RESEARCH ARTICLE-ELECTRICAL ENGINEERING

Optimal Economic Dispatch to Minimize Load Shedding and Operation Cost for Networked Microgrids

Khaldon Ahmed Qaid[1] · Aziah Khamis[1] · Chin Kim Gan[1]

Abstract

In this paper, an optimal economic dispatch model is proposed for networked microgrids in normal and contingency operations using particle swarm optimization. To solve the optimal economic dispatch problem, a summation of two objective functions is formulated, which is to minimize the amount of load to be shed and operation cost of the networked microgrids. The performance of the proposed optimal economic dispatch model was evaluated for several scenarios in independent and networked modes based on two IEEE 9-bus test systems. An analytical model based on optimal power flow was developed to identify the optimal buses of the microgrids that should be linked to form the networked microgrids. The results indicate that the proposed model minimizes the operation cost by up to 2.8% and minimizes the amount of load to be shed by up to 5.6% of the networked microgrids. Moreover, the findings show that the operation of the microgrids is more favorable when the microgrids operate in networked mode compared with that when the microgrids work independently, and the cooperation strategy for power sharing significantly reduces the amount of load to be shed for the microgrids.

1 Introduction

Microgrids (MGs) are integrated electrical distribution networks that generally consist of generators, transformers, loads, feeders, as well as other electrical components installed on-site. MGs can be regarded as isolated distribution systems where the main grid is not accessible [1]. When two or more MGs are connected (networked), it is expected that the system reliability will increase. This is driven by the diversity of loads and unutilized margin of generation assets available in the respective MGs [2]. In terms of the operation mode, MGs can be classified into independent and networked modes [3, 4]. Networked MGs are defined as the interconnection of two or more MGs via a tie line to share power between them. Networked MGs offer an economic, more effective, and resilient replacement to conventional independent MGs [5]. The economic dispatch of networked MGs is typically modelled as a non-linear optimization problem [6]. There

are several mathematical optimization techniques commonly used to solve this problem, including sequential quadratic optimization [7], interior-point method [8], and mixed integer programming [9]. Intelligent heuristic algorithms such as genetic algorithm (GA) [10] and particle swarm optimization (PSO) [11] are also often used. In the literature, there are two types of energy management system (EMS) used to monitor and control the flow of energy within the off-grid MGs, namely, centralized and decentralized EMS [12]. By treating each MG as an autonomous agent with its own operational objectives, the decentralized method addresses both the model complexity and the low computational efficiency of the centralized method. Based on the overall efficiency and reliability of networked MGs, the EMS compiles each self-scheduling record and issues adjustment orders [13, 14].

Many researchers have proposed optimal economic dispatch operation scheduling schemes for networked MGs. For instance, Hussain et al. [15] introduced a resilience-oriented approach for optimal operation of networked MGs, taking into account feasible islanding in normal operations and powering of important loads in contingency operations.

✉ Chin Kim Gan
  ckgan@utem.edu.my

1   Faculty of Electrical Engineering, Universiti Teknikal
    Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

Li et al. [16] proposed a centralized model to analyse and coordinate the economic dispatch problem of a distribution system with multiple MGs. Zhou et al. [17] made a detailed comparison between two types of economic dispatch frameworks for a distribution network with multiple MGs. By using centralized optimization, this framework can solve the economic dispatch problem of networked MGs. Meanwhile, Hussain et al. [18] proposed day-ahead scheduling of the EMS for networked MGs. The results showed that the proposed scheme was more cost-effective than conventional EMS in terms of the operation cost. Wei et al. [19] developed a rule-based metaheuristic optimization algorithm for EMS and sizing of independent MGs. The EMS of the microgrid was responsible to supply power to the various components that make up the microgrid. Ren et al. [20] proposed a software-defined networking framework. This framework can transform stand-alone MGs into networked MGs, allowing power sharing among the MGs and increasing the efficiency and robustness of the system. Zhao et al. [21] introduced a privacy-preserving decentralized economic dispatch scheme in order to optimize the EMS of the networked MGs. Bazmohammadi et al. [22] proposed a stochastic predictive control scheme for EMS operation of multi-microgrid. They examined the power sharing between the networked MGs and the main network. A hierarchical EMS strategy was developed by Bazmohammadi et al. [23] to operate and coordinate networked MGs. In this strategy, the power was shared locally between the networked MGs and externally between the networked MGs and the main grid, taking into consideration the various sources of uncertainty.

Wang et al. [24] devised a strategy for a decentralized EMS of optimally networked MGs in both off-grid and on-grid operations. Fesagandis et al. [25] proposed an outage management scheme and a decentralized planning structure for networked MGs. By applying the proposed scheme, the MGs can be scheduled separately and concurrently, and they can provide consistent power to their own loads during real-time outages. Wang and Huang [26] discussed an energy exchange model for networked MGs and its impacts on the operation cost of MGs. In this model, the networked MGs are the decision makers for the amount and cost of power sharing. The collaboration between networked MGs has been discussed by Wang and Huang [27], where each microgrid shares power with others in the distribution system. An operation mechanism based on the Nash bargaining hypothesis was used to oversee the power sharing process. Xuanyue et al. [28] proposed a multi-microgrid distributed coordinated operation model as a reference for multi-microgrid coordinated operation. In this model, the Nash bargaining method was used to assign the total operation cost. However, the network constraints were not taken into account. Cao et al. [29] formulated an objective function for the operation of networked MGs, which involved the amount of necessary power from the grid and the amount of power shared between the interconnected MGs.

In reality, the most crucial elements of networked MGs are the capacity to share and support during a contingency and the ability to continuously provide all or selected vital loads for the neighbouring MGs. Hence, the economic benefits of networked MGs cannot be realized unless optimization techniques such as PSO and GA are considered. The PSO algorithm has a chance of reaching global optimality. PSO is useful in algorithms to improve optimization and find satisfactory solutions to a given problem. Its convergence rate is fast, and the algorithm is simple to implement. PSO comes in two flavours, depending on the neighbourhood topology [30]. In the global variant, PSO employs a star-like neighbourhood topology, with each particle having the entire swarm as its neighbourhood. In this case, all particles are drawn to a global best position. The local PSO employs a ring topology, with each particle having two neighbours. As a result, each particle is drawn to the best position in the local neighbourhood [31]. Therefore, many studies employed PSO to address economic dispatch problems [32–34]. The PSO algorithm was used in [35] to determine the optimal load shedding as the last resort for balancing generation and demand. In this paper, PSO is used to solve both economic dispatch and optimal load shedding problems using the same fitness function. The optimization technique will reduce the operation costs in both normal and contingency operations to maintain the operating point balance. In addition, load shedding is represented as a penalty factor in the cost optimization function [36].

In previous studies [4, 8, 12, 21, 24], it is assumed that the MGs are networked with each other through a common bus or that the MGs are connected to the main grid. There are limited studies concerning the networking of isolated MGs in the absence of the main grid. In this paper, the MGs are assumed to be in an isolated area and the MGs are networked with each other through a tie line. Moreover, the buses used to tie the MGs together are optimally selected to ensure that the voltage of all buses is within the limits and the operation cost is minimum. Few studies have been done to propose an optimal economic dispatch operation strategy for networked MGs, taking into consideration power sharing and load shedding. In contrast to the load shedding limitations proposed by Xu and Girgis [37], in this study, there are no limitations imposed concerning which load and the amount of load to be shed. The amount of load to be shed is dependent on the amount of generated power and the maximum power capacity of the transmission lines. Most studies [24, 29, 38–40] are focused on the planning or control aspects of networked MGs, and little is known on the operation characteristics of networked MGs during contingencies. Hence, the operation of networked MGs in normal and contingency scenarios is analysed and discussed. Power sharing and load shedding of

the networked MGs during contingencies are also considered.

This article presents an optimal economic dispatch model for independent and networked MGs. A decentralized EMS strategy is used to coordinate the decision-making process in order to balance the power generation and loads of the networked MGs. A dual-layer EMS is used for the operation of the networked MGs. In normal operation, the MGs dispatch their generation resources and loads within the internal layer. In contingency operation, the MGs share power with one another within the external layer. The networked MGs and independent MGs are modelled and analysed in terms of the operation cost and amount of load to be shed. PSO is used to minimize the operation cost and amount of load to be shed simultaneously. The power shared between the networked MGs, the total operation cost, and the total load to be shed are determined. The significant contributions of the study are as follows:

- An analytic algorithm for optimal power flow is developed to identify which buses should be tied for the networked MGs.
- A PSO algorithm is developed to address the optimal economic dispatch and optimal load shedding problems simultaneously using one fitness function.
- A summation of two objective functions is formulated, which is to minimize the operation cost of the networked MGs in normal operation and minimize the amount of load to be shed in contingencies.
- A critical analysis is made regarding the operation cost, shared power, and amount of load to be shed in normal operation and contingencies.

The remainder of this article is structured as follows. Section 2 introduced concepts of networked MGs and their EMS. In Sect. 3, the mathematical model used to minimize the operation cost and amount of load to be shed is formulated. The simulation results are presented in Sect. 4 and the conclusions drawn based on the findings of this study are presented in Sect. 5.

2 Networked Microgrids Concepts

2.1 Networked Microgrids

A networked MGs system is a set of connected MGs that can exchange power to reduce operating costs and prevent load shedding, improving the system's reliability. There are three types of networked MG systems: low-voltage MGs networked through a low-voltage tie line [41], medium-voltage MGs networked through a medium-voltage feeder [42], and low-voltage MGs networked through a medium feeder and

distribution transformer [43]. A single microgrid within a networked MGs system can operate in a variety of configurations, including independent MGs, grid-connected MGs, and networked MGs. These networked MGs configurations present difficulties in power sharing and energy management of the networked MGs for all operating scenarios. The operation of networked MGs in conjunction with the distribution system enables high penetration of locally available distributed energy resources (DERs). The most efficient use of DERs can be accomplished with networked MGs [5]. If one of the MGs temporarily experiences high power generation from one of its DERs, the other neighbouring MGs can be networked together to import power and thus offer cheap electricity. After a major generator outage, networking MGs to form a networked MGs system has proven to be an effective option for improving system reliability through Power-sharing [44]. Adjacent MGs can also be networked to help each other through normal operation to reduce the levelized cost of electricity [38] or when a fault occurs, resulting in a section outage [4]. The main benefit of networked MG systems is that different MGs in neighbouring locations can be interconnected to supply larger bulk power demands, and these MGs can mutually exchange power to meet their load demands, both during grid-connected and off-grid modes of operation [45].

2.2 Energy Management System

According to the IEC 61970 standard, which relates to the EMS application program interface in power systems, the EMS is defined as a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities to assure adequate security of energy supply at a minimum cost [46]. In networked MGs, an EMS is responsible for coordinating and controlling the operation of multiple microgrids that are connected together. This coordination is necessary to ensure that the networked microgrids operate safely and efficiently, as it enables them to share power with each other to reduce load shedding [47]. A microgrid EMS typically consists of modules that perform decision-making strategies. These modules are designed to ensure that EMS decision-making strategies are implemented efficiently by delivering optimal decisions to each generation and load [48]. Microgrid EMS assigns set points for the generation units and commands to control controllable loads based on the operating conditions of microgrid components [49]. Then EMS receives information on energy generation and load demand from all local sources and determines decision strategies for each local source by optimizing various objectives [12]. According to the supervisory control architecture of MG, EMS can be classified as centralised or decentralised

[18]. In this paper, the decentralised EMS is considered to coordinate and control the networked MGs system.

2.3 Decentralized Energy Management System

Decentralized EMS is appropriate for coordinating multiple autonomous MGs and provides autonomy to each microgrid in the networked MGs system [50]. In decentralised EMSs, each microgrid is an independent entity with its own EMS that seeks to maximise profit. Each microgrid trades power with other MGs on an individual basis. Local decentralised EMSs of a microgrid can communicate with neighbouring MGs [51]. For the optimization of decentralised EMSs, each microgrid optimizes its power to maintain the power-load balance [14]. Decentralised EMSs are ideal for networked MGs systems and grid-connected MGs with a mix of fast-changing distributed generators owned by different parties [52]. Furthermore, for decentralised EMSs, extensive communication infrastructure is not required [51]. An equilibrium may exist in decentralised EMSs due to the individual objectives of different units. In normal operation cases, MGs can improve their goal by changing only their local decisions [38]. In contingency operation cases, local controllers in decentralised EMSs are aware of system-level parameters and thus are able to use them optimally [53]. Therefore, the decentralised EMS is a critical component for increasing economic benefit and maintaining the operational reliability of networked MGs.

3 Proposed Energy Management System

An EMS in a networked MG aims to control and coordinate the generation and consumption of electricity to ensure a stable and reliable power supply, operate efficiently, evaluate the economic dispatch, determine the amount of load to be shed, and enable energy trading with other MGs for secure, reliable, and cost-effective operation. Figure 1 illustrates the proposed EMS for off-gird networked MGs. The proposed system operates in a fully decentralized manner, as each microgrid autonomously optimizes its own load and generation. The microgrid then transmits its load and generation status to the EMS, which continuously monitors the energy supply and demand across the networked MGs. In case of any imbalances, the EMS efficiently optimizes the total power for each microgrid and shares it seamlessly through the power line, ensuring the energy needs of all networked MGs are met. The economic dispatch function calculates the amount of power that should be supplied by the generators to the system. This generated power is dependent on the fuel cost of the generators and the maximum and minimum power constraints of the generators. The load shedding function is used to sustain balance between the load demand and power supply in order to determine the loads that should be curtailed after each generator in the system reaches its maximum power. In contingencies, the EMS will use the power sharing function to support the MGs that are deficient in power. The shared power is dependent on the availability of power and the load curtailment of each microgrid. Networked MGs have a more economic and reliable operation than independent MGs [21], because the distributed power resources in each microgrid are optimised and the power is shared with other MGs whose power resources are unable to fulfil the load demands [20, 54]. In addition, networked MGs provide additional flexibility to manage real and reactive power imports and exports of the MGs in the EMS, which enhance reliability and resilience by sharing generation resource outputs for critical loads, thereby minimising load shedding [26, 36].

### 3.1 Economic Dispatch of Networked Microgrids

Two objectives were considered for the networked MGs, one for normal operation and the other for contingency operation. In normal operation, the objective is to reduce fuel costs by running the generators whose fuel is cheaper. In contingency operation, the objective is to improve reliability and resilience by extending the duration of electrical services to critical loads. This will reduce the operation cost, make effective use of generation resources, improve power quality, as well as enhance reliability and resiliency. The proposed optimal economic dispatch for networked MGs is a combination of both operations (normal and contingency operations), which can be formulated as Eq. (1).

$$\min C(P) = \sum_{j=1}^{m} \sum_{i=1}^{n} C_{ji}(P_{ji}) \tag{1}$$

where $C_{ji}(P_{ji})$ is the cost function for generator i connected to microgrid j, m is the total number of MGs to be networked, n is the overall number of generators, and $C(P)$ is the overall fuel cost for the networked MGs. In power system economic dispatch, the generator cost function is often represented as a quadratic function because it is a simple and convenient way to model the relationship between the cost of generating electricity and the amount of power that is generated. The cost of generating electricity typically increases as the amount of power generated increases, so the cost function is typically a convex curve. A quadratic function is a type of convex curve that can be used to accurately model this relationship over a wide range of power generation levels [55]. The cost function can be represented as a quadratic function, which is given by Eq. (2).

$$C_{ji}(P_{ji}) = a_{ji} P_{ji}^2 + b_{ji} P_{ji} + c_{ji} \tag{2}$$

Fig. 1 Proposed EMS for the networked MGs
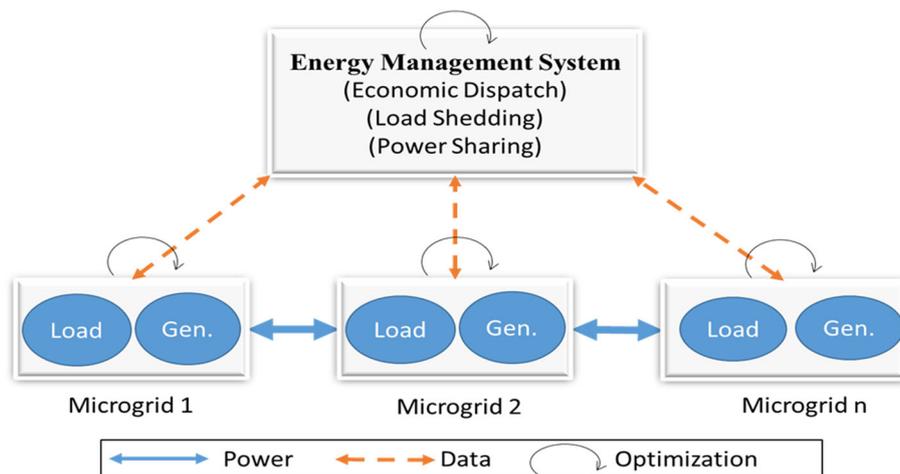
where P is the power output of the generator i in microgrid j, and a, b, and c are the cost coefficients of generator i in microgrid j. Those coefficients represent different factors that influence the cost of generating electricity and can be used to accurately model the relationship between the cost of generation and the power output of the generator. The coefficient a represents the incremental cost coefficient, which represents the increase in the cost of generating electricity as the power output increases. The coefficient b represents the linear cost coefficient, which is the cost of generating a unit of power. The coefficient c represents the fixed cost coefficient, which is the cost of operating the generator regardless of the power output. These coefficients can be used to accurately model the relationship between the cost of generating electricity and the power output of the generator. For the IEEE 9-bus case study, these coefficients are obtained from [56].

Transmission line losses in a power network are often calculated using Kron's approximated loss formula. An expression for transmission line losses in terms of source loading and a set of loss coefficients which are usually referred to as B-coefficients [57]. The B-coefficients technique is used to calculate the total transmission line loss of the networked MGs. The total transmission line loss, L_t, for the networked MGs is given by Eq. (3).

$$L_t = \sum_{i=1}^{N} \sum_{j=1}^{N} B_{ij} P_i P_j + \sum_{i=1}^{N} B_{i0} P_i + B_{00} \tag{3}$$

where B_{ij}, B_{i0}, and B_{00} are the loss coefficients (B-coefficients), which can be computed from the basic load flow evaluation for the networked MGs. Here, B_{ij} is a $N_i \times N_j$ matrix. The variable B_{00} is fixed whereas the coefficients B_{ij} and B_{i0} summarize the quadratic and linear dependence of total transmission line loss L_t on the generations. Equation (3) is known as the B matrix loss formula, and the B coefficients are called the loss factors. The B coefficients for the IEEE 9-bus transmission lines are obtained from [58].

3.2 Optimal Load Shedding of the Networked MGs

One of the strategies of networked MGs is to minimise the amount of load to be shed by sharing power between the MGs. To accomplish this, it is assumed that each load in the networked MGs is a dispatchable load, which can be entirely or partially curtailed. Therefore, to calculate the optimal load to be shed for the networked MGs, an optimal load shedding problem is formulated, which involves minimising the load shedding cost and this in turn, minimises the amount of load to be shed, D_{ji}. The optimal load shedding can be formulated as Eq. (4).

$$\min C(D) = \sum_{j=1}^{m} \sum_{i=1}^{k} C_{ji}(D_{ji}) \tag{4}$$

where k is the total number of loads and $C(D)$ is the total load shedding cost. If the available power supplies are less than the load demand, load shedding must be scheduled to maintain the power supply–demand balance and system stability. The optimal load shedding problem is designed to determine the best amount of load shedding in each load bus. In this paper, each load has been modelled as negative real power injections with high marginal costs. This is done by specifying a generator with a negative output, ranging from a minimum injection equal to the negative of the largest possible load to a maximum injection of zero [59]. The load shedding cost of networked MGs is minimised leading to minimizing the total load shedding. Therefore, the optimal load shedding solutions will prefer to fully utilize the generation resources before evoking load shedding. That means the solver will be forced to get the power from the available generators unless there is a power-demand unbalance, then the loads will be curtailed with high cost [60]. The cost function $C_{ji}(D_{ji})$ of each load i connected to microgrid j can be written as a quadratic function given by Eq. (5).

$$C_{ji}(D_{ji}) = a_{ji}D_{ji}^2 + b_{ji}D_{ji} + c_{ji} \tag{5}$$

where a, b, and c are the cost coefficients of load i in microgrid j.

3.3 Power Sharing Between the Networked MGs

During the operation of the networked MGs, power sharing occurs if one or more MGs are unbalanced in terms of load and power, and the other MGs have extra reserves. For any two networked MGs, the amount of power needed by MG A equals to the amount of power sent by MG B plus losses of the tie line. The total power shared between the networked MGs, P_{sh}, of microgrid j can be determined from Eq. (6).

$$P_{sh(j)} = \sum_{j=1}^{m} P_{t(j)} - D_{t(j)} - L_{t(j)} \tag{6}$$

where P_t, D_t, and L_t denote the total power generated, total connected load, and total transmission line loss in microgrid j, respectively. The total connected load of microgrid j is equal to the connected load added to the shed load for each load, as given by Eq. (7).

$$D_{t(j)} = D_{con(j)} + D_{Shed(j)} \tag{7}$$

where D_{con} and D_{shed} denote the connected load and shed load in microgrid j, respectively.

3.4 Operational Constraints

The optimal economic dispatch of networked MGs is subjected to several functional constraints, fuel cost restrictions, and equipment limitations. These constraints are modelled using mathematical equations, as described below.

- **Power-load balance constraint**
  The total output power of the generators must be equal to the sum of the system loads and transmission line losses. This constraint can be expressed mathematically as Eq. (8).

$$\sum_{j=1}^{m} P_{t(j)} = D_{t(j)} + L_{t(j)} \tag{8}$$

where P_t, D_t, and L_t represent the total power, total connected load, and total transmission line loss of the microgrid j, respectively.

- **Generator limits**
  The generated power (in MW) of each generator in the networked MGs is subject to the following constraint. The power output of each generator in the system must be within its minimum and maximum limits, as represented by Eq. (9).

$$P_{ji,\min} \leq P_{ji} \leq P_{ji,\max} \tag{9}$$

where $P_{\min}$ and $P_{\max}$ represent the minimum and maximum power output of the generators, respectively.

- **Line capacity limits**
  The line capacity limits within the individual MG as well as for the networked MGs are represented by Eq. (10). The tie line between the two MGs is also included. The power flow through the lines must not surpass the line rated MW.

$$-Lp_{i,\text{rated}} \leq Lp_i \leq Lp_{i,\text{rated}} \tag{10}$$

Here, $Lp_{i,\text{rated}}$ is the maximum loading capacity of line i.

- **Load shedding constraint**
  The load shedding constraint is formulated to model the lower and upper limits of the load to be shed, as given by Eq. (11). It is assumed that the load can be entirely or partially curtailed in order to obtain the optimal solution.

$$D_{ji,\min} \leq D_{ji} \leq D_{ji,\max} \tag{11}$$

Here, D_{ji} is the load i to be shed in microgrid j, $D_{ji,\max}$ is the maximum load to be shed, and $D_{ji,\min}$ is the minimum load to be shed.

3.5 Particle Swarm Optimization Algorithm

PSO is an effective population-based metaheuristic optimization algorithm. PSO promotes constructive collaboration and information sharing among all particles by learning from the local experience of each particle in order to find a global optimal solution. It distributes particles across many regions of the solution space and allows particles to exchange information in order to find global solutions in the search space. PSO has gained popularity due to it ease of use and adaptability in solving optimization problems across a wide range of domains. PSO is used in this paper to solve the fitness function, where their complementary merits are leveraged to find optimal solutions in economic dispatch and load shedding problems. In the PSO algorithm, a swarm of particles traverses search space in search of a near-globally feasible solution to the optimization problem. The best position visited by a particle is referred to as its personal best, while the best position visited by the entire swarm is referred to as the global best. Let X and V represent the particle's position and velocity in the search space. In d-dimension space, each i particle is expressed as $X_i = (X_{i(1)}, X_{i(2)}, \ldots X_{i(n)})$. The i particle remembers the best previous position, which is expressed as

$P_{\text{best}i} = (P_{\text{best}i(1)}, P_{\text{best}i(2)}, \ldots P_{\text{best}i(n)})$. The global best particle, denoted as $G_{\text{best}d}$, is the index of the particle that is best among all particles in multidimensional search space. Every particle's modified position and velocity are computed based on its current velocity and distance from $P_{\text{best}d}$ and $G_{\text{best}d}$, which can be expressed as Eqs. (12) and (13) [61].

$$V_i^{k+1} = \omega \cdot V_i^k + c_1 \cdot$$
$$rn_1 \cdot \left(P_{\text{best}}^k - X_i^k\right) + c_2 \cdot rn_2 \cdot \left(G_{\text{best}}^k - X_i^k\right) \tag{12}$$

$$X_i^{k+1} = X_i^k + V_i^{k+1} \tag{13}$$

where V_i^k is donated to velocity of particle i at iteration k, c_1 and c_2 acceleration coefficients, rn_1 and rn_2 random numbers between 0 and 1, and X_i^k position of particle i at iteration k. The velocity of the i particle must satisfy the constraint at (14).

$$V_i^{\min} \leq V_i^k \leq V_i^{\max} \tag{14}$$

The worth $V_i^{\max}$ determines the resolution with which the search space between the target position and the current position should be searched. Particles may fly past good solutions if $V_i^{\max}$ is too high. If $V_i^{\max}$ is too small, particles may not venture far enough beyond their local solutions. The constants c_1 and c_2 attract all particles to their personal best (P_{best}) and global best (G_{best}) positions. Based on previous experience, the acceleration constants c_1 and c_2 are frequently set to 2.0 [62]. Inertia weight w maintains a balance of local and global explorations. According to Eq. (15), the inertia weight factor w decreases linearly between 0.9 and 0.4 [63].

$$w^k = w_{\max} - \frac{w_{\max} - w_{\min}}{\text{iter}_{\max}} * \text{k} \tag{15}$$

where w is the inertia weight factor, k is the pointer of iterations and $\text{iter}_{\max}$ corresponds to the maximum iteration number. Using the new position X_i^{k+1}, the G_{best} and P_{best} are updated at iteration $k+1$ using the greedy selection.

3.6 Fitness Function

The main objective is to solve the optimal economic dispatch and optimal load shedding problems concurrently. These two objective functions are formulated as Eq. (16).

$$\text{FF} = \min \sum_{j=1}^{m} \sum_{i=1}^{n} C_{ji}\left(P_{ji}\right) + \min \sum_{j=1}^{m} \sum_{i=1}^{n} C_{ji}\left(D_{ji}\right) \tag{16}$$

The fitness function (FF) is the sum of the optimal economic dispatch problem Eq. (1) and the optimal load shedding problem Eq. (4). To obtain a feasible solution, both equations must be optimised simultaneously. Thus, it is hypothesised that the proposed optimal economic dispatch model will fulfil the main objective function, which is to minimise the operation cost and amount of load to be shed. This model aims to simultaneously solve the optimal economic dispatch when it is feasible and yield the optimal load shedding when it is not feasible. When the optimal economic dispatch is infeasible, the system will schedule load shedding based on the simple minimization of those two objective functions. When the optimal economic dispatch is feasible, the proposed objective function is decomposed by an additional cost to produce zero load shedding. As a result, the problem can be solved without the use of a decomposition algorithm. Solving this problem is critical to reducing computation time when the optimal economic dispatch is determined quickly and accelerating the system's response. This paper proposes the PSO optimization technique for solving the integrated optimal load shedding problem within the optimal economic dispatch. Furthermore, transmission line losses are considered in the optimal economic dispatch formulation. Numerical simulations show that the proposed method automatically generates optimal load shedding when an imbalance occurs due to generation losses.

3.7 Application of the Proposed Model on the Networked MGs

In this study, two MGs are studied, namely MG A and MG B. The optimal network connection between MG A and MG B is identified first using the MATPOWER AC optimal power flow (OPF) tool. As shown in Fig. 2, each bus in MG A is connected to all the buses in MG B to select the optimal bus to connect to each microgrid. An AC-OPF simulation is executed after each bus connection to check the convergence of the networked MGs. The best buses for connecting the two MGs are those with the lowest losses and costs. This formed networked MGs is the input network to the PSO model shown in Fig. 3. This PSO model is used to solve the optimal economic dispatch and optimal load shedding problems of networked MGs. The total number of buses, loads, generator's maximum and minimum limits, and operation cost are the inputs for the networked MGs model. The procedure of the proposed PSO is outlined in Algorithm 1. The N_i indicates the number of iterations, and the N_p indicates the number of particles. First, the fitness function, which is the total cost function from the individual cost functions of the various generators and loads, is identified. Then the PSO parameters N_i, N_p, w, c_1, and c_2 are initialised. Following that, the input cost and limits of each generator and load in the networked MGs are determined. The process starts with the population of particles, which are randomly generated and initialized, with each particle represented by position and velocity vectors. The fitness function is calculated for

each value of active power in each generator and load in the networked MGs. All values obtained in each iteration are compared to obtain the P_{best}. At each iteration, all the values of the whole population up until then are compared to obtain the G_{best}. At every step, P_{best} and G_{best} values are updated. This final value of G_{best} is the minimum cost and the active power vector for the generators and load shedding, representing the optimal economic dispatch solution.

4 Results and Discussion

4.1 Networked Test System

Two IEEE 9-bus test systems were used to evaluate and validate the proposed optimal economic dispatch model, one representing MG A and the other representing MG B. The networked test system consists of 18 buses, 6 generators, 6

Algorithm 1: Particle swarm optimization (PSO)	
01:	**Begin**, initialize the parameters: N_i, N_p, w, c_1, c_2
02:	Initialize inputs for the networked MGs: number of buses, loads, maximum and minimum limit of generators, operation cost
03:	Evaluate the optimal power flow on networked MGs
04:	Evaluate fitness of particles *f(fitness)* using equation (16)
05:	Initialize *Pbest*, *Gbest*
06:	**For** k = 1 to maximum number of iterations, N_i
07:	**For** i = 1 to maximum number of particles, N_p
08:	Update the velocity of the particles V_i^{k+1} using equation (12)
09:	Update the position of the particles X_i^{k+1} using equation (13)
10:	Evaluate the fitness of the updated position X_i^{k+1}
11:	**if** *f(fitness)* satisfies constraints in (8), (9), (10), (14) **then**,
12:	Save *f(fitness)*= f_i^k
13:	Update the personal best by:
14:	**if** $f_i^k < Pbest_i^k$ **then**,
15:	$Pbest = f_i^k$
16:	**end if**
17:	Update the global best by:
18:	**if** $Pbest_i^k < Pbest$ **then**,
19:	$Gbest = Pbest_i^k$
20:	**end if**
21:	**else** *f(fitness)* checks constraints for optimal load shedding
22:	**if** *f(fitness)* satisfies constraints in (11), (14) **then**,
23:	Save *f(fitness)* = f_i^k
24:	Update the personal best by:
25:	**if** $f_i^k < Pbest_i^k$ **then**,
26:	$Pbest = f_i^k$
27:	**end if**
28:	Update the global best by:
29:	**if** $Pbest_i^k < Pbest$ **then**,
30:	$Gbest = Pbest_i^k$
31:	**end if**
32:	**end if**
33:	**end** i
34:	Update the inertia weight factor w using equation (15)
35:	Check stopping criteria, if $k < N_i$ go to step 6, else go to next step.
36:	**end** k

transformers, 12 transmission lines, and 1 tie line, as illustrated in Fig. 4. In addition, the system consists of 6 loads, amounting to 630 MW. The optimal network connection was first identified and it was found that bus 9 of MG A should be connected to bus 18 of MG B. The fuel cost of the generators and loads used in the simulations are tabulated in Table 1. The power–fuel cost curves of generators G1, G2, and G3 are shown in Fig. 5. It shall be noted that the power–fuel cost curves of generators G4, G5, and G6 are also the same as those for generators G1, G2, and G3. To draw these curves, different power generation output MW values are assumed starting from 0 to the $P_{\max}$ of each generator. These power values are substituted in variable P in Eq. (2) and used to obtain the operation cost $C(P)$. Then the assumed power values and the obtained operation costs are plotted to show the power-fuel cost curve for each generator.

4.2 Operation Scenarios

Various operation scenarios were considered to evaluate the performance of the proposed optimal economic dispatch model for the networked MGs, as shown in Table 2. For instance, all the generators are connected to the system for the baseline case, which is considered the normal operation scenario. This scenario was chosen to demonstrate minimisation of the operation cost using the proposed model. The other scenarios were considered to evaluate the power sharing and load shedding for each MG. All operation scenarios were simulated using MATLAB for the following cases:

- Baseline case for each microgrid (MG A and MG B).
- Untied MGs (MG A and MG B work independently).
- Tied MGs (MG A and MG B are networked).

4.3 Simulation Results of the Optimal Economic Dispatch Model

4.3.1 Operation Cost

The effectiveness of the proposed optimal economic dispatch model was assessed by determining the operation cost for untied and tied MGs and the results were compared with those before optimisation, as shown in Table 3. Based on the results, it is apparent that the operation cost is lower for both untied and tied MGs after optimisation, indicating that proposed model indeed reduces the operation cost for both systems. It shall be highlighted that for tied MGs, the operation cost is minimised simultaneously whereas for the untied MGs, the operation cost is minimised separately for MG A and MG B. Figure 6 shows the convergence characteristic of the proposed optimal economic dispatch model for the tied and
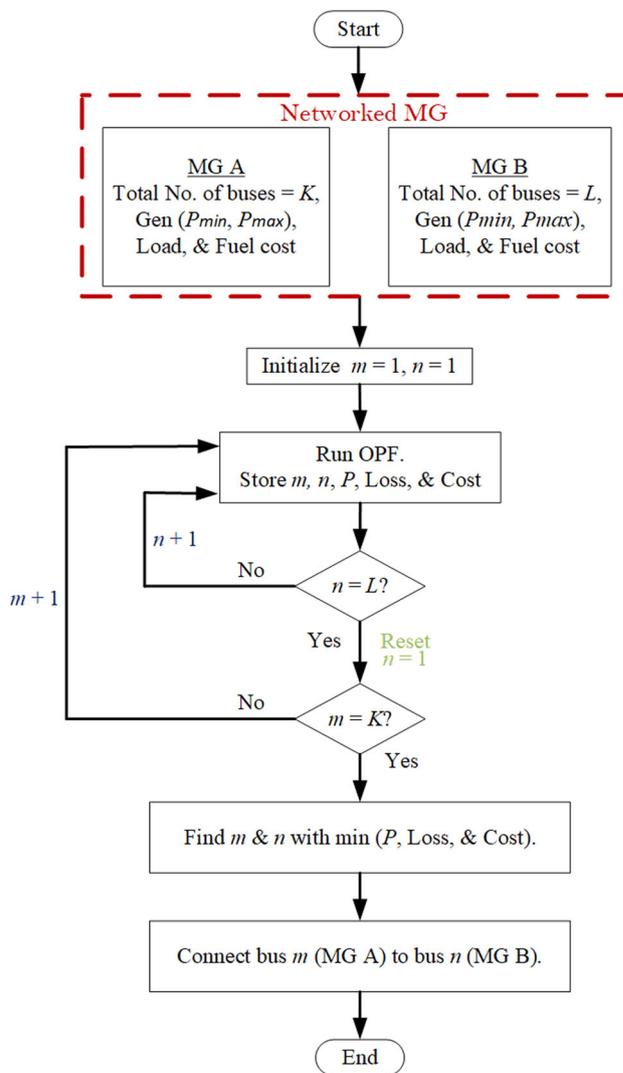

Fig. 2 Identification of the optimal network connection for networked MGs

untied MGs. It can be seen that the solution converges faster for the untied MGs compared with that for the tied MGs.

Figure 7 shows the amount of load to be shed, shared power, and operation cost obtained using the conventional load flow technique and the optimal economic dispatch model for networked MGs. The light blue and orange legends represent the amount of load to be shed in MW using the conventional load flow technique and optimal economic dispatch model, respectively. The grey and yellow legends represent the shared power in MW obtained using the conventional load flow technique and optimal economic dispatch model, respectively. It can be observed that the proposed model outperforms the conventional load flow technique in terms of load shedding. However, it shall be noted that the power shared between the networked MGs makes the amount of load to be shed zero, where the operation cost is dependent

Fig. 3 Procedure used to solve the optimal economic dispatch and optimal load shedding problems using PSO
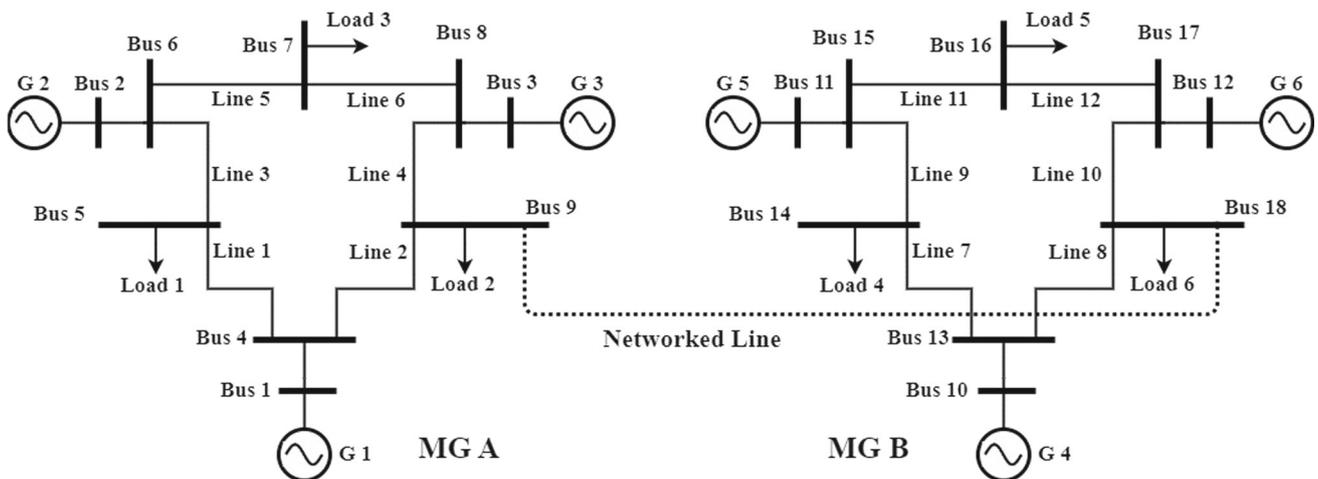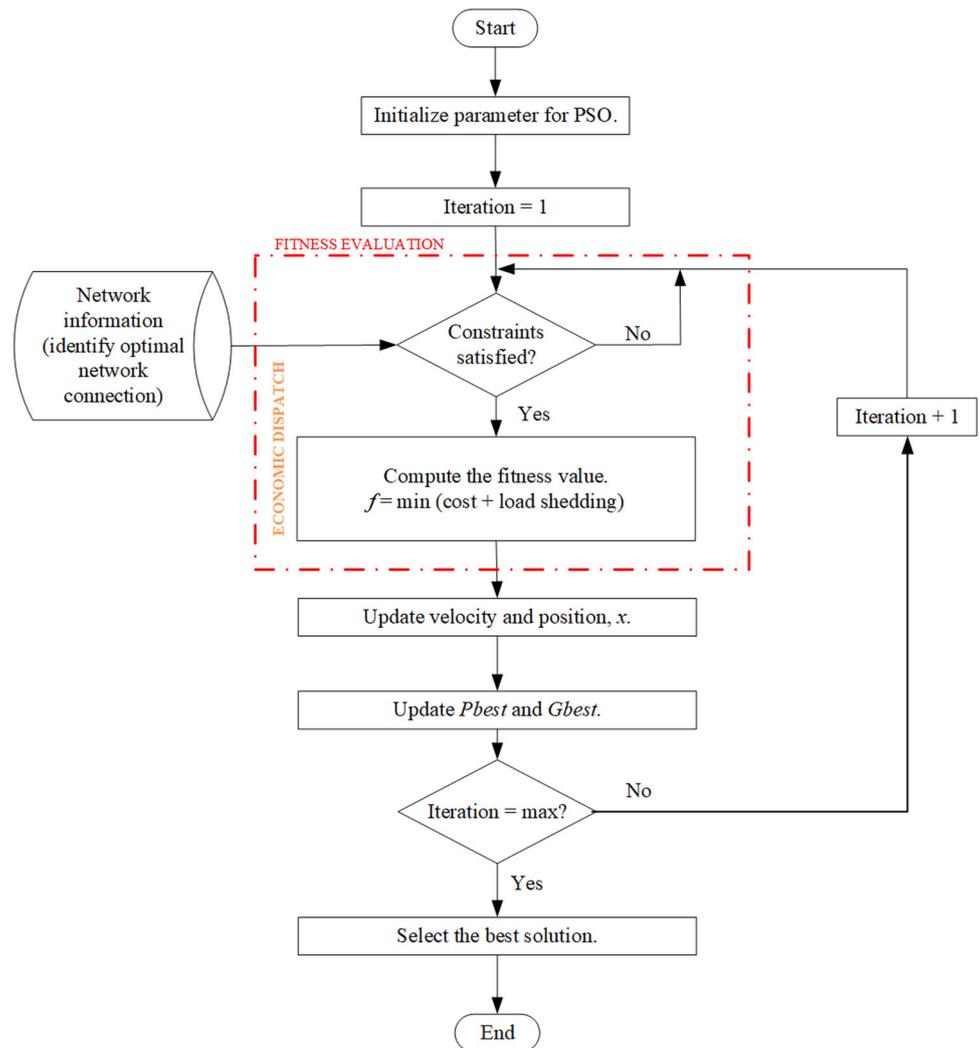

Fig. 4 Proposed IEEE 9-bus test systems for the networked MGs: MG A and MG B

Table 1 Fuel cost of the generators and loads used in the simulations

Data	G1, G4	G2, G5	G3, G6	L1, L4	L2, L5	L3, L6
Max. MW	250	300	270	90	100	125
Min. MW	10	10	10	0	0	0
a ($/(MWh)^2)	0.11	0.085	0.1225	5000	5000	5000
b $/MWh	5	1.2	1	0	0	0
c ($/h)	150	600	335	0	0	0
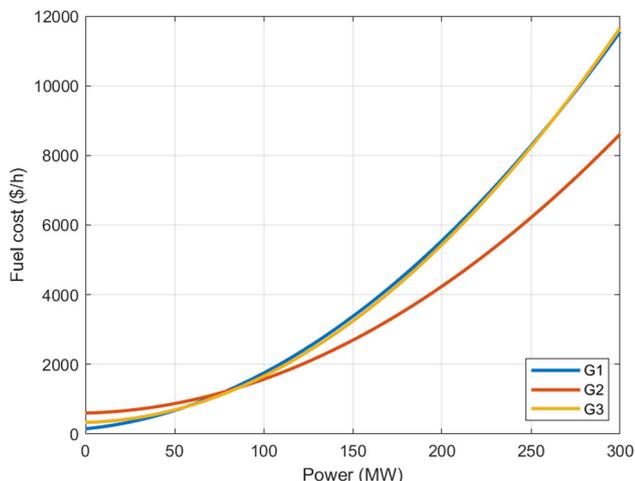
Fig. 5 Power–fuel cost curve of generators G1, G2, and G3 for MG A

Table 3 Operation cost for untied and tied MGs before and after optimisation

	Untied MGs		Tied MGs
	MG A	MG B	MG A + MG B
Before optimisation	5438.22 $/h	5438.22 $/h	10,876.45 $/h
After optimisation	5296.68 $/h	5296.68 $/h	10,593.37 $/h

4.3.2 Performance of the Proposed Optimal Economic Dispatch Model for Untied MGs

The performance of the proposed optimal economic dispatch model in terms of amount of load to be shed and operation cost for untied MGs is summarised in Table 4. It can be seen that there is no power sharing for all scenarios investigated in this study, which is expected since the MGs are untied, meaning that MG A and MG B work independently. However, more load shedding is needed for scenarios 3–6 due to the limited number of operating generators in these scenarios (see Table 2).

The proposed economic dispatch model was used to determine the amount of load to be shed and operation cost for the untied MGs and the results were compared with those obtained using the conventional load flow technique, as shown in Table 5. It can be observed that the proposed model outperforms the conventional load flow technique for
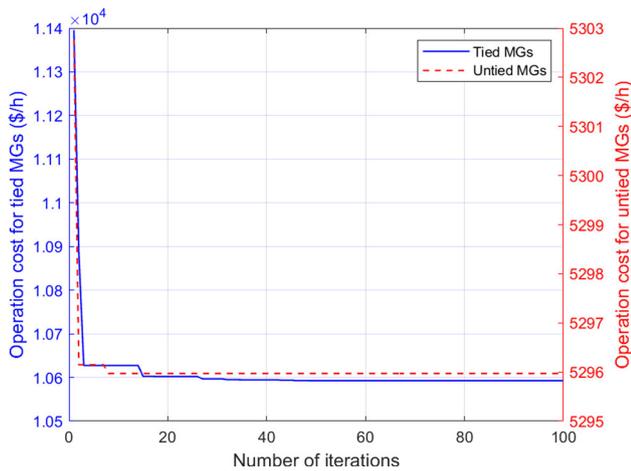
on the operating generator prices. If the fuel cost of the operating generator is high, then the cost of power sharing will also be high. Surprisingly, in scenario 4, the operation cost obtained using the proposed model is higher than the operation cost obtained using the conventional load flow technique. This is because most of the generators are out of service, and more power sharing is needed to reduce the amount of load to be shed. In addition, selection of the cheapest operating generator is limited due to the limited number of operating generators. In general, the results indicate that the proposed optimal economic dispatch model is more economical than the conventional load flow technique for the networked MGs.

Table 2 Operation scenarios for MG A and MG B

Scenario	G1	MG A G2	G3	G4	MG B G5	G6
Baseline case	On	On	On	On	On	On
1	On	On	Off	On	On	On
2	On	On	Off	Off	On	On
3	Off	On	On	Off	On	Off
4	On	On	Off	Off	Off	Off
5	Off	Off	Off	On	Off	Off
6	Off	Off	Off	Off	Off	Off

Fig. 6 Convergence characteristic of the proposed optimal economic dispatch model for tied and untied MGs

Table 4 Amount of load to be shed and operation cost obtained using the proposed optimal economic dispatch model for untied MGs

Scenario	Load to be shed (MW)	Operation cost ($/h)
Baseline case	0.00	10,593.53
1	0.00	12,143.05
2	0.00	13,529.03
3	24.07	15,777.75
4	315.00	7931.28
5	384.44	10,295.00
6	630.00	0.00

the baseline case and scenarios 1–4, where the operation cost is lower for the proposed model. In scenario 2, the proposed model gives a lower amount of load to be shed and lower operation cost compared with the conventional load flow technique, which fulfils the objective of this study. The results support the hypothesis mentioned earlier in this article, where the proposed optimal economic dispatch model minimises the operation cost and amount of load to be shed concurrently.

4.3.3 Performance of the Proposed Optimal Economic Dispatch Model for Tied MGs

The proposed optimal economic dispatch model was used to determine the amount of load to be shed, shared power, and operation cost for the tied MGs (networked MGs) and the results were compared with those for untied MGs, as

presented in Table 6. Interestingly, in scenario 3, the operation cost is lower for untied MGs compared with that for tied MGs. However, the main objective of this study is to minimise both the operation cost and amount of load to be shed simultaneously. The results appear promising, where the proposed economic dispatch model gives the minimum amount of load to be shed for tied MGs. Likewise, in scenario 4, the operation cost is lower for untied MGs compared with that for tied MGs. However, the amount of load to be shed is lower for the tied MGs, with a value of 91.91 MW. This can be attributed to the optimal power sharing between the tied MGs. The results support the hypothesis that the proposed economic dispatch model minimises the operation cost and amount of load to be shed simultaneously.

Tables 7 and 8 show the amount of load to be shed for MG A and MG B, respectively. The output power of the generators and the loads is included for comparison. For MG A, there are loads to be shed for scenarios 5 and 6 whereas for MG B, there are loads to be shed for scenarios 4–6. Load shedding occurs for scenarios 4 and 5 because more than 50% of the generators of the networked MGs are out of service. In these scenarios, load shedding is acceptable to maintain

Fig. 7 Comparison of the amount of load to be shed, shared power, and operation cost obtained using the conventional load flow technique and proposed optimal economic dispatch model
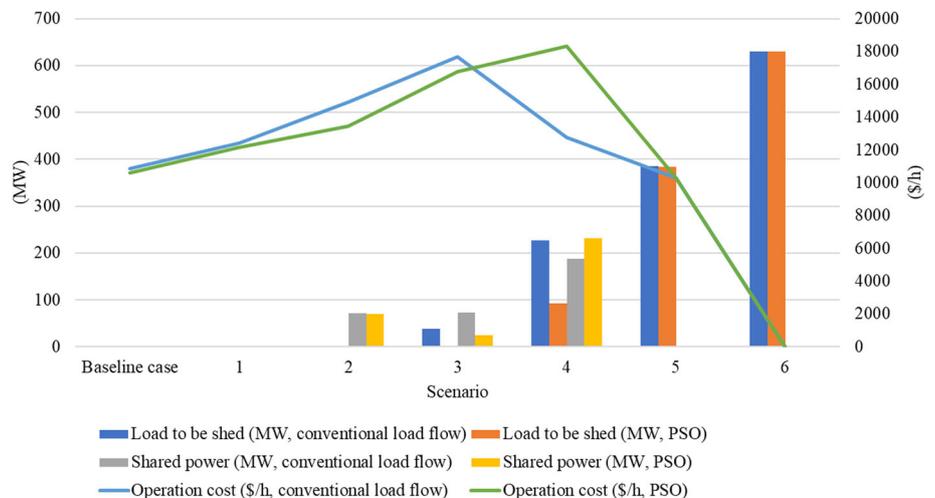
Table 5 Comparison of the amount of load to be shed and operation cost between the conventional load flow technique and proposed optimal economic dispatch model for untied MGs

Scenario	Load to be shed (MW)		Operation cost ($/h)	
	Conventional load flow technique	Proposed optimal economic dispatch model	Conventional load flow technique	Proposed optimal economic dispatch model
Baseline case	0.00	0.00	10,876.65	10,593.53
1	0.00	0.00	12,431.38	12,143.05
2	69.66	0.00	14,727.09	13,529.03
3	24.07	24.07	18,395.84	15,777.75
4	315.00	315.00	8078.06	7931.28
5	384.44	384.44	10,295.00	10,295.00
6	630.00	630.00	0.00	0.00

Table 6 Comparison of the performance of the proposed optimal economic dispatch model for untied and tied MGs

Scenario	Load to be shed (MW)		Shared power (MW)		Operation cost ($/h)	
	Untied MGs	Tied MGs	Untied MGs	Tied MGs	Untied MGs	Tied MGs
Baseline case	0.00	0.00	0.00	0.00	10,593.53	10,593.53
1	0.00	0.00	0.00	0.00	12,143.05	12,143.05
2	0.00	0.00	0.00	0.00	13,529.03	13,458.81
3	24.07	0.00	0.00	24.74	15,777.75	16,756.39
4	315.00	91.91	0.00	231.34	7931.28	18,305.00
5	384.44	384.44	0.00	0.00	10,295.00	10,295.00
6	630.00	630.00	0.00	0.00	0.00	0.00

Table 7 Output power of generators G1–G3, loads L1–L3, and amount of load to be shed for MG A

Scenario	MG A								
	Output power (MW)			Load (MW)			Load to be shed (MW)		
	G1	G2	G3	L1	L2	L3	L. Sh.1	L. Sh.2	L. Sh.3
Baseline case	89.80	134.32	94.19	90.00	100.00	125.00	0.00	0.00	0.00
1	131.05	187.61	0.00	90.00	100.00	125.00	0.00	0.00	0.00
2	135.17	184.60	0.00	90.00	100.00	125.00	0.00	0.00	0.00
3	0.00	180.96	166.82	90.00	100.00	125.00	0.00	0.00	0.00
4	250.00	300.00	0.00	90.00	100.00	125.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.00	0.00	90.00	100.00	125.00
6	0.00	0.00	0.00	0.00	0.00	0.00	90.00	100.00	125.00

system stability. In scenario 6, load shedding takes place for loads L1, L2, and L3 (for MG A) and loads L4, L5, and L6 (for MG B) because all the generators in the networked MGs are out of service, which means that there is a total loss of electrical power (system blackout).

Table 9 shows the summary for MG A and MG B, including the total shared power between MG A and MG B. For the baseline case and scenarios 1, 2, 5, and 6, there is no power shared between the networked MGs because each MG supplies its own loads. For these scenarios, if there is power shortage, the generators of each MG will increase their power to supply the loads. In contrast, for scenarios 3 and 4, the networked MGs will share power to support each other. The negative sign for the total shared power indicates that the MG is receiving power whereas the positive sign indicates that the MG is sending power. The difference between the

Table 8 Output power of generators G4–G6, loads L4–L6, and amount of load to be shed for MG B

Scenario	MG B								
	Output power (MW)			Load (MW)			Load to be shed (MW)		
	G4	G5	G6	L4	L5	L6	L. Sh.4	L. Sh.5	L. Sh.6
Baseline case	89.80	134.32	94.19	90.00	100.00	125.00	0.00	0.00	0.00
1	89.80	134.32	94.19	90.00	100.00	125.00	0.00	0.00	0.00
2	0.00	184.40	135.17	90.00	100.00	125.00	0.00	0.00	0.00
3	0.00	300.00	0.00	90.00	100.00	125.00	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	98.09	125.00	90.00	1.91	0.00
5	250.00	0.00	0.00	80.82	49.08	115.66	9.18	50.92	9.34
6	0.00	0.00	0.00	0.00	0.00	0.00	90.00	100.00	125.00

Table 9 Summary for MG A and MG B

Scenario	MG A					MG B				
	Total output power of generators (MW)	Total connected load (MW)	Total transmission line loss (MW)	Total load to be shed (MW)	Total shared power (MW)	Total output power of generators (MW)	Total connected load (MW)	Total transmission line loss (MW)	Total load to be shed (MW)	Total shared power (MW)
Baseline case	318.31	315.00	3.31	0.00	0.00	318.31	315.00	3.31	0.00	0.00
1	318.66	315.00	3.66	0.00	0.00	318.31	315.00	3.31	0.00	0.00
2	319.77	315.00	4.77	0.00	0.00	319.57	315.00	4.57	0.00	0.00
3	347.78	315.00	8.04	0.00	24.74	300.00	315.00	9.07	0.00	− 24.07
4	550.00	315.00	3.66	0.00	231.34	0.00	223.09	3.12	91.91	− 226.21
5	0.00	0.00	0.00	315.00	0.00	250.00	245.56	4.44	69.44	0.00
6	0.00	0.00	0.00	315.00	0.00	0.00	0.00	0.00	315.00	0.00

power sent and power received for scenarios 3 and 4 is the tie line losses.

5 Conclusion

An optimal economic dispatch model based on PSO for networked MGs has been developed in this study. The model involves finding the solution for the summation of two objective functions, which is to minimise the operation cost and amount of load to be shed. The optimal network connection was first identified before the MGs were networked. Various scenarios were used to assess the performance of the optimal economic dispatch model. Based on the results, it is concluded that the proposed model is more effective in minimizing the operation cost and amount of load to be shed compared with the conventional load flow technique.

Moreover, numerical simulations show that when an imbalance occurs due to generation losses, the proposed method automatically generates the optimal load shedding with the optimal operation cost.

Declarations

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