Cheng et al. (2017)	✓	✓	✓			✓	✓		✓		
Li et al. (2017)		✓							✓	✓	
Sawle et al. (2017)		✓	✓		✓		✓		✓		
Zheng et al. (2018)		✓	✓		✓				✓		

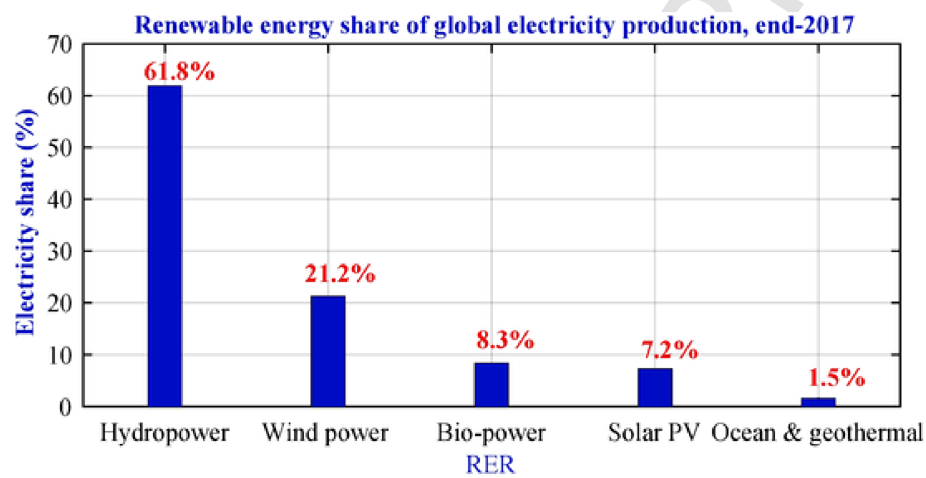

Fig. 7. Renewable energy sources share.

RESs also includes the dynamic control of reactive and active powers with load-side control. Consequently, the future of electrical systems and the power industry is technically starting, thus indicating that a new covenant depends on the interconnection of RESs (Basak et al., 2012). For example, in the past, when faults or disturbances occurred in the grid, these RESs should be immediately disconnected to prevent islanding. However, many grid codes have recently required RESs to act as traditional power plants to maintain the connection to the grid and support the network by reactive power to overcome the faults (Al-Shetwi et al., 2016). An integration method for RESs development in low- and medium-voltage distribution systems was reported by Haidar et al. (2014). A dynamic energy management strategy that considers the large-scale integration of the RES of an MG-based distribution system was studied by Lv and Ai (2016). Their results indicated that the integration of RES could enhance system stability. Protection approaches for RESs have been extensively studied in the literature. The protection methods during the advancement of MG were reviewed by Gopalan et al. (2014). The review result proved that the development of fast and reliable operation protection could improve the safe and reliable integration of RESs.

Different standards and requirements have been developed with the increase in the installation and integration of RESs to guarantee the proper integration of these sources into the utility grid. A few standards, such as. EN 50160 and IEC 61000 in Europe and IEEE 1547, IEEE C37.95 and IEEE 37.118 in the US (de Carvalho et al., 2013; Moschakis et al., 2011; Photovoltaics and Storage, 2009), are applicable in MGs. Table 3 summarises the American and European standards relevant to MG.

5. MG optimised controller considerations

MG planning optimisation is essential to enhancing the system in terms of cost, reliability, power quality and environmental issue (Luo et al., 2015). Hence, the optimisation model of MG planning must be established. Based on the literature, the mathematical constraints and objectives considered in optimisation algorithm formulation are as follows.

5.1. Objective functions

In the literature, a few objective functions were formulated by some researchers. Indragandhi et al. (2018) focused on finding the best solution for power management from all available solutions based on the fitness function. Other objective functions have also been introduced for battery energy storage (BES) charging, battery sizing and optimum energy management (Correia et al., 2017). Fig. 8 generally shows four areas that should be considered in MG optimisation (Li et al., 2018). The most important or key objective functions in the field, namely, pollution, economy, reliability and renewable technology integration (Aghajani et al., 2015; Cannata et al., 2019; Jiménez-Fernández et al., 2019; Li et al., 2018; Niknam et al., 2012; Ramli et al., 2018; Shen et al., 2016), are considered to improve the operation and obtain additional benefits from the aggregation

Table 3
Integration standards applicable to RESs.

Standard	Description	Standard domain
EEE 1547	Requirements and criteria concerning the integration of DESs to the utility grid.	- Integration, design and operation of DESs. - Control and monitoring. - Application guide. - Interconnection requirement for DESs higher than 10 MVA. - Rules and guidelines regarding the connection with secondary distribution networks. - Studies on the impact of DES interconnection. - Recommended practice for establishing procedures and methods.
IEEE C37.95	Protective relaying guide for utility grid-RESs integration.	- Protection system design. - Ideal grid–consumer connection configurations. - Supply methods. - Load considerations.
IEEE C37.118	Standard and requirements for synchrophasors and data transformation for the grid system.	- Synchronised phasor definition. - Time tags and synchronisation applications. - Verification methods of standards compatibility with measurements. - Phasor measurement unit methods.
EN 50160	Voltage characteristics of power supplied by distribution systems.	- Specify the main voltage characteristics at the PCC in low, medium and high voltages during steady-state operation. - Determine the power frequency, harmonics, voltage unbalance, voltage variation and flicker limits at PCC. - Describe the indicative values for some power quality events.
IEC 61000	Common rules and conditions required for obtaining electromagnetic compatibility.	- Electromagnetic compatibility levels. - Integrity requirements and safety functions. - Testing and measurement techniques. - Limits of emission and immunity. - Short interruptions, voltage sags and voltage variation immunity tests. - Mitigation methods and installation guidelines.

of DGs in MGs. Thus, this study mainly focused on these objective functions.

5.1.1. Economy

The general objective of MG in terms of the economy is to minimise the cost of usage. A few formulations are used in the cost minimisation of MGs.

- *Cost minimisation*

The cost minimisation of MG is formulated as follows (Bahmani-Firouzi and Azizipanah-Abarghooee, 2014; Kamboj et al., 2016; Sheng et al., 2015):

$$Min\ F(x) = \sum_{t=1}^{T} f_t + OM_{DG} + TCPD_{BES} + TCPD_{BEV} + TCPD_{PHEV}, \quad (1)$$

where

$$f_t = \sum_{t=1}^{T} Cost_{grid,t} + Cost_{DG,t} + Cost_{BES,t} + Cost_{BEV,t} + Cost_{PHEV,t} + SUC_{FC,t} + SUC_{MT,t} + SUC_{FCEV,t} + SDC_{FC,t} + SDC_{FCEV,t}\ . \quad (2)$$

The grid supply cost can be defined by Eq. (3):

$$Cost_{grid,t} = \begin{cases} B_{grid,t}P_{grid,t} & if\ \ P_{grid,t}>0 \\ (1-tax)\,B_{grid,t}P_{grid,t} & if\ \ P_{grid,t}<0 \\ 0 & if\ \ P_{grid,t}=0 \end{cases}, \quad (3)$$

where f is the objective function, and OM_{DG} is the operation and maintenance cost of DG. $TCPD_{BES}$, $TCPD_{BEV}$ and $TCPD_{FCEV}$ are the total cost per day for BES, battery electric vehicle (BEV) and fuel cell vehicle (FCEV), respectively. $SUC_{FC,t}$, $SUC_{MT,t}$ and $SUC_{FCEV,t}$ are the start-up costs for fuel cell (FC), micro-turbine (MT) and FCEV at time t, respectively. $SDC_{FC,t}$ and $SDC_{FCEV,t}$ are the shutdown costs for FC and FCEV at time t, respectively. The tax rate of the utility grid is represented by tax. $P_{grid,t}$ and $B_{grid,t}$ are the grid-generated power in kW and the bid of the utility grid for period t, respectively. The fuel and operation costs of the DGs can be obtained by the following equations:

$$Cost_{DG,t} = B_{MT,t}P_{MT,t}\mu_{MT,t} + B_{FC,t}P_{FC,t}\mu_{FC,t} + B_{FCEV,t}P_{FCEV,t}\mu_{FCEV,t} + P_{PV,t}B_{PV,t} + P_{WT,t}B_{WT,t}. \quad (4)$$

The start-up and shut down costs of FC, $FCEV$ and MT are expressed as follows:

$$SUC_{MT,t} = SU_{MT,t} \times \max\left(0,\ \mu_{MT,t} - \mu_{MT,t-1}\right), \quad (5)$$

$$SUC_{FC,t} = SU_{FC,t} \times \max\left(0,\ \mu_{FC,t} - \mu_{FC,t-1}\right)\ , \quad (6)$$

$$SUC_{FCEV,t} = SU_{FCEV,t} \times \max\left(0,\ \mu_{FCEV,t} - \mu_{FCEV,t-1}\right)\ , \quad (7)$$

$$SDC_{FC,t} = SD_{FC,t} \times \max\left(0,\ \mu_{FC,t} - \mu_{FC,t-1}\right), \quad (8)$$

$$SDC_{FCEV,t} = SD_{FCEV,t} \times \max\left(0,\ \mu_{FCEV,t} - \mu_{FCEV,t-1}\right). \quad (9)$$

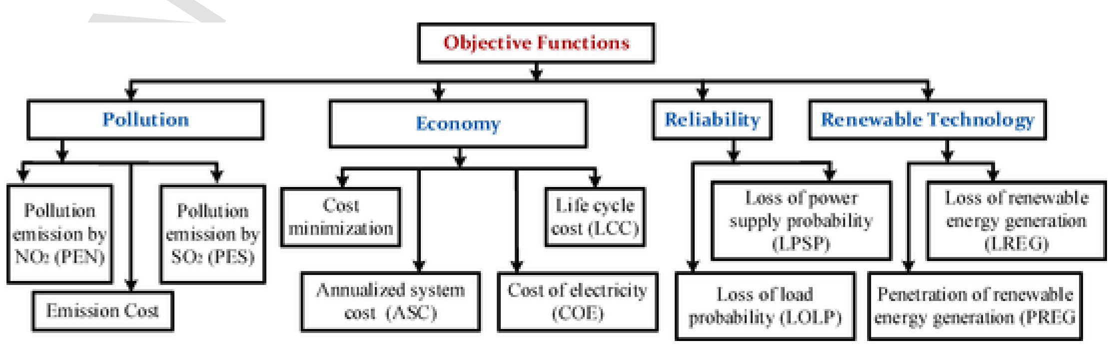

Fig. 8. Key objective functions for the MG optimum operation.

The constant cost of operation and maintenance for DG can be presented as follows:

$$OM_{DG} = \left(OM_{MT} + OM_{FC} + OM_{FCEV} + OM_{PV} + OM_{WT}\right) \times T \quad . \tag{10}$$

The battery costs, including the yearly repair and the single-time constant costs, are as follows:

$$Cost_{BES,t} = \left(FC_{BES,t} + MC_{BES,t}\right) \times C_{BES,max}, \tag{11}$$

where C_{max} is the maximum size of the battery. The time horizon, T, is one day (24 h), in which the calculation of time was based on the time. $TCPD$ can be achieved by accounting for the interest rate (IR) of the financial installation and the lifetime (LT) of the battery using the following equation (Chen et al., 2012):

$$TCPD_{BES} = \frac{C_{BES,max}}{365}\left(\frac{IR(1+IR)^{LT}}{(1+IR)^{LT}-1}FC_{BES} + MC_{BES}\right) \quad , \tag{12}$$

$$TCPD_{BEV} = \frac{C_{BEV,max}}{365}\left(\frac{IR(1+IR)^{LT}}{(1+IR)^{LT}-1}FC_{BEV} + MC_{BEV}\right) \quad , \tag{13}$$

$$TCPD_{PHEV} = \frac{C_{PHEV,max}}{365}\left(\frac{IR(1+IR)^{LT}}{(1+IR)^{LT}-1}FC_{PHEV} + MC_{PHEV}\right) \quad . \tag{14}$$

- *Cost of electricity*

The cost of electricity determines the financial effectiveness of the MG system, and this cost is represented as shown below (Borhanazad et al., 2014):

$$COE = \frac{C_{total} \times CRF}{\sum_{t=1}^{T} P_l(t)}, \tag{15}$$

where $P(t)$ is the load power, and C_{total} is the total net present cost. The capital recovery factor, which converts the current value to equal the yearly payment during a specific period, is represented by CRF as follows:

$$CRF = \frac{\omega(1+\omega)^n}{(1+\omega)^n - 1} \quad , \tag{16}$$

where ω is the real interest rate, and n represents the system life span.

5.1.2. Emission cost

The generation units from the main grid and the energy reserving resources from the MG are the main culprit of pollution emission (Aghajani et al., 2015). The pollution emission mainly includes the emission of carbon dioxide (CO_2), nitrogen dioxide (NO_2) and sulphur dioxide (SO_2). The formulation of pollutant emission is represented by Eq. (17) (Aghajani et al., 2015; Fathy and Abdelaziz, 2018):

$$\min F(x) = \sum_{t=1}^{T} Emission_{DG}^{t} + Emission_{S}^{t} + Emission_{grid}^{t}$$
$$= \sum_{t=1}^{T}\left[\sum_{i=1}^{N} u_i(t) P_{DG,i}(t) E_{DG,i}(t) + \sum_{j=1}^{N} u_j(t) P_{S,j}(t) E_{S,j}(t) + P_{grid}(t) E_{grid}(\right.$$

where $E_{DG,i}(t)$, $E_{S,j}(t)$ and $E_{grid}(t)$ are the emissions injected from the installed DG, the storage device and the grid at time t, respectively. $E_{DG,i}(t)$, $E_{S,j}(t)$ and $E_{grid}(t)$ can be respectively calculated as follows:

$$E_{DG,i}(t) = CO_2^{DG}(t) + SO_2^{DG}(t) + NO_2^{DG}(t) \quad , \tag{18}$$

$$E_{S,j}(t) = CO_2^{S}(t) + SO_2^{S}(t) + NO_2^{S}(t), \tag{19}$$

$$E_{grid}(t) = CO_2^{grid}(t) + SO_2^{grid}(t) + NO_2^{grid}(t) \quad . \tag{20}$$

5.1.3. Loss of power supply probability (LPSP)

The LPSP is a parameter or an indicator for determining the probability of power supply breakdown due to technical failure or low renewable energy supply. These conditions eventually cause failure matching between the supply and the load demand. The probabilistic techniques per energy storage accumulative effect can be used to calculate the LPSP as stated in the following equation (Yang et al., 2008):

$$LPSP = \frac{\sum_{t=1}^{T} P_{loss}(t)}{\sum_{t=1}^{T} P_l(t)} \tag{21}$$

and

$$P_{loss}(t) = P_l(t) - P_{PV}(t) - P_{WT}(t) + P_{SOC,min}(t) + P_{diesel}(t), \tag{22}$$

where $P_{loss}(t)$ is the total power loss, and $P_l(t)$ is the load power. $P_w(t)$, $P_{diesel}(t)$ and $P_{pv}(t)$ are the wind, diesel and PV power, respectively. $P_{soc,min}$ is the battery state of charge minimum limits.

5.2. Renewable energy optimisation constraints

Constraints in the optimisation problems can emerge from a few perspectives, such as network system, DERs, ESS and loads. Containing these constraints will lead to different optimisations due to the different maximum limits that can be sustained by the system. In this context, Fig. 9 lists the recent constraint functions according to researchers (Azaza and Wallin, 2017; Khodayar et al., 2012; Mirzaei et al., 2019; Moradi et al., 2015). Therefore, the succeeding sub-sections will focus on describing the most important constraints.

5.2.1. Electrical demand and supply balance

The accumulative power produced by the distributed generation, the ESS and the grid should be adequate to supply the load of the MG at all times. Eq. (23) shows the sum of powers (Yu et al., 2016).

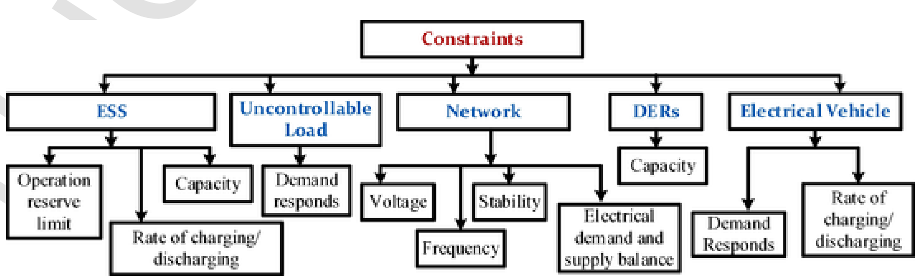

Fig. 9. Constraint functions.

$$\sum_{n=1}^{N} P_{supply} = \sum_{n=1}^{N} P_{load} + \sum_{n=1}^{N} P_{loss} \ , \tag{23}$$

where P_{suuply}, P_{load} and P_{loss} are the power supply, load power and power loss in kW, respectively.

5.2.2. Capacity limit constraints

The limits of the power output for various distributed generations (i.e. PV, WT, DG, FC and energy battery storage system) must be within the maximum and minimum limits (Azaza and Wallin, 2017; Moghaddam et al., 2012). Therefore, the capacity limit constraints can be calculated as per the following equations:

$$P_{MT,\ min} \le P_{MT,\ t} \le P_{MT,\ max} \ , \tag{24}$$

$$P_{PV,\ min} \le P_{PV,\ t} \le P_{PV,\ max} \ , \tag{25}$$

$$P_{WT,\ min} \le P_{WT,\ t} \le P_{WT,\ max}, \tag{26}$$

$$P_{FC,\ min} \le P_{FC,\ t} \le P_{FC,\ max} \ , \tag{27}$$

$$P_{PHEV,\ min} \le P_{PHEV,\ t} \le P_{PHEV,\ max}, \tag{28}$$

$$P_{grid,\ min} \le P_{grid,\ t} \le P_{grid,\ max}, \tag{29}$$

where $t = 1, \ldots, T$. $P_{MT,max}$, $P_{PV,max}$, $P_{WT,max}$, $P_{FC,max}$, $P_{PHEV,max}$ and $P_{grid,max}$ are the maximum generated powers in kW of MT, PV, WT, FC, PHEV and the grid, respectively. Meanwhile, $P_{MT,m}$, $P_{PV,min}$, $P_{WT,min}$, $P_{FC,min}$, $P_{PHEV,min}$ and $P_{grid,min}$ are the minimum generated powers in kW of MT, PV, WT, FC, PHEV and the grid, respectively. $P_{MT,t}$, $P_{PV,t}$, $P_{WT,t}$, $P_{FC,t}$, $P_{PHEV,t}$ and $P_{grid,t}$ are the generated powers in kW of MT, PV, WT, FC, PHEV and the grid at time t, respectively.

ESS or PHEV plays an important role in ensuring MG reliability. Therefore, charging and discharging of the ESS and the PHEV are of concern. The discharging and charging of PHEV and ESS indicate the limitations of the released and discharged energies. The discharging equation and mode can be calculated and represented by Eqs. (30) and (31), respectively (Bahramirad et al., 2012):

$$C_{ESS,t+1} = max\left\{ \left(\frac{C_{ESS,t} - \Delta t P_{ESS,t}}{\eta_{discharging}} \right), \ C_{ESS,min} \right\} \ , \tag{30}$$

$$C_{ESS,t+1} = min\left\{ \left(C_{ESS,t} - \Delta t P_{ESS,t} \eta_{charging} \right), \ C_{ESS,\ max} \right\} \ , \tag{31}$$

where $t = 1, \ldots, T$. $C_{ESS,t}$ is the stored energy in the ESS (kWh) at time t, Δt is the time duration and $\eta_{discharging}$ and $\eta_{charging}$ are the efficiencies of ESS discharging and chagrining, respectively. $C_{ESS,min}$ and $C_{EES,max}$ are the minimum and maximum sizes of the ESS, respectively. $P_{ESS,t}$ is the charge rates of the ESS at time t.

5.2.3. MG reserve constraint

The MG reserve is defined as the total reserved power generation capacity to ensure high reliability and energy efficiency. According to Jiao et al. (2017), the MG reserve should satisfy no less than 15% of the total load demand per hour. It is formulated as follows:

$$R_{total,t} = \mu_{D,t}(1+\theta)^{n-1} P_{D,t} + \sum_{k}^{K} \mu_{k,t} P_{k,t} \ , \tag{32}$$

where $R_{total,t}$ is the total reserve power, $\mu_{D,t}$ is the prediction error of the load demand and $\mu_{k,t}$ is the prediction error of the distributed generations. The reserve constraint can also be used to turn on MT, FC, utility and BES. This constraint can be injected into the MG in less than 10 min and formulated as follows (Bahmani-Firouzi and Azizipanah-Abarghooee, 2014):

$$P_{MT,max} u_{MT,t} + P_{FC,max} u_{FC,t} + P_{BES,max} u_{BES,t} + P_{grid} \ge OR + P_{demand}, \tag{33}$$

where $P_{MT,max}$, $P_{FC,max}$, $P_{BES,max}$ and P_{grid} are the maximum generated powers in kW of MT, FC, BES and the grid, respectively. $u_{MT,t}$, $u_{FC,t}$ and $u_{BES,t}$ are the statuses (either off or on) of MT, FC and BES at time t, respectively. P_{demand} is the load power, and OR is the operating reserve power.

6. MG intelligent optimised controller

6.1. Fuzzy logic-based controller

Fuzzy logic control (FLC) is well adapted for applications that resemble human decision-making with an aptitude to generate a reliable solution from either predicted or definite data. FLC is an approach that uses 'degrees of truth' for computation rather than Boolean logic, which only contains 'true or false'. Moreover, FLC does not require an exact equation or detailed input probably due to its wide range of input variation. Various outputs can be generated on the basis of system design, and several inputs can be processed as a result of the rule-based operation (Shahid et al., 2016).

The basic structure of the fuzzy logic controller process is illustrated in Fig. 10 (Bhavani et al., 2015). The input data can be altered into appropriate linguistic values using the fuzzification interface. Few membership functions are created for the input set. The rule base comprises data with fundamental linguistic definitions and a control rule set. The fuzzy interface acts as a decision-maker, which gathers the fuzzy controller action from the information of the linguistic variable descriptions and the rule base. A defuzzification interface is used to produce the optimal result for the output (Bhavani et al., 2015).

The fuzzy logic-based controller is widely utilised in different applications, including the integration of RES in MG. For example, Kyriakarakos et al. (2012) introduced the design of an autonomous poly-generation MG using a fuzzy logic energy management system (EMS). They proved that the fuzzy logic EMS effectively utilises energy and decreases the size of the component. Lagorse et al. (2009) introduced FLC in MG to switch the operation modes of the storage unit by ensuring reliable and secure energy supply. The integration of renewable energy in a residential grid-connected MG by using a FLC enhances the voltage profile with minimum fluctuations in the frequency as investigated by Arcos-Aviles et al. (2015). Fossati et al. (2015) introduced the fuzzy logic controller for optimal scheduling in MG systems. Their study indicates a significant cost reduction due to the use of optimised fuzzy expert systems instead of conventional charge/discharge methods. This optimisation method saves 3.34% and 1.43% in MG operation costs in island and grid-connected modes, respectively. Nair et al. (2016) proposed an FL-optimised controller for power sharing between MG and the main power grid and enhancing the quality of power at PCC. Their results showed an efficient sharing of active power between both sides with a 3.64% reduction in total harmonic distortion at PCC. Fuzzy controller was also used to manage the load and maximum power point tracking (MPPT) of MGs containing solar PV and bat-

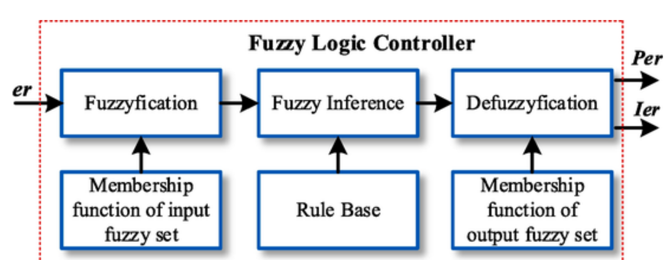

Fig. 10. General block diagram of fuzzy logic controller.

teries. The relevant findings revealed that the FLC effectively managed the loads and increased the efficiency of the produced power at different irradiation levels with different load conditions (Angalaeswari et al., 2017). In summary, utilising FLC in MG demonstrated high optimisation levels at different applications.

6.2. Harmony search algorithm (HSA)

HSA was developed by Zong Woo Geem et al., in 2001 (Geem et al., 2001). This algorithm is based on music and aims to search for an ideal state of harmony in a piece. Harmony in music is a process of finding the optimal state. HSA has also been used for different optimisation purposes, such as function optimisation, economy dispatch, engineering optimisation and vehicle routing optimisation (Fesanghary et al., 2008). Fig. 11 shows the HSA process.

Three components must be formalised to obtain optimal results: pitch adjustment, harmony memory and randomisation. It is similar to the improvisation process of a skilled musician, which involves playing any famous music piece, playing something similar to a known music piece and composing new or random notes. Harmonic checking is performed to ensure satisfactory results, which will then serve as solutions to the problem (El-Abd, 2018; Fesanghary et al., 2008). HSA possesses a good diversification and comprises the following two components: randomisation similar to other metaheuristic algorithms and pitch adjustment characterised by r-pa Pitch modification is a refinement procedure for local solutions to enhance the optimal result. Moreover, HSA has a good intensification by the harmony memory accepting rate (r-accept). The harmony memory accepting rate can speed up the optimisation process when the value is high. Moreover, the implementation of HSA is easy, and this algorithm can be combined with other algorithms in various applications (El-Abd, 2018).

The HSA is widely used in MG applications. Jha et al. (2015) utilised HSA to overcome the dynamic economic dispatch issues for MG. This utilisation not only minimised the cost of generated power but also established coordination between different kinds of distributed generation technologies, such as WT, PV, diesel engines and fuel cell, over numerous scheduling by considering the dynamic grid cost. The modified HSA (MHSA) is then used to solve the poor robustness and slow convergence rate of the conventional HSA (Jiao et al., 2017). The convergence rate, computation time and economy of MHSA are more satisfactory than those of the traditional method. Elattar (2018) adopted the MHSA in the economic emission distich of MG by incorporating renewable sources. The results exhibited substantially high reduction cost and efficiency under different conditions. Overall, using the harmony search optimisation method can increase the efficiency of different applications in MG.

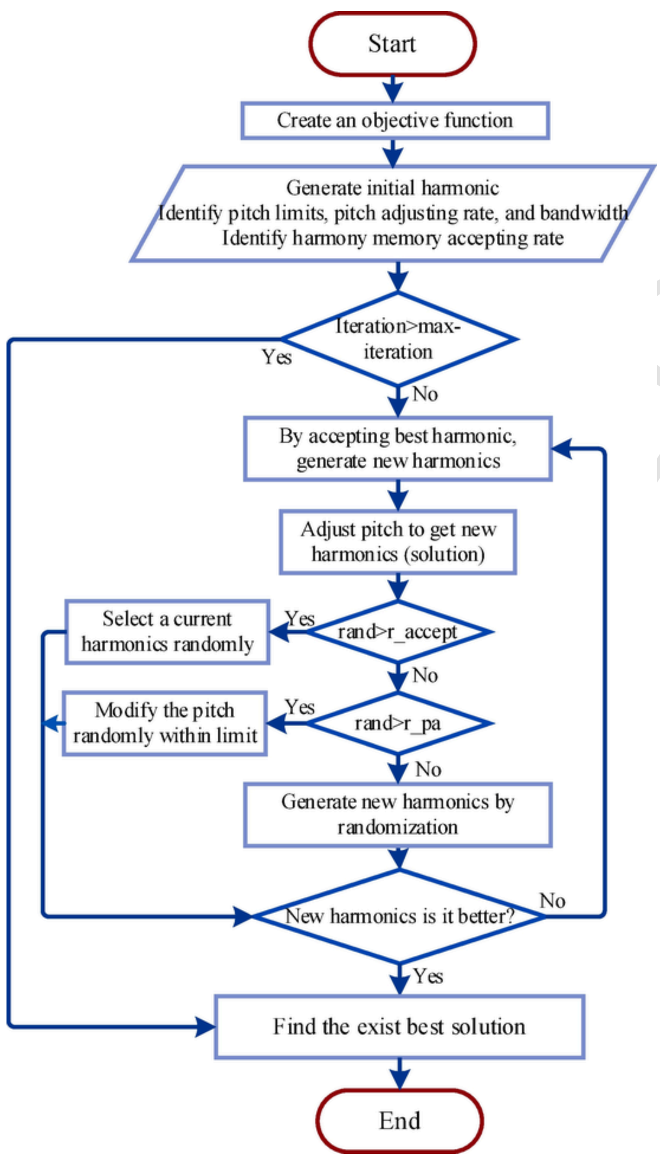

Fig. 11. Basic structure of HSA.

6.3. Artificial neural network (ANN)

ANN is utilised in different aspects of MG control. For example, ANN is employed to reduce the environmental effect of MG and the operation price by considering the pre-operational variables to be future availabilities for RESs and load demand (Chaouachi et al., 2013). Madureira and Lopes (2009) demonstrated the excellent performance of the ANN optimisation control of coordinated voltage support at grid distribution networks associated with large-scale MGs. The ANN was also used to enhance the generated power in solar PV systems associated with MG. A previous study by Elobaid et al. (2015) reviewed and compared various works regarding the enhancement of the power produced by PV systems. The results showed that ANN provided a more satisfactory performance than those of other artificial intelligence-based approaches. ANN was also utilised to control the power exchange between hybrid DC/AC MG and utility grid at PCC as introduced in Chettibi et al. (2018). Their results demonstrated the high robustness and effectiveness of the introduced control strategy. Another study proposed a novel utilisation of ANN to discover faults and determine their location in MG. This study demonstrated that the ANN has a fast and accurate detection of faults (Yang, Q. et al., 2016). The ANN was further used in islanded MG for forecasting, energy management, reduction of power purchased from the main electrical grid and accurate power sharing (Nagapurkar and Smith, 2019; Vigneysh and Kumarappan, 2016).

6.4. Adaptive neuro-fuzzy inference system (ANFIS)

Over recent years, the ANFIS has been used in different control and optimisation processes related to MG. Shokoohi et al. (2013) applied ANFIS to decrease the frequency and voltage deviations in MG systems under drastic load changes. Their results indicated that this ANFIS can minimise the voltage–frequency deviations and maintain system stability regardless of the severity of load deviations or MG structure. The work of Elena Dragomir et al. (2015) revealed the impact of ANFIS in controlling and predicting the power produced from RESs integrated with MG. Authors in [54] studied the short-term prediction of the generated power from wind systems in MGs in Beijing. In their study, the test of the ANFIS strategy was based on practical data of wind power generation and weather conditions. Their results demonstrated that the proposed approach has an accurate prediction, accuracy and reliability. Renduchintala and Chengzong (2016) tested the power quality enhancement of grid-connected MG using the ANFIS technique. They found that the suggested control could reduce frequency variation and minimise the harmonics in the load current and the grid voltage. Overall, ANFIS is more useful than other optimisation controllers, such as generalised droop control.

6.5. Tabu search algorithm (TSA)

The TSA considers an efficient search optimisation technique in treating classical problems. TSA is similar to the human memory process. By using a tabu list, the solution regularly moves to the best assessment function value that could memorise seek histories. In case a possible solution has been formerly penetrated inside a specific brief time duration, this solution is marked as ‘tabu’ to forbidden potential and repeated. The TSA starts with a random answer convinced to the constraints similar to the preliminary of GA and PSO. A new candidate schedule is then provided to discover the best answer after creating neighbourhood solutions for brand spanking. A standard flowchart of TSA is shown in Fig. 12 (Glover et al., 1993).

TSA has recently demonstrated its value in many applications, including MG control. Takeuchi et al. (2012) introduced TSA based on the optimal scheduling of MG, which comprises different fuel cells types, batteries and solar PV located in Japan. They also compared TSA and GA optimisation methods and found that the TSA can secure highly precise solutions despite its dependence on the initial solution. Khamsawang et al. (2002) revealed the impact of TSA in economic dispatch optimisation. The TSA result was compared with that of other conventional techniques; TSA demonstrated a good performance. Moosavian et al. (2016) applied the optimisation of economic dispatch (ED) problem using TSA considering non-smooth cost functions. The accuracy of their results emphasised that the TSA could be an effective tool for power system optimisation. Based on the literature, the use of TSA in MG control optimisation produces a higher accuracy than that of other algorithms despite its low search space.

6.6. Genetic algorithm (GA)

GA was firstly introduced by Holland to understand the adaptive process of the natural system. This algorithm is a technique for solving optimisation problems by applying a series of crossover, mutation and evaluation of fitness to multiple chromosomes. GA can be called as optimisation via systemically random search method because it starts with a ‘random solution’. The solution suggested by GA is common because the problem itself may have more than one solution. The GA solves difficult or impossible problems by providing the optimal solution (Kramer, 2017).

Fig. 13 shows the process of GA. The algorithm starts with the creation of a random initial population. Next, fitness values for each population (chromosome) are calculated on the basis of the strength of each chromosome. The parent selection process is then performed to se-

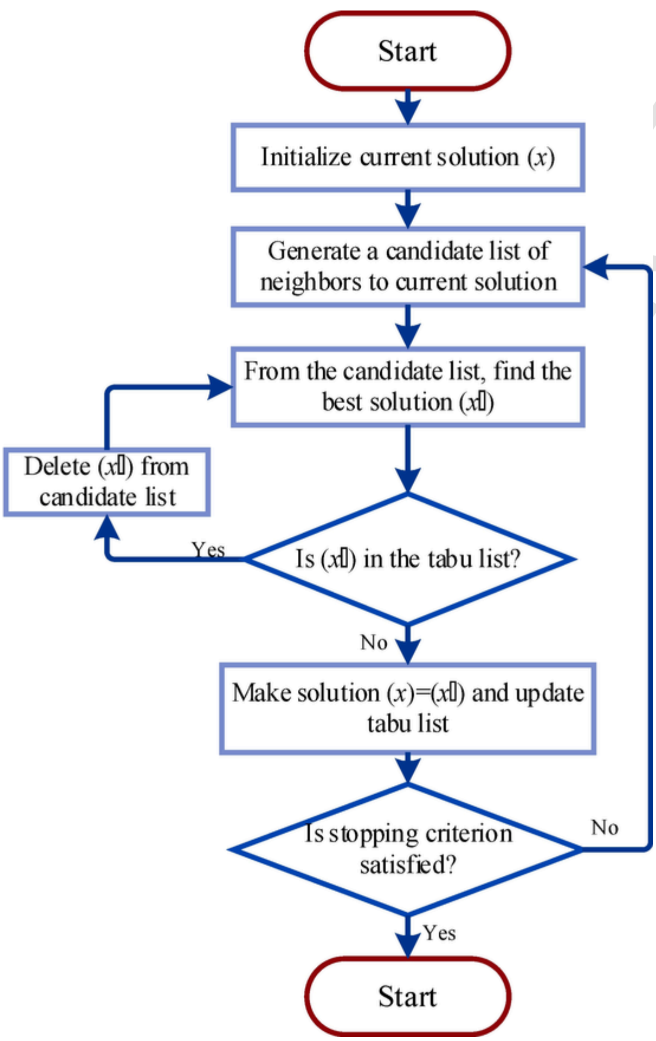

Fig. 12. Standard flowchart of TSA.

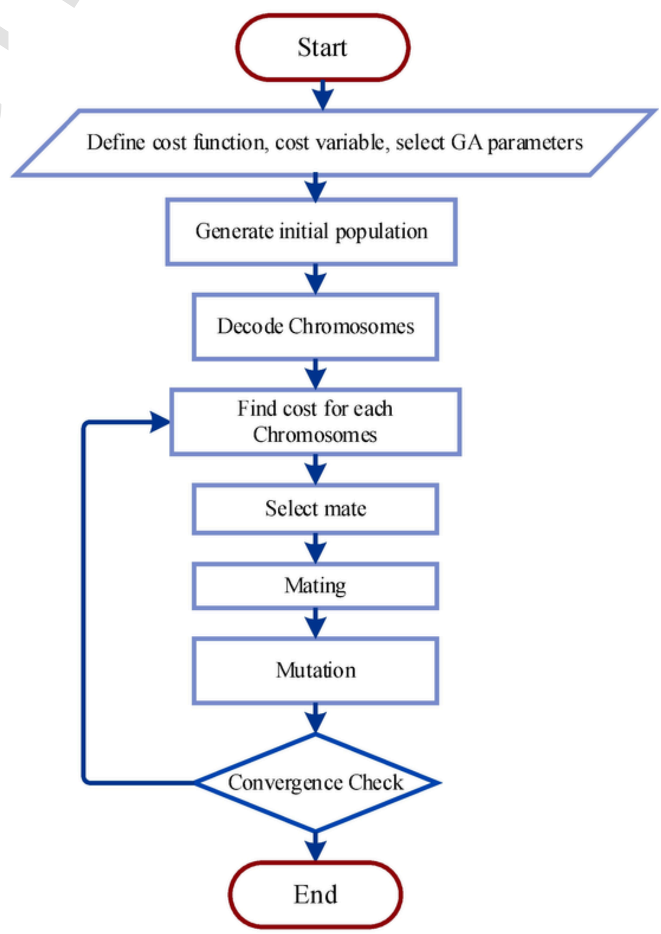

Fig. 13. General structure of GA.

lect the strong parent chromosome to undergo mutation of offspring. The step is repeated until the optimal solution is finally achieved (Kramer, 2017).

The GA-based controller is widely used in MG application because it can obtain optimal solutions. Abbes et al. (2012) proposed a non-dominated storing GA approach to maximise the reliability of hybrid WT and PV with the energy storage system. The results demonstrated that the GA has acceptable efficiency to increase MG stability but was accompanied by slow convergence. Mohamed et al. (2019) used GA to create an efficient planning algorithm for hybrid remote MGs and ensure reliable and smooth operation of the system. Their study revealed good planning, which led to substantial cost reduction compared with TSA. Mohamed and Koivo (2012) introduced online management GA of MGs to ensure safety of the system and minimisation of the cost function to satisfy customer demand.

6.7. PSO

PSO is a stochastic optimisation-based metaheuristic optimisation technique. This algorithm was firstly discovered by Kennedy et al., in 1995 and was inspired by the movement of organisms, such as fish schooling and bird flocking (Marini and Walczak, 2015). PSO uses a velocity vector to upgrade the existing position of every particle in the swarm. According to the social behaviour of a population of individuals, the position of each particle is updated and adapted to its environment by returning to the previously discovered promising regions. The knowledge gaining process of the swarm is stochastic in nature and utilises the memory of the particle (Al-Saedi et al., 2017a,b). Fig. 14 illustrates the flow chart of the PSO algorithm. The procedure for PSO search can be summarised as follows (Marini and Walczak, 2015).

1. A random particle is initialised during the space design.
2. The velocity vector is calculated for every particle in the swarm based on the corresponding constraints.
3. The position of every particle is updated using the velocity vector based on the particle's previous location.
4. Steps 2 and 3 are repeated until convergence is realised.

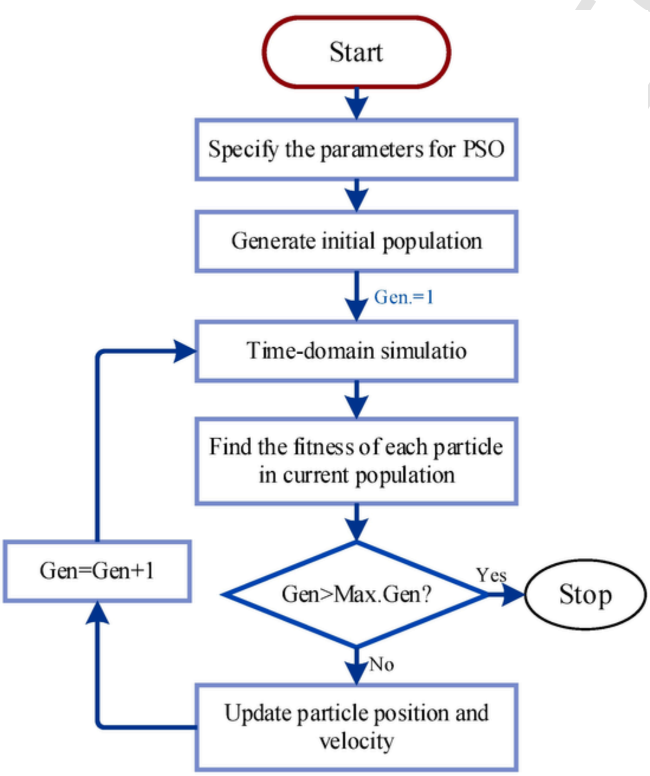

Fig. 14. Flowchart of the PSO algorithm.

PSO is simple, easy to implement and possesses a few tuning parameters. In addition, this algorithm consumes low computational time and has efficient memory capacity, thus allowing the retainment of the neighbourhood best position and its own previous best position (Al-Saedi et al., 2017a,b). PSO is widely used in different applications, such as mathematical problems, vehicle application, automatic control systems and power system applications, as reviewed by Zhang et al. (2015). They concluded that adaption, modification and hybridisation of the conventional PSO would increase its efficiency. PSO is also utilised in MG applications. Al-Saedi (201) introduced the PSO method to improve the power quality in MGs. The results showed the satisfactory performance of the PSO algorithm in controlling the frequency and voltage in MG, especially the harmonic reduction. Borhanazad et al. (2014) adopted multi-objective PSO (MOPSO) to determine the best configuration for the hybrid MG (HMG) systems and for sources sizing (e.g. PV, wind, diesel generator and battery). MOPSO is also used in a case study in Sweden to identify the optimal system configuration to control different component operations of the system after feeding the load (Hlal et al., 2019). The results of the two aforementioned studies depended on the modification of the traditional PSO to overcome the difficulty in determining suitable initial design parameters. Power management in MGs utilised PI controllers tuned by PSO to ensure a good response of the system between MG and grid sources (Malathi and Saravanan, 2017). The results demonstrated that the PI controller optimisation based on PSO can improve the control operation. In the power sector, economic load dispatch is essential in supplying electricity at a low cost whilst obtaining profit. Sheeba and Jayaraju (2017) adopted PSO to achieve these requirements. Their findings proved that after considering transmission losses, PSO delivered a more satisfactory result than that of the Lambda iteration method. In the case of the latter, the number of iterations for convergence increased. By contrast, the number of iterations in the former is unaffected when the transmission line losses are considered. Dynamic dispatch optimisation-based PSO algorithm is implemented for MG systems to reduce the operation cost and maximise the environmental profit by utilising renewable energies as reported in (Nikmehr and Ravadanegh, 2015; Nivedha et al., 2018). Although PSO can reduce the cost and GHG emission, this algorithm easily falls into a local optimum in high-dimensional space and has a low convergence rate during the iterative process. Therefore, the hybridisation and adoption of this algorithm will be beneficial to overcome these limitations.

6.8. Grey wolf optimisation (GWO)

GWO, which was introduced by Faris et al. was formulated from the hunting strategy and the social hierarchy of grey wolves (Faris et al., 2018). The social hierarchy leader of the grey wolves is known as the alpha, followed by the beta wolves, which help the alpha in decision-making. The next level in the hierarchy is occupied by the delta wolves, which follow the instructions of the alpha and beta wolves and lead the omega wolves. The omega wolves rank the lowest in the hierarchy and must obey all the instructions of the dominant wolves (Luo et al., 2019).

The social hierarchy of grey wolves can be mathematically modelled as follows: (*a*) selecting and considering the best fitness solution as the alpha (α); (*b*) considering the second- and third-best solutions as the beta (β) and the delta (δ) wolves, respectively; and (c) the remaining fitness solutions will be considered the omega (ω) wolves (Faris et al., 2018). Fig. 15 presents the general operation procedure of the GWO method (Zhang et al., 2017).

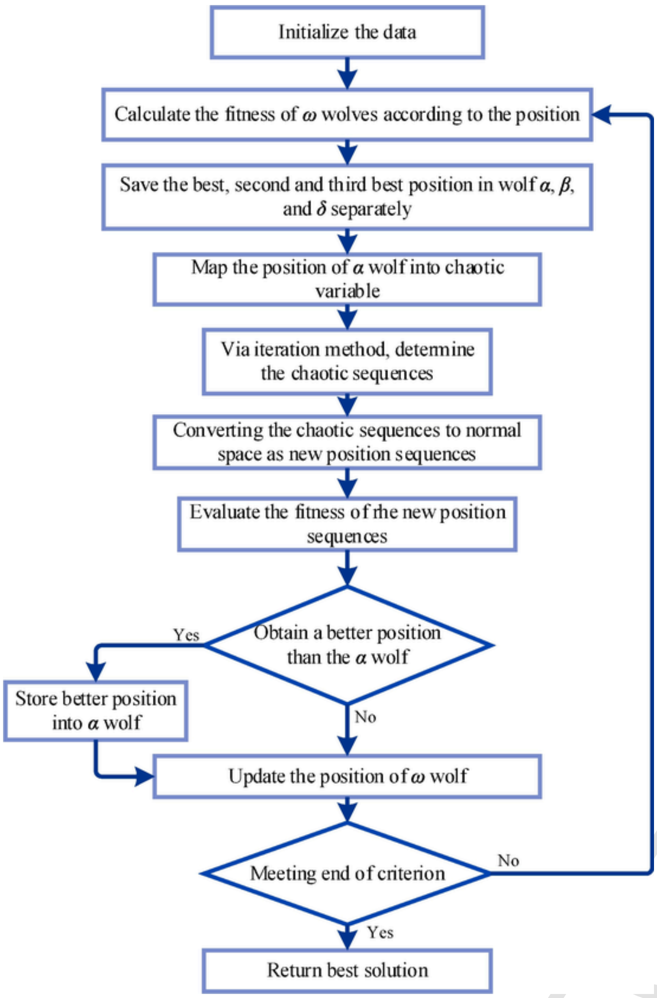

Fig. 15. Flowchart of the GWO

The GWO algorithm can generally be applied to reduce the operation cost in MGs and optimise the size of the renewable energy system and the battery energy storage. Kamboj et al. (2016) proposed an optimisation solution for non-convex and dynamic load dispatch of the power system using the GWO algorithm. Their method reduced the total fuel cost and transmission losses and then facilitated convergence to a high-quality near-optimal solution. Similarly, GWO is used in the size optimisation of energy storage systems to minimise the operation cost of MGs under different conditions. GWO produced a good solution quality (5%), improved convergence speed and high robustness of up to 93.33% in solving cost minimisation problems (Sharma et al., 2016). GWO-based optimal energy management and sizing of the batteries for grid-connected MG minimised the operation costs of MGs by 33.185% compared with GA, OSI, BA and IBA (Nimma et al., 2018). Zhang et al. (2018) proposed a GWO strategy based on the dynamic adjustment for the proportional weight and presented a convergence factor to enhance the operating model of the distribution network. The presented optimiser controller-based GWO enhanced the voltage stability and economic benefits of the network and simultaneously minimised the active power loss of the system. However, the poor local searching capability of the GWO must be improved. Table 4 compares the most popular optimisation algorithms to achieve an objective function concerning RES aggregation in MGs.

6.9. Additional control optimisation methods used in MG

Table 5 presents some additional optimisation methods that are used to optimise the controller of RESs in terms of MG application. Several of these optimisation strategies can obtain better solutions than those of the above-mentioned algorithms.

6.10. Analytical optimisation methods

Most of the popular machine learning and heuristic optimisation methods used are discussed above to solve many complex problems concerning RESs integration into MG. Meanwhile, the literature on the usage of analytical techniques is lacking compared with the first two techniques due to their high efficiency in MG optimisation. However, a few analytical techniques, such as rule-based optimisation (RBO) and analytic hierarchy techniques, are used for MG optimisation. RBO is an old technique that uses a set of rules to determine the execution process of a query. This technique is used for MG scheduling, which comprises PV, WT, FC, BES and diesel generator (Abdolrasol et al., 2017). The same system was later optimised using heuristic method and showed superior performance to RBO (Abdolrasol et al., 2018). For MG, the RBO hybrid with heuristic optimisation is developed to enhance its performance (Pippia et al., 2019). The results of this hybrid demonstrated improved performance of MG energy management. Rietz and Suryanarayanan (2008) comprehensively review the application of developed analytic hierarchy methods for MG planning and operation and presented a variant response. Renjit et al. (2017) proposed analytical methods to improve the frequency stability in MG. The proposed methods depend on the calculation of frequency metrics, such as initial rate-of-change and minimum value, to determine the frequency deviation. These methods were compared with other simulation studies and showed their capability to determine the frequency deviation during disturbance. Bae and Kim (2008) used an analytical technique to evaluate the reliability of MG and RESs. However, analytical models require mathematical assumptions to simplify the problem, thus leading to some errors. Moreover, these models are unable to deal with large data.

7. Issues and challenges

The current status of RES integration into MG technologies can reduce several challenges faced by the former technology, such as the type of renewable energies or the workability of the integration system. Nevertheless, the scope of enhancement of this technology for further application in MG technologies despite losing attractiveness for many researchers achieved the requirement. Recent research works focused on the sizing, placement, scheduling, safety, stability or energy management efficiency of energy in the system. Accordingly, the challenges and key issues concerning sizing and costing of RES, placement of RES, harmonisation of the integration standards, scheduling, environment impact and safety issues can be identified. The following sub-sections below present an overview of these key issues along with some selective recommendations.

7.1. Sizing and costing of RES

The cost and size of different RES technologies are substantially high. In case of size increase, the cost also increases, as presented in various studies on solar panel, wind turbine, biomass, ESS system and distributed generator; the size is also influenced by the power and energy ratings (Ahmad and Alam, 2018; Flores and Brouwer, 2018; Li et al., 2012; Nimma et al., 2018; Sharma et al., 2016). Most of these studies confirmed that the oversized RES will increase the cost; thus, optimal sizing is important. In this regard, Nimma et al. (2018)

Table 4
Technical comparison of the commonly used optimisation strategies for the integration of RESs into MG.

Method	Objective function	Performance	Advantage	Disadvantage	Ref.
FLC	Scheduling	-Complex design and implementation.	-No mathematical model is required. -Suitable scheduling leads to operating cost reduction.	-Not always accurate. -The results are perceived based on assumption. -In scheduling, not tested in the case of MG-connected grid mode.	Fossati et al. (2015)
HSA	Planning	-Bound by the evolution stage, which is not always accurate.	-Reduced cost via best planning compared with ANFIS. -Few adjustable parameters.	-Few RESs considered (only PV and BES). -Premature convergence. -Inaccurate in multimodal and high-dimensional functions.	Jiao et al. (2017)
ANN	Power sharing and cost reduction	-Easy design and implementation. -Excellent prediction.	-Minimised the energy purchased from the electrical grid under different operating conditions. -No mathematical model is needed. -No restrictive assumptions are needed.	-Weather condition not considered. -Stability is not guaranteed. -Requires careful selection of size and structure.	Chettibi et al. (2018)
ANFIS	Voltage and frequency stability	-Moderately complex design and implementation.	-Achieved the balance between consumption and generation, thus reducing voltage–frequency fluctuation. -No mathematical model is required. -Rapid learning capacity.	-No grid connection to MG to achieve accurate results, especially in terms of stability. -Unsatisfactory when dealing with problems with large inputs. -Training complexity.	Shokoohi et al. (2013)
TSA	Optimal scheduling	-Lower efficiency compared with GA.	-Highly precise solution was obtained within a short computation time. -Optimal scheduling was achieved, which reduced CO_2 emission and cost.	-In some cases, the solution was trapped in a local minimum. -Slow convergence.	Takeuchi et al. (2012)
GA	Planning and sizing	-Easy to implement. -Excellent performance.	-More efficient than TSA. -Obtained fit solutions in a short time. -Wide range of solutions.	-Not always accurate. -Difficulty in parameter selection.	Mohamed et al. (2019)
PSO	-Sizing -Scheduling	-Robust. -Simple to implement.	-Fast convergence. -High probability in finding the optimum solution.	Difficulty in finding the initial design parameters.	(Hlal et al., 2019; Sheeba and Jayaraju, 2017)
GWO	Sizing	-High performance; -Low computation time.	-Fast searching and initialisation. -High efficiency in MG sizing and higher cost reduction compared with that of PSO, GO and BA.	Poor local searching capability.	Sharma et al. (2016)

proposed GWO to find the optimal size of MG sources. Their results were compared with those of other existing methods, namely, GA, BA and PSO. Their results showed that the smart sizing using GWO minimised the operational costs by 33.185%. Bahmani-Firouzi and Azizipanah-Abarghooee (2014) utilised the improved bat algorithm to attain optimal size of BES in MG containing FC, PV, WT and MT. The following three cases were investigated: without BES, with BES and with BES with full initial charge. The results showed that installing an optimal size of 150 kW/h BES without initial charge will decrease the cost by approximately 40% per day compared with the MG without BES. In addition, installing an optimal size of 250 kW/h BES with an initial charge of 250 kW/h will decrease the cost by approximately 15% per day compared with the MG comprising an optimal size of 150 kW/h BES without initial charge. Isolated MG comprising PV, WT, diesel generator and battery with different operation scenarios demonstrated that the most cost-effective scenario was the combination of PV–WT–battery, which attained the lowest cost (0.21 €/kWh) (Dufo-López et al., 2016). In terms of power cost from the PV system, the following example is presented: the cost of power in Yemen is 0.266 $/kWh, which is higher than Oman (0.21 $/kWh) and lower than Palestine (0.662$/kWh) with the same system application (Al-Shetwi et al., 2016). The cost of the RESs usually comprises maintenance and installation costs. One of the important factors that must be considered in energy technology is the per-unit cost of energy. In this context, the overall cost depends on the operation cost (Khodayar et al., 2012), maintenance cost (Nazarpour et al., 2017), initial investment cost (Corso et al., 2010) and lifecycle cost (Nimma et al., 2018). These costs all affect the kWh cost. Although the cost of various RESs is high in different categories, RESs are an unavoidable source in MGs. Despite cost minimisation in some new technologies, many limitations were still observed in terms of efficiency and MG stability. Thus, with the advancement of technologies, HRES was developed to integrate additional renewable sources into one MG to achieve an efficient operation. Overall, developing a comprehensive renewable energy policy to balance the power-based RES size and simultaneously increase the reliability whilst reducing the cost would be a major challenge in future MG systems.

7.2. RESs placement

Placements are the most important criteria for RESs integration in MG. Placement of RESs determines their reliability in the system. Several development strategies for RES placement, such as mathematical modelling and mixed-integer nonlinear programming (MINLP) optimal methods, have been discussed in different studies (Dawoud et al., 2017; Kaur et al., 2014; Nazarpour et al., 2017). However, the placement choice is not optimum in most cases (Nazarpour et al., 2017). For further development of RESs integration in MG application, the optimal placement of the RESs with their important contributions must be addressed. Sizing, capacity, reliability and energy storage system can be considerably influenced by the placement of the RES in MG. Consequently, in MG application, a cost-effective long-term advanced technology may guide the placement development of RESs with enhanced reliability and stability.

Table 5
Additional control optimisation methods used in MG.

Optimisation method	Purpose of optimised controller	Outcomes	Refs.
Ant Colony Optimisation (ACO)	- Optimum energy management.	- MG performance is enhanced. - Significant reduction in the cost. - Cost reduction was around 20% and 5% in comparison with traditional energy management methods and PSO, respectively.	Marzband et al. (2016)
	- Power flow control optimisation.	- Equal sharing of load power between MG and power grid.	Sellamna et al. (2018)
	- Optimal sizing of hybrid MG (WT, PV and battery).	- Decreased annual cost. - Increased system reliability. - Addressed the loss of power supply probability.	(Dong et al., 2016)
Cuckoo Search (CS) Algorithm	- Attain a proper sharing of active power between different DGs in MGs.	- Organised power sharing of DGs. - Output power of DGs is optimised in terms of settling time and overshooting.	Raghami et al. (2015)
Bacterial Foraging Optimisation (BFO)	- Optimise the dynamic performance of MGs.	- Improved MG dynamic performance. - Minimised harmonic reference content. - Enhanced voltage profile, power factor and power quality.	Othman and Gabbar (2017)
	- Parameter extraction of solar PV modules.	- Efficient extraction of module parameters. - More accurate than PSO in parameter extraction.	Subudhi and Pradhan (2018)
Teaching–Learning Based Optimisation (TLBO)	- Power management in MGs with six different types of RESs.	- Attained precise results concerning power management.	Collins and Ramachandran (2017)
	- Optimal energy dispatch for island and grid-connected modes.	- Faster in finding the best solution with low operation cost than that of GA and PSO.	Tavakoli et al. (2018)
	- Optimal operational scheduling for RESs integration into MG.	- Minimised 24/h operation cost. - Specified optimal scheduling of RESs and load control.	Kasaei et al. (2017)
Pigeon-Inspired Optimisation (PIO)	- Optimal sizing of hybrid PV/wind/battery-connected MGs.	- Increased reliability. - Provided healthy charging of the battery - Wind/battery was more costly than PV/wind/battery system	Mahesh and Sandhu (2016)
Artificial Bee Colony (ABC)	- Energy management optimisation.	- Achieved an optimal scheduling dispatch of MGs. - ABC diversity of solutions improved the quality of results	Lin et al. (2016)

Table 5 (*Continued*)

Optimisation method	Purpose of optimised controller	Outcomes	Refs.
	- Optimal sizing of GGs in AC/DC hybrid MGs.	- Cost reduction by around 30%. - Increased convergence speed. - Notable enhancement in terms of accuracy and efficiency.	Marzband et al. (2017)
Shuffled Frog Leaping Algorithm (SFLA)	- Optimisation of environmental ED with heat in RESs.	- Solved the emission and economic dispatch as well as combined heat problems. - More efficient than heuristic and non-heuristic optimisation techniques.	Elattar (2019)
	- Improving the load controllability and priority for islanding of MGs.	- Controlled the loads, line capacity constraints and bus voltage during islanding. - Increased the system reliably.	Oboudi et al. (2016)
Differential Evolution (DE)	- Voltage and frequency control.	- Enhanced the quality of delivered power to the utility grid by RESs. - Demonstrated remarkable response of voltage and frequency control with less harmonic distortion at PCC. - Obtained a short transient time.	Srinivas and Ram (2018)
	- Optimal sizing of wind/diesel/PV hybrid MGs.	- Presented some of the design solutions for the hybrid MG to provide reliable power supply. - Regulated diesel generation to operate within normal range.	Ramli et al. (2018)
Coral Reef Optimisation (CRO)	Optimal design and placement of RESs in MGs.	- Improved the capability to provide good solutions in terms of placement. - Reduced the power losses by approximately 23% compared with HAS. - Enhanced the MG topology design.	Jiménez-Fernández et al. (2019)

7.3. Scheduling

Optimisation of RESs output power distribution in MG applications could be achieved by scheduling the load and RES (Abdolrasol et al., 2018; Liu et al., 2018; Lu et al., 2018; Zhao et al., 2014). Several RESs, such as PV, WT, tidal, biomass, ESS and DG, can be modelled for different scales for energy management. For efficient scheduling, control of the load shading and overall system loss reduction would play an essential role in reserve maintenance for future demand and efficiency optimisation of MGs (Javidsharifi et al., 2018). Moreover, power fluctuation can be controlled by scheduling the load or RES. Hence, the limits of the maximum active power changing rate and power quality can be improved. Thus, MG application with stable and reliable properties can be optimised by scheduling the load and RES, improving the overall efficiency and minimising the total costs.

7.4. Environmental impact

Based on the current study, environmental impact has proven that the emission of GHGs or other kinds of toxic emission will drop by increasing the energy production based on RES (Li et al., 2018). The combustion of fossil fuels, recyclable materials, magnetic fields and chemicals during the manufacturing of the PV panel and the energy storage will lead to environmental hazards. HRES can integrate the intermittence of RESs in MG and reduce the fuel consumption and emissions of GHGs (Abdolrasol et al., 2018). Although fully utilising RES is overpriced, researchers aim to minimise the operation, maintenance and initial investment costs of RESs for sustainable development.

7.5. RESs safety issues

The safety of RES is necessary for the MG application. The awareness of people regarding safety has strengthened in recent years. For secure and safe operations, numerous factors, such as location of the RES, type of material using RES, grid faults and disturbances, overloading and insufficient power of RES, must be efficiently addressed (Papaspiliotopoulos et al., 2017). The intermittency and uncertainty of the mean-field system can be minimised by the process. Consequently, an effort should be made by the researchers to solve these problems and contribute to making the MG highly user-friendly.

7.6. Islanding in MG

At the distribution level, the DGs should be directly disconnected from the grid once the fault is detected. This action has been imposed to prevent islanding. The islanding is a scenario that occurs in case part of the network is disconnected from the electrical grid but still energised by one or more DGs (Oboudi et al., 2016). This phenomenon can cause the following issues: (*a*) safety problems due to the unexpected partly energised network, (*b*) damage to the equipment due to the out-of-phase re-closure problems and (c) lack of control for voltage levels and system frequency. Furthermore, the disconnection will cause large amounts of power due to the high integration of DRESs, thus leading to stability and security problems (Ustun et al., 2011). Therefore, this issue remains a challenge for power system operators.

7.7. Harmonisation of RESs integration standards

The standards concerning RESs integration have some differences. Thus, realising a specific economical or technical justification of the existing integration standards is difficult. This difference is due to the dissimilar operational method, control system and penetration levels of the RESs in different locations worldwide. European renewable energy council EREC (Re-thinking, 2015, 2015) urges the system operators to improve new integration standards harmonically. The harmonisation of the integration standards will help the power system operators to share experiences and assist manufacturers and developers to internationalise their items and consequently decrease the cost of RESs. Global harmonisation of RESs standards would achieve the following goals: (*a*) creation of proper guidelines for the integration of RES in MG; (*b*) improvement of efficient standards based on various experiences and backgrounds of operators; (*c*) reduction of the cost; and (*d*) realisation of a win-win situation for RES manufacturers and power system operators.

7.8. MG controls

Based on the literature and RESs reports (Re-thinking, 2015, 2015; Renewable energy policy network, 2018), integration and installations of MG into the distribution systems will extensively grow in the future. Therefore, distribution systems associated with MG can have different characteristics from the current traditional system. This difference might be crucial with an expanded number of MGs. Hence, appropriate control techniques must be designed to anticipate the difference (Salam et al., 2008). Moreover, the controllers of MG must optimise the system operation, power management, consumption and production of electricity, gas and heat to enhance the overall efficiency. Furthermore, limited communication and probability of conflicting requirements may emerge due to the various characteristics of controlling different numbers of energy sources. Moreover, the simultaneous involvement of a large number of sources in MG can cause severe frequency and voltage control problems due to the switching from island mode to grid-connected mode, causing mismatches between loads and generation (Luo et al., 2019).

7.9. Ancillary services

Many grid codes have recently required the RESs to act similar to a conventional power plant by supporting the grid during fault events or disturbances. Currently, the RESs should be separated compared with the main grid in the event of disturbances (Sadeghkhani et al., 2018). However, due to the high integration of RESs into the utility grid, the disconnection of these sources at the grid disturbances will lead to large portions of generated power loss. Therefore, many new grid codes impose the RESs to remain in connection mode during disturbance and support the grid and voltage stability. These ancillary services include voltage and frequency regulations and high and low fault-ride through active and reactive power support requirements (Al-Shetwi et al., 2016). In addition, the traditional ancillary services related to power quality, such as harmonics, voltage unbalance and reactive power, are available (Neukirchner et al., 2017). Consequently, the application of these new regulations remains a challenge and needs considerable attention from RESs manufacturers and power system operators.

8. Conclusion and recommendations

The exponential growth of global energy consumption is the main culprit that causes the high usage of fossil fuel and high emission of GHGs. These issues have prompted extensive research on RESs to replace conventional fossil fuels in the power industry and minimise environmental problems. In this regard, MG, which comprises multiple RESs, is an alternative energy system that can be used to fulfil the energy needs in the future. MG systems operate autonomously; accordingly, these systems need a complex control system to improve its operation. Therefore, many research studies have introduced artificial intelligence for control optimisation in MGs to supply an efficient, secure, reliable and sustainable power to the customers. Therefore, this study reviewed, discussed and highlighted different optimised controllers for RESs integrated into MG. The architecture, operation, characteristic, current status, pros and cons of these optimised controllers have been discussed to present a comprehensive overview to guarantee the sustainability of MG systems in the future. Despite many studies on the MG intelligent optimised controller were presented, the vast majority of these studies are restricted to simulation analysis and are not expanded to experimental setup or real-time application. Therefore, simulation optimisation must be validated with an actual-time application or experimental setup. Moreover, the paper analysed RESs optimisation constraints to find a suitable solution for efficient MG energy systems. In this context, the suitable optimisation method applied for sizing was the GWO based on the review. The best cost reduction for MG containing multiple RESs was obtained using binary BSA. In addition, this technique achieved the lowest emission by the optimal sharing of RESs output power. By contrast, GA was the best in scheduling, SFLA showed the best performance in islanding detection to decrease the number of islanded MGs and MINLP for placement, whilst HAS and PSO are efficient for planning. However, the performance may vary based on different factors, such as the size, type and number of RESs integrated into the MG, weather condition and uncertainty conductions. Furthermore, issues and challenges concerning RESs integrated to MGs have been discussed to tailor to the purpose of the current research properly and significantly add to the existing literature with regard to the research trends in the field.

From this review, several significant and selective recommendations for further improvement related to the integration of RESs and MG intelligent optimised controller techniques are summarised as follows:

- Hybrid optimisation techniques (i.e. ANN-based PSO) can be developed towards sustainable power operation and smart grid to achieve optimal scheduling, design, power sharing and emission reduction.
- Further research on heuristic methods based on multi-objective optimisation and parallel processing could be promising research areas in the field of renewable and sustainable energy.
- Further research on optimisation of MG containing RES, non-RES such as diesel generators and BES in the case of MG connected to the main grid is important to achieve optimal power sharing between the sources based on weather condition, load and fuel type.
- Optimisation techniques, such as PSO, GA and has, are used as improved existing techniques to attain best sizing and scheduling in MG. However, these algorithms have the limitation of complex parameter calculation or formulation, coding difficulties and long computational time in finding the best fitness value. Therefore, advance research can be conducted to address these issues.
- In the literature, a new binary optimisation method is recently developed to solve complex problems under uncertainty conditions. Therefore, further research on binary methods can be developed for current techniques (i.e binary PSO (BPSO)) to attain best sizing, emission reduction and power sharing in MG systems.
- A generalised validation and benchmark method for sizing, placement and scheduling, along with weather estimation method under various uncertainties, is necessary.

The recommendations provided above could be key contributors in the direction of the optimisation, maturity and development of RESs integrated into MG systems, which are expected to dominate the power market in the near future. Thus, further research based on this review might also address the disadvantages of current MGs with regard to the future development of control optimisation and RESs integration.

Yang et al., 2016aAl-Shetwi and Sujod, 2018

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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