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Hybrid energy management for islanded networked microgrids considering battery energy storage and wasted energy

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ABSTRACT

The penetration of renewable energy sources in the distribution systems had been led to the rapid development of microgrids. In this paper, a two-level energy management strategy is proposed to optimize the operation costs of the islanded networked microgrids and manage uncertainties. The proposed hybrid energy scheduling considers the surplus and shortage powers to determine the transactive energy among microgrids. To achieve this goal, we define the adjustable power concept (increasing or decreasing the production of controllable distributed generators) for the microgrids to determine the optimal transactive energy. At the lower-level of the optimization framework, an autonomous operation scheduling is performed to minimize the total operation cost of each microgrid. The global optimization is performed at the upper-level of optimization to minimize the total operating costs of the networked microgrids. The primary energy management of microgrids is rescheduled in the lower-level to ensure the best plan for the system. Also, various demand response programs have been applied to the model to enhance the flexibility of the microgrids. The proposed model has been tested on a standard case study for different scenarios. The simulation results show that the proposed model reduces the operating cost of the system by 174.75$.

1. Introduction

According to the increasing electric load worldwide, reducing greenhouse gas emission, incorporating large-scale renewable generation penetration, and blending communication technologies, the modern power systems are going to the smart active networks. The microgrids (MGs) are usually considered the decentralized group of local energy sources, load demands, and energy storage systems that integrate renewable and non-renewable energy sources [1,2]. The MGs improve the flexibility, resilience, reliability, and power quality of the power systems. Also, they are one of the main solutions to reduce the emission of greenhouse gasses [3].

The high penetration of renewable energy sources (RESs) in the distribution systems creates new challenges because of the fluctuations and randomness of uncontrollable units (such as photovoltaic and wind turbines). Some research works integrate the battery energy storage systems (BESSs) to improve the efficiency of the renewable energy sources in the distribution systems [4–6]. Better and more coordinated of RESs utilization, reducing operation costs, reducing the amount of load shedding, increasing the reliability, reducing the environmental effects, and the economic and technical developments of MGs have caused to MGs connected to the each other. Therefore, the concept of networked MGs had been introduced [7,8].

Networked MGs have been defined as a cluster of MGs that are in the spatial vicinity and can transact energy together [9]. Moving towards energy-efficient management in networked MGs has led to the emergence of the microgrid community (MGC). As shown in Fig. 1, an MGC has composed of at least two MGs and MG community-level devices (MCLDs) that are directly connected to the upstream network. The community microturbine (CMT), community battery energy storage system (CBESS), community renewable energy sources, and community electrical loads are the main elements of MCLDs [10].

Compared to distribution networks, networked MGs have limited energy management capabilities. The main differences between networked MGs and distribution networks include topology, control structure, energy management system, prevent fault extension from one part of the network to another, load routing, and increased reliability. Also, the scale of the networked MGs is less than distribution networks. Unlike distribution networks, the networked MGs can be operated as islanded mode. It should be noted that a private company could form the networked MGs, while distribution system operator (DSO) is responsible

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Nomenclature

Abbreviations

CBESS	community battery energy storage systems
CMT	community microturbine
CDG	controllable distributed generator
DRP	demand response program
EMS	energy management system
IL	interruptible load
MGs	microgrids
MGC	microgrid community
MCLDs	microgrid community level devices
MILP	mixed integer linear programming
RESs	Renewable energy sources
SOC	state of charge

Indices

t	index of time (t =1,2,…, T)
i	index of MG (i=1,2,…, I)
j	index of CDGs (j=1,2,…, J)
s	index of scenario (s=1,2,…, S)

Parameters

a_j^{CDG}	cost coefficient of CDG
a^{IL}	cost coefficient of interruptible load
C_t^{CDG}	operation cost of CDG
C_t^{ES}	operation cost of BESS
C_t^{IL}	the cost of interruptible load
C_t^{M}	exchanged power cost of the ith MG
C_t^{CM}	cost of exchanged power in MGC
$C_t^{R\&S}$	receiving/sending price at time t by MGs
C_{ng}	price of natural gas
c	scale index of Weibull PDF
DR^{min}/ DR^{max}	minimum/maximum DR %
E_t^{ES}	stored energy in BESS at time t
E_R^{ES}	rated capacity of BESS
$K_{O\&M}^{WT}$/ $K_{O\&M}^{PV}$/ $K_{O\&M}^{CDG}$/ $K_{O\&M}^{ES}$	constant coefficient for O&M cost
k	shape index of Weibull PDF
L_{ng}	low-hot value of natural gas
N^{PV}	the number of photovoltaic panels
p_w^r	rated power of WTs
$\overline{p^{CDG}}$/ $\underline{p^{CDG}}$	lower/upper limits of CDG power output
$\overline{p^{ES.\ Dis}}$/ $\overline{p^{ES.\ Chr}}$	upper limits of BESS discharging/charging power
p_t^{Inflex}/ p_t^{B}	inflexible/base flexible load of MGs at time t
ρ_t^{Buy}/ ρ_t^{sell}	buying/selling price at time t
ρ_t^{DE}/ ρ_t^{DS}	units cost for power surplus/shortage
ρ_t^{Rec}/ ρ_t^{sen}	receiving/sending price at time t by MGs
ρ_s	probability for scenario s
ϕ_t/ T_t	sun irradiation/outside air temperature at time t
S^{PV}	solar array area
SUC_j^{CDG}/ SDC_j^{CDG}	start-up/shut-down costs of CDG
$\overline{SOC}$/ $\underline{SOC}$	lower/upper limits of state of charge
v_t	wind turbines speed at time t
v_w^r	rated speed from WTs
v_w^{ci}/ v_w^{co}	wind turbines cut-in and cut-out speed
δ	Mean value from the wind speed
$\eta^{ES.\ Dis}$/ $\eta^{ES.\ Chr}$	BESS discharging/charging efficiencies
η^L	leakage loss factor of BESS
η_j^{CDG}	electrical efficiency of CDG (%)
η^{PV}	conversion efficiency of solar array (%)
μ	standard deviation from the wind speed
ΔT	length of time slot

Variables

By_t/ Sl_t	power buying/selling indicator for MGs
DR_t	the participation factor of load in DRP at hth load level (%)
Ldr_t	the amount of shifted load from other load level to hth load level
p_t^{CDG}	CDG power output
$p_t^{ES.Dis}$/ $p_t^{ES.Chr}$	BESS discharging/charging power
p_t^{IL}	the amount of interruptible load
$p_t^{M\_short}$/ $p_t^{M\_surplus}$	shortage/surplus power at time t
p_t^{Buy}/ p_t^{Sell}	buying/selling power of ith MG at time t
p_t^{PV}/ p_t^{WT}	output power of PVs and WTs at time t
p_t^{Load}	total load of ith MG of time t
p_t^{Flex}	flexible load of ith MG
p_t^{Rec}/ p_t^{Sen}	receiving/sending power at time t by MGs
SOC_t	state of charge Battery at time t
Δp_t^{adj}	adjustable power of unit jth in ith MG at time t
$\overline{\Delta p_t^{adj}}$/ $\underline{\Delta p_t^{adj}}$	maximum/minimum adjustable power of unit jth
$x_t^{ES.Dis}$/ $x_t^{ES.Chr}$	BESS discharging/charging indicator
x_t^{SU}/ x_t^{SD}	start-up/shut-down indicator of a CDG
x_t^{CDG}	commitment status indicator of a CDG

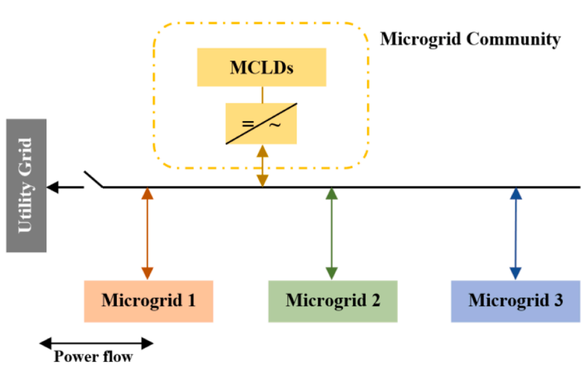


Fig. 1. View of an MGC.

for the operation of the distribution network [11].

Most research works focused on the grid-connected mode scheduling of networked MGs. The authors in [12] presented an optimal energy management strategy based on robust optimization for the operation of an MG considering the uncertain nature of renewable generation. Du et al. in [13] suggested a collaborative game to minimize the operation cost of multi-microgrid systems in a grid-connected mode. However, the uncertain behavior of renewable generation and the role of battery energy storage systems had been ignored. Wang et al. in [14] compared the hybrid and decentralized energy management of networked MGs in the grid-connected mode. This comparison had been performed unfairly because the number of the available devices in the two schemes was not the same.

Bui et al. in [15] introduced the adjustable power concept to improve the transactive energy among microgrids in a grid-connected mode.

Table 1
A summary of the literature review.

Ref.	Model	Pros	Cons
[2]	• Multi-objective optimization • Deterministic optimization • Heuristic algorithm (FMGPSO)	• The proposed model was tested on the multi-microgrid systems • The renewable generation and energy storage system integrated into the model • The emission of greenhouse gasses had been considered	• The uncertainty of renewable generation and load demand was not considered • The impact of DR programs on optimal energy scheduling had not been investigated • The adjustable power concept and wasted energy of MGs were not studied • The proposed model cannot ensure the privacy of MGs
[3]	• Cost minimization • Deterministic optimization • Heuristic algorithm (PSO-IPM)	• The operation of the islanded multi-microgrid systems had been studied • The renewable generation and energy storage system integrated into the model	• The impacts of DR programs on the wasted energy and optimal capacity of energy storage system were not investigated • The uncertainty of renewable generation and load demand was not considered • The adjustable power concept for transactive energy had not been considered
[10]	• Cost minimization • Deterministic optimization • Mixed-integer linear programing	• The proposed model provided a layer privacy for the MGs • The proposed model was tested on the islanded multi-microgrid systems • The renewable generation and energy storage system integrated into the model	• The wasted energy was not considered • The adjustable power concept had not been considered • The opportunity of cost-saving by the DR programs was not provided • The uncertainty of renewable generation and load demand was not studied
[13]	• Cost minimization • Deterministic optimization • Benders decomposition approach	• Both renewable generation and dispatchable resources had been considered • The proposed model was tested on the multi-microgrid systems	• The impacts of DR programs and battery energy storage systems were not investigated • The wasted energy was not considered • The uncertainty of renewable generation and load demand was not studied • The adjustable power concept for transactive energy among MGs had not been considered • The proposed model cannot ensure the privacy of MGs
[15]	• Cost minimization • Deterministic optimization • Mixed-integer linear programing	• The adjustable power was introduced to manage the transactive energy • The PBDR programs, energy storage systems, renewable energy resources had been integrated into the model • The proposed mode ensure the privacy of MGs	• The efficiency of the proposed model on the wasted energy was not studied • The impact of DR programs on the optimal capacity of energy storage system was not investigated • The probability behavior of demand loads and renewable resources had been ignored • The islanded multi-microgrid system was not studied
[16]	• Cost minimization • Deterministic optimization • Mixed integer linear programing	• The islanded microgrid was studied • The waste of energy had been investigated • The role of DR programs and energy storage systems had been studied	• The efficiency of the proposed model in the multi-microgrid systems was not evaluated • The uncertain nature of renewable generation had been ignored • The adjustable power was not considered
[19]	• Cost minimization and reliability maximization • Deterministic optimization • Mixed integer linear programing	• The proposed model was tested on the islanded systems • The reliability problems had been considered • The proposed model provided a layer privacy for the MGs	• The impacts of DR programs on the operation scheduling of the system and the optimal capacity of BESS were not studied • The waste of energy had not been investigated • The adjustable power was not defined • The probability behavior of demand loads and renewable resources had been ignored
[22]	• Cost minimization • Deterministic optimization • Incorporating CPLEX with Java, Net Beans	• The islanded multi-microgrid system had been investigated • The adjustable power was considered • The energy storage systems and renewable energy resources had been integrated into the model	• The proposed model cannot ensure the privacy of MGs • The impact of DR programs on the optimal capacity of energy storage system was not investigated • The waste of energy was ignored • The uncertainty of renewable generation and load demand had been neglected
This study	• Cost minimization • Stochastic optimization • Mixed integer linear programing	• The proposed model provides a layer privacy for the MGs • The adjustable power for energy trading is considered • The efficiency of the proposed model on the wasted energy is investigated • The impact of DR programs on the optimal capacity of the energy storage system is investigated • The uncertain nature of renewable generation and load demand has been applied to the model by probability technique	• The performance of the proposed model on the multi-energy system will be investigated in the future work

Although the role of battery energy storage systems had been studied, the uncertain natures of renewable generation and demand loads were not considered. However, the impact of demand response programs on the optimal capacity of battery energy storage systems and wasted energy were not investigated. In [10], Tian et al. presented hierarchical energy management for the economic operation of a grid-connected MGC and various islanded modes. In islanded operation mode, MGs are unaware of MGC disconnection from the grid. MGs inform the surplus and shortage powers to MGC and trade energy between themselves and the MGC. Therefore, if MGC cannot transact energy with the upstream network at periods that the surplus of power is high, the wasted energy in MGC will be enhanced. As a result, the operation costs and environmental pollution will be increased [10]. Nevertheless, the impacts of the uncertain nature of RES and demand response programs (DRPs) were not investigated.

On the other hand, some research works had been focused on the operation of microgrids in the islanded mode. In [16], an optimal coordinated energy dispatch model was proposed for a multi-energy microgrid in the grid-connected and islanded modes without considering uncertainties. In [17], the authors presented a robust optimization model to determine the optimal dispatch of a microgrid in both grid-connected and islanded modes. However, the role of a price-based demand response program and battery energy storage systems was not studied. A decentralized energy scheduling framework had been suggested in [18] to increase the reliability in the islanded mode. Hussain et al. proposed nested energy management by prioritizing electrical loads for networked MGs to minimize the operation cost of the system in the grid-connected and islanded modes [19]. Also, in [20], the authors minimized the operation cost in the grid-connected and islanded modes, while the privacy of MGs and the cost of local transactive energy had been ignored. When MGs collaborate together, privacy becomes crucial. In centralized energy management, the operator needs the load profile of the consumers and characteristics of power generation units. The required information will destroy the privacy of microgrids [21].

Hussain et al. [22] focused on the allocation of load shedding amount in the multi-microgrid systems by an effort-based reward framework to define the contribution of microgrids based on their capacity. In the proposed model, the individual energy management of microgrids had been performed by the local energy management system (MEMS). Also, the community energy management system (CEMS) is responsible to manage the power-sharing among the microgrids. Nevertheless, the proposed model did not provide the rescheduling opportunity for the microgrid to reduce the operation costs and the amount of wasted energy. However, the uncertainty of renewable generation, and load demands was not applied to the model. Also, the efficiency of demand response programs on the proposed model was not studied.

In the hybrid energy management frameworks, MGs can exchange power between each other and the MGC. In the hierarchical models [10] and [14], the surplus and shortage powers were sent to EMS-MGC. However, MGs can prevent unnecessary energy exchange with the upstream network and waste of energy using the concept of adjustable power. In the islanded mode, some part of the energy abandons to provide a balance in supply and demand, which is called a waste of energy. Therefore, it is necessary to consider the energy deviation cost (because of wasted energy) in the objective function [16].

In this paper, we utilize the concept of adjustable power to manage the controllable distributed generators (CDGs) and prevent wasted energy in the system. Also, we investigate the role of demand-side management for peak shaving and cost-saving. The EMS-MGC is responsible to decide for the optimal generation of CDGs. In this paper, we investigate the islanded mode from the upstream network that is very important to evaluate the efficiency of MGC. However, the battery energy storage systems are used to control RESs fluctuations, maintain system reliability, and enhance system flexibility. A summary of the literature in the multi-microgrid systems has been discussed in Table 1. The main contributions of the proposed model are listed as follows:

1) A two-level optimization model based on a hierarchical optimization method is provided to minimize the operating cost of networked MGs in islanded mode. In this model, individual MGs are networked under an MGC to increase reliability, prevent waste of energy, integration RESs, and improve their privacy than centralized energy management mode.
2) Considering adjustable power concept to improve the internal transactive energy among MGs and reduce the operation costs. Also, we evaluate the efficiency of the proposed model on the wasted energy and the amount of load shedding.
3) Various uncertainties are considered to handle the renewable generation fluctuations and demand loads.
4) A price-based demand response program is considered to reduce the involuntary load shedding and provides the opportunity for cost-saving for MGs. Also, the impact of DR programs on the optimal capacity of the energy storage system is investigated.

The rest of this paper is organized as follows: Section 2 describes the model description. Section 3 presents the mathematical modeling of the proposed model. The mathematical formulation of the objective function is shown in Section 4. The case studies and simulation results are presented in Section 5. Finally, conclusions and future works have been presented in Section 6.

2. Problem statement

The structure of the networked microgrids system, components, and the proposed energy scheduling strategy are described in this section. The studied system consists of four MGs that one of them is considered as MGC to provide a fair comparison with other related works. We integrate various controllable sources (such as microturbines and fuel cells), battery energy storage systems, and renewable energy sources (photovoltaic and wind turbine) to supply the electric load in microgrids. Also, the community microturbine, the community battery energy storage system, community renewable energy sources, and community electrical loads are considered in the MGC [10].

The battery energy storage systems and demand response programs play an important role in enhancing flexibility. The battery energy storage system is used to increase the availability time of RESs and store surplus energy. Also, the demand response programs (DRPs) reduce the amount of load shedding, provide the opportunity for cost-saving, and maintain the balance in the distribution system by load shifting and voluntary curtailment. Cost reduction and maintaining system reliability at acceptable levels are the main goals of energy management in the islanded mode. The networked MGs are consists of MGs that are geographically close to each other and can work together to accomplish some goals [9]. Maintaining the connection between the MGs to increase the system stability compared to decentralized energy management is one of the advantages of MGC in islanded mode. Unlike centralized energy management, hybrid energy management has a single level of privacy. In a centralized energy management system, the flexibility and reliability of the system will be lost if the central EMS (C-EMS) destroyed. According to the disadvantages and deficiencies of both centralized and decentralized energy management strategies, a hybrid energy management strategy has been proposed that is a combination of both centralized-decentralized energy management [19].

According to Fig. 2, the MGs interact closely with each other in MGC. MGs have different owners, that they may have different purposes for interaction. In the hybrid energy management system, MGs optimize their local resources in parallel (without being aware of other MGs). In the proposed energy management, the upper-level and the lower-level are focused on the management of MCLDs and MGs, respectively. The flexibility and operation costs of the hybrid energy management strategy are better than centralized and decentralized strategies. More benefits of MGC can be found in [10].

This paper covers the day-ahead scheduling of islanded MGs that consists of two levels. At the lower-level, an autonomous operation scheduling is performed that each MG optimizes its objective. Uncertainties of RESs and electricity load demands are considered at this level. The commitment status of CDGs, the charge/discharge status of the BESS, the DR participation, the surplus and shortage amounts of power, and the adjustable power ranges, have been defined at this level. The surplus and shortage of energy, adjustable power range, and marginal cost of CDG units have been sent to EMS-MGC after lower-level optimization. When the MGC is disconnected from the main grid, MGC continues to maintain connections between MGs.

The upper-level focuses on coordination between MGs and MCLDs to reduce the total operating cost of the networked MGs. Similar to the lower-level, the uncertainties of RESs and electrical loads have been considered at this level. The commitment status of the community microturbine, the charge/discharge status of the community battery energy storage system, the amount of load shedding, and the optimal amount adjustable powers have been determined by MGC at the upper-level.

After performing global optimization at the upper-level, EMS-MGC sends information to MCLDs and each EMS-MG. According to the results of the global optimization, MGs modify their primary scheduling, while

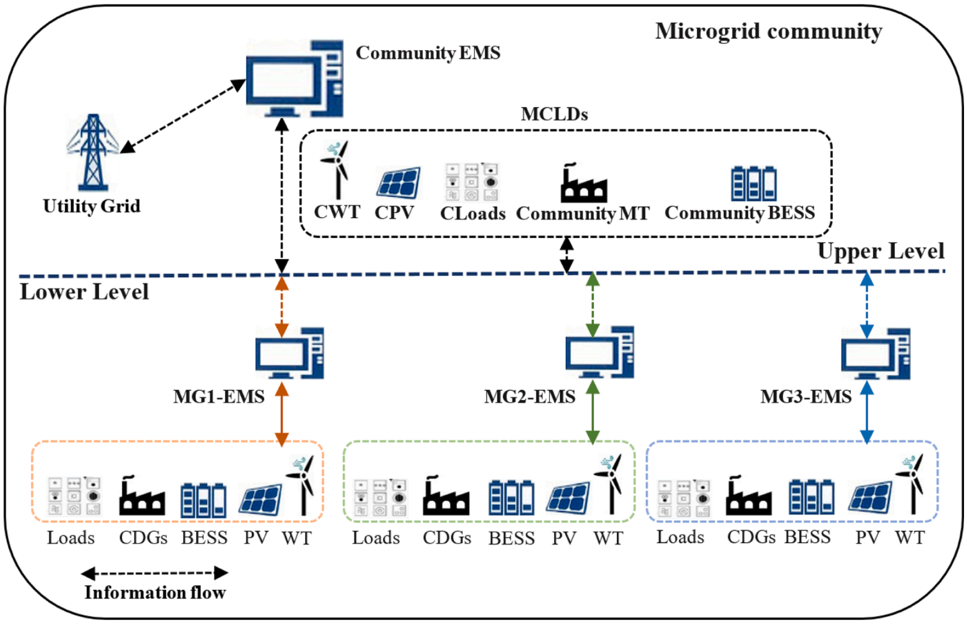


Fig. 2. The structure of networked microgrids.

MGs consider the amount of adjustable power in the day-ahead scheduling. The adjustable powers modify the generation of CDGs according to the marginal cost of dispatchable resources in the other MGs and MGC.

3. Mathematical model

The energy scheduling of networked MGs in islanded mode is formulated as MILP. The goal of the optimization problem is cost minimization of the studied system considering the technical constraints.

3.1. Photovoltaic panels

Power generation of PVs is calculated as (1) [23]:

$$P_{t,i}^{PV} = N^{PV}\eta_i^{PV}S_i^{PV}\Phi_{t,i}\left(1-0.005\left(T_{t,i}-25\right)\right) \tag{1}$$

3.2. Wind turbines

Output power of wind turbines is determined as (2) [24]:

$$P_{t,i}^{WT} = \begin{cases} 0, if\, v_t \le v_w^{ci} or v_t \ge v_w^{co}, \\ P_w^r \dfrac{v_t - v_w^{ci}}{v_w^r - v_w^{ci}}, if\, v_w^{ci} \le v_t \le v_w^r, \\ P_w^r, otherwise \end{cases} \tag{2}$$

3.3. Controllable distributed generators (CDGs)

The microturbines and fuel cells are considered as the controllable resources, and their operating costs are formulated as the linear function according to (3)–(4) [23]:

$$C_{t,i}^{CDG} = a_j^{CDG}.P_{t,j}^{CDG} \tag{3}$$

$$a_j^{CDG} = \frac{C_{ng}}{L_{ng}\eta_j^{CDG}} \tag{4}$$

The following constraints have been imposed on the operation of CDGs:

$$\underline{P^{CDG}}.X_{t,j}^{CDG} \le P_{t,j}^{CDG} \le \overline{P^{CDG}}.X_{t,j}^{CDG}; X_{t,j}^{CDG} \in \{0,1\} \tag{5}$$

$$X_{t,j}^{SU} + X_{t,j}^{SD} \le 1; X_{t,j}^{SU}, X_{t,j}^{SD} \in \{0,1\} \tag{6}$$

$$X_{t,j}^{CDG} - X_{t-1,j}^{CDG} = X_{t,j}^{SU} - X_{t,j}^{SD} \tag{7}$$

Eq. (5) shows the power generation limits for CDGs. Eq. (6) shows that the CDG unit cannot be started up and shut down simultaneously. Finally, the relationship between binary variables is presented in Eq. (7).

3.4. Battery energy storage systems

The BESSs store energy during off-peak periods to import the stored energy to the system during peak periods. The operation and maintenance costs of battery energy storage systems can be formulated as the linear function as (8) [16,25]:

$$C_t^{ES} = K_{O\&M}^{ES}.P_t^{ES,Dis}.\Delta t + K_{O\&M}^{ES}.P_t^{ES,Chr}.\Delta t + K_{O\&M}^{ES}.E_t^{ES}.\eta^L.\Delta t \tag{8}$$

Given that each MG is the owner of the local generation units and BESS, the operation cost of them are imposed directly on the MGs. In another word, the BESSs are not independent units, and there is no need to receive a reward for cost-saving. The battery energy storage system should satisfy the following constraints:

$$E_{t+1}^{ES} = E_t^{ES} - P_t^{ES,Dis}.\Delta t/\eta^{ES,Dis} + P_t^{ES,Chr}.\Delta t.\eta^{ES,Chr} - E_t^{ES}.\eta^L.\Delta t \tag{9}$$

$$SOC_t = E_t^{ES}/E_R^{ES} \tag{10}$$

$$\underline{SOC} \le SOC_t \le \overline{SOC} \tag{11}$$

$$\begin{cases} 0 \le P_t^{ES,Dis} \le X_t^{ES,Dis}.\overline{P^{ES,Dis}} \\ 0 \le P_t^{ES,Chr} \le X_t^{ES,Chr}.\overline{P^{ES,Chr}} \end{cases} \tag{12}$$

$$X_t^{ES,Dis} + X_t^{ES,Chr} \le 1; X_t^{ES,Dis}, X_t^{ES,Chr} \in \{0,1\} \tag{13}$$

$$E_t^{ES} = E_{INIT}^{ES} if\, t = 1 \tag{14}$$

$$E_t^{ES} \ge E_{END}^{ES} if\, t = T \tag{15}$$

where, SOC_t is the state of charge of BESS. Eq. (9) defines the dynamic state of charge of BESS. The state-of-charge constraints of the BESS are presented in Eqs. (10) to (12). Eq. (13) prevents from charging and discharging of BESS at the same time. Eqs. (14) and (15) represent the amount of initial and final energy in BESS, respectively.

3.5. O&M cost modeling

The O&M cost of each unit is formulated by (16) to (19) [10]:

$$C_t^{O\&M,WT} = K_{O\&M}^{WT}.P_t^{WT} \tag{16}$$

$$C_t^{O\&M,PV} = K_{O\&M}^{PV}.P_t^{PV} \tag{17}$$

$$C_{t,j}^{O\&M,CDG} = K_{O\&M,j}^{CDG}.P_{t,j}^{CDG} \tag{18}$$

$$C_t^{Total\_O\&M} = C_t^{O\&M,WT} + C_t^{O\&M,PV} + \sum_{j=1}^{2} C_{t,j}^{O\&M,CDG} \tag{19}$$

where $C_t^{Total\_OM}$ is the total O&M cost of the units.

3.6. Demand response programs

- Interruptible loads (ILs): Most load shedding programs are performed in islanded operation mode to increase stability and feed sensitive loads by voluntary curtailment. The reward for voluntary curtailment and the bounds of interruptible loads are shown in (20) and (21), respectively [24]:

$$C_t^{IL} = a^{IL}.P_t^{IL} \tag{20}$$

$$0 \le P_t^{IL} \le P_t^{Inflex} \tag{21}$$

The MGs sign a contract according to their load profile with consumers who are willing to participate in the interruptible load program. The minimum and maximum bounds, the incentive prices, and the number of hours allowed to be interruptible loads have been marked in this contract. More information on the types of interruptible load programs can be found in [26].

- Controllable loads (CLs): MGs can participate in the price-based demand response programs (PBDRP) to shift some part of their demands to off-peak periods. The mathematical formulation of shiftable DRPs are presented in (22) to (25) [24]:

$$P_t^{Flex} = (1 - DR_t).P_t^B + Ldr_t \tag{22}$$

$$\sum_{t=1}^{T} Ldr_t = \sum_{t=1}^{T} DR_t.P_t^B \tag{23}$$

$$DR^{Min} \le DR_t \le DR^{Max} \tag{24}$$

$$P_t^{Load} = P_t^{Flex} + P_t^{Inflex} - P_t^{IL} \tag{25}$$

Eq. (22) represents the load profile after participation in the PBDRP. Eq. (23) ensures each MG can only shift loads. The minimum and maximum DR levels are presented in (24). Finally, the total load profile of MGs is calculated by (25).

3.7. Models of other uncertainties along with generating and reducing scenarios

To enhance the reliability of the work, we model the uncertain nature of RES and demand loads by stochastic scenario-generation and reduction techniques. The wind speed, solar radiation, and load demands follow a probability distribution function (PDF) that is based on the corresponding historical data [27]. Although the stochastic technique enhances the reliability of the work, it has not any effect on the performance of the proposed model. To describe the uncertain behavior of a wind turbine, the Weibull distribution function (26) is used:

$$PDF(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^{k}\right) \Big| k = \left(\frac{\delta}{\mu}\right)^{-1.086} \tag{26}$$

$$c = \frac{\mu}{\Gamma\left(1 + \frac{1}{k}\right)} \tag{27}$$

The Beta distribution function has been used to handle the uncertainty of PVs. The Beta distribution function is modeled by (28):

$$PDF(x) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} \times x^{\alpha-1} \times (1 - x)^{\beta-1} \tag{28}$$

where α and β are calculated using the mean value μ and the standard deviation δ as (29) and (30):

$$\beta = (1 - \mu) \times \left(\frac{\mu \times (1 - \mu)}{\delta^2} - 1\right) \tag{29}$$

$$\alpha = \frac{\mu \times \beta}{1 - \mu} \tag{30}$$

Electric load scenarios are modeled with normal distribution (31):

$$PDF(x) = \frac{1}{\delta\sqrt{2\pi}} \exp\left(-\frac{(x - \mu)^2}{2\delta^2}\right) \tag{31}$$

We choose a set of PDFs intervals to consider the uncertainties. The n_x indicates the number of selected intervals. The probability of each scenario is calculated by (32) and (33):

$$\rho_{x,n_x} = \int_{x_{start,n_x}}^{x_{end,n_x}} PDF(x)dx, n_x = 1, 2, ..., N_x \tag{32}$$

$$\chi_{x,n_x} = \frac{1}{\rho_{x,n_x}} \times \left(\int_{x_{start,n_x}}^{x_{end,n_x}} x.PDF(x)dx\right), n_x = 1, 2, ..., N_x \tag{33}$$

The number and probability of scenarios are calculated by (34) and (35):

$$N^s = \prod_x N_x \tag{34}$$

$$\rho_s = \prod_x \rho_{x,s} s = 1, 2, ..., N^s \tag{35}$$

If all the scenarios are considered, the problem will be complicated. As a result, reducing the scenario is necessary to increase the computational speed of the optimization. In this paper, a MILP scenario reduction method is used that is shown in (36) to (43):

$$\min f = \sum_{n_1}^{N_1} \sum_{n_2}^{N_2} \sum_{n_3}^{N_3} W_{n_1,n_2,n_3} \tag{36}$$

$$s.t \sum_{n_2=1}^{N_2} \sum_{n_3=1}^{N_3} \rho_s(n_1, n_2, n_3) = \rho_{1,n_1}, n_1 = 1, 2, ..., N_1 \tag{37}$$

$$\sum_{n_1=1}^{N_1} \sum_{n_3=1}^{N_3} \rho_s(n_1, n_2, n_3) = \rho_{2,n_2}, n_2 = 1, 2, ..., N_2 \tag{38}$$

$$\sum_{n_1=1}^{N_1} \sum_{n_2=1}^{N_2} \rho_s(n_1, n_2, n_3) = \rho_{3,n_3}, n_3 = 1, 2, ..., N_3 \tag{39}$$

$$\sum_{n_1=1}^{N_1}\sum_{n_2=1}^{N_2}\sum_{n_3=1}^{N_3}\rho_s(n_1,n_2,n_3)=1,\forall n_1,n_2,n_3 \tag{40}$$

$$\rho_s(n_1,n_2,n_3)\leq W_{n_1,n_2,n_3},\forall n_1,n_2,n_3 \tag{41}$$

$$0\leq\rho_s(n_1,n_2,n_3)\leq 1,\forall n_1,n_2,n_3 \tag{42}$$

$$W_{n_1,n_2,n_3}\in\{0,1\} \tag{43}$$

The number of scenarios is minimized by Eq. (36). $W_{n_1.n_2.n_3}$ is a binary variable that indicates the status of scenario selection n_1, n_2, and n_3 if its value is 1; and also, the parameter $\rho_s(n_1.n_2.n_3)$ determines the probability of scenario n_1, n_2, and n_3 [27].

3.8. Market model

In MGC islanded mode scheduling, the power transactions are performed only between the MGs and the MGC. In this case, there are two market participants: 1) MGC agent and 2) MG agents. Power transactions are done through bilateral contracts, which is a major method for energy trading [14]. Power transactions between MGs and MCLDs are performed in MGC. Therefore, the MG can supply its load by buying/selling electricity from/to other MGs or MCLDs. As a result, the price of energy exchange between MGC and MGs is a fixed time-of-use tariff [19]. Detailed and complete steps on bilateral contracts can be found in [10].

4. Proposed two-level operation model

In this section, we proposed a two-level hierarchical control framework for the day-ahead hourly scheduling of the networked microgrids systems. The control structure is composed of autonomous energy management (MG energy scheduling) at the lower-level and global energy management at the upper-level (MGC energy scheduling).

4.1. Lower-level EMS

The goal of energy management at this level is cost minimization of MGs in islanded mode to increase the reliability of MGs, which should satisfy the operational constraints. The objective function of the lower-level is formulated as (44) and (45):

$$CF_i=\sum_{s=1}^{N_S}\rho_s\sum_{t=1}^{T}\left(\begin{array}{l}\left(\sum_{j=1}^{2}C_{s,t,i,j}^{CDG}+SUC_{i,j}^{CDG}.X_{s,t,i,j}^{SU}+SDC_{i,j}^{CDG}.X_{s,t,i,j}^{SD}\right)+C_{s,t,i}^{ES}\\+C_{s,t,i}^{IL}+C_{s,t,i}^{Total\_O\&M}-C_{s,t,i}^{M}\end{array}\right) \tag{44}$$

$$C_{s,t,i}^{M}=\rho_{t,i}^{Buy}P_{s,t,i}^{M\_Short}+\rho_{t,i}^{Sell}P_{s,t,i}^{M\_Surplus} \tag{45}$$

The energy balance for each MG has been presented in (46):

$$\sum_{j=1}^{2}\left(P_{s,t,i,j}^{CDG}\right)+P_{s,t,i}^{ES,Dis}+P_{s,t,i}^{WT}+P_{s,t,i}^{PV}-P_{s,t,i}^{ES,Chr}-P_{s,t,i}^{Load}=P_{s,t,i}^{M\_Short}+P_{s,t,i}^{M\_Surplus} \tag{46}$$

The bounds of transactive energy have been defined in (47) to (49):

$$\underline{P^{Short}}.By_t\leq P_{s,t,i}^{M\_Short}\leq\overline{P^{Short}}.By_t \tag{47}$$

$$\underline{P^{Surplus}}.Sl_t\leq P_{s,t,i}^{M\_Surplus}\leq\overline{P^{Surplus}}.Sl_t \tag{48}$$

$$By_t+Sl_t=1 \tag{49}$$

Also, the adjustable power range for each MG is formulated as (50):

$$\begin{array}{l}if\,\rho_t^{Sell}\leq a_j^{CDG}+K_{O\&M,j}^{CDG}<\rho_t^{Buy}\\ \left|\left(\underline{P_{i,j}^{CDG}}-P_{s,t,i,j}^{CDG}\right)\leq\Delta P_{s,t,i,j}^{adj}\leq\left(\overline{P_{i,j}^{CDG}}-P_{s,t,i,j}^{CDG}\right)\right.\\ else\\ \left|\Delta P_{s,t,i,j}^{adj}=0\right.\\ endif\end{array} \tag{50}$$

After local optimization, the MGs send surplus/shortage powers, the adjustable power range of controllable units, and the marginal cost of their local resources to EMS-MGC.

4.2. Upper-level EMS

The operation cost MGC is the objective of the upper-level of the optimization framework. The cost function of the upper-level is formulated as (51):

$$CF^{MGC}=\sum_{s=1}^{N_S}\rho_s\sum_{t=1}^{T}\left(\begin{array}{l}\left(C_{s,t}^{CMT}+SUC^{CMT}.X_{s,t}^{SU}+SDC^{CMT}.X_{s,t}^{SD}\right)+C_{s,t}^{CES}\\+C_{s,t}^{IL}+C_{s,t}^{Total\_O\&M}+C_{s,t}^{CM}+\sum_{i=1}^{3}\sum_{j=1}^{2}\left(a_j^{CDG}.\Delta P_{s,t,i,j}^{adj}\right)\end{array}\right) \tag{51}$$

The cost of exchanged power and the power balance limits are formulated in (52) and (53), respectively. Also, the bound of adjustable power is shown in (54):

$$C_{s,t}^{CM}=\rho_t^{DS}P_{s,t}^{Buy}+\rho_t^{DE}P_{s,t}^{Sell} \tag{52}$$

$$\begin{array}{l}P_{s,t}^{CMT}+P_{s,t}^{CES,Dis}-P_{s,t}^{CES,Chr}+\sum_{i=1}^{3}\left(P_{s,t,i}^{M\_Short}+P_{s,t,i}^{M\_Surplus}\right)\\+\sum_{i=1}^{3}\sum_{j=1}^{2}\left(\Delta P_{s,t,i,j}^{adj}\right)+P_{s,t}^{WT}+P_{s,t}^{PV}-P_{s,t}^{Load}=P_{s,t}^{Sell}-P_{s,t}^{Buy}\end{array} \tag{53}$$

$$\underline{\Delta P_{s,t,i,j}^{adj}}\leq\Delta P_{s,t,i,j}^{adj}\leq\overline{\Delta P_{s,t,i,j}^{adj}} \tag{54}$$

At the upper-level, MGC focuses on the connection between MGs to control the adjustable power and the amount of transactive energy. Also, MGC can supply shortage power in MGs with the generation units in the community or using energy storage systems that store the surplus energy of MGs during off-peak periods. After the upper-level optimization, EMS-MGC sends information to MGs. Therefore, each MG modifies the output power of CDGs according to the adjustable power.

4.3. Lower-level EMS rescheduling

After performing global optimization in MGC, each MG modifies the primary scheduling by performing local optimization to set the amount of adjustable power. The objective function of the rescheduling step is formulated as follows:

$$CF_i^{R}=\sum_{t=1}^{T}\left(\begin{array}{l}\left(\sum_{j=1}^{2}C_{s,t,i,j}^{CDG}+\left(\left(a_j^{CDG}+K_{O\&M,j}^{CDG}\right).\Delta P_{s,t,i,j}^{adj}\right)+SUC_{i,j}^{CDG}.X_{s,t,i,j}^{SU}+SDC_{i,j}^{CDG}.X_{s,t,i,j}^{SD}\right)+C_{s,t,i}^{ES}\\+C_{s,t,i}^{IL}+C_{s,t,i}^{Total\_O\&M}-C_{s,t,i}^{M}-C_{s,t,i}^{R\&S}\end{array}\right) \tag{55}$$

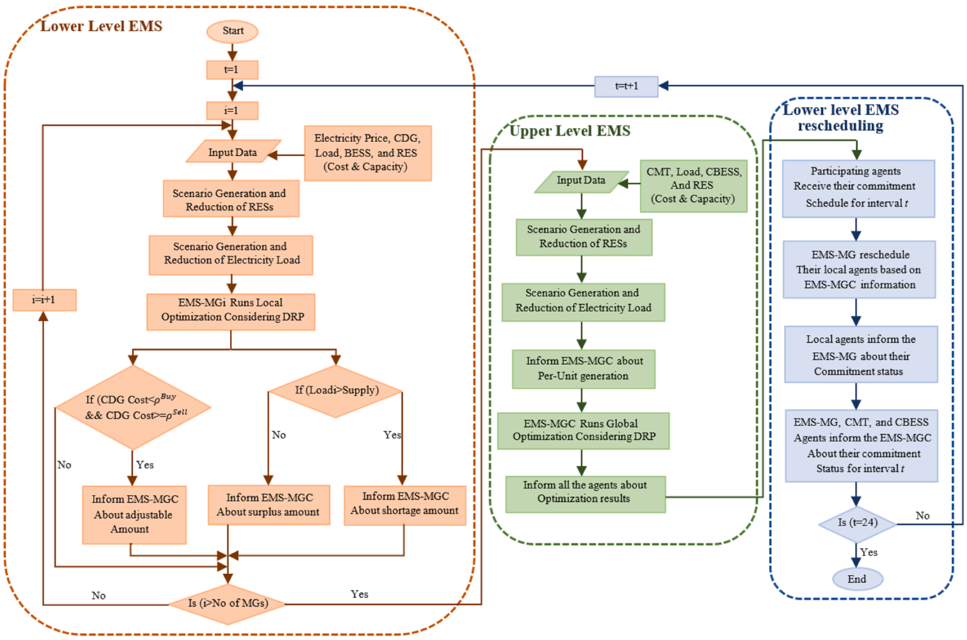


Fig. 3. Flowchart of the proposed energy management strategy of networked MGs.

The power balance of the rescheduling step is shown by (56).

$$\sum_{j=1}^{2}\left(P^{CDG}_{s,t,i,j}+\Delta P^{adj}_{s,t,i,j}\right)+P^{ES,Dis}_{s,t,i}+P^{WT}_{s,t,i}+P^{PV}_{s,t,i}-P^{ES,Chr}_{s,t,i}$$
$$-P^{Load}_{s,t,i}=P^{M\_Short}_{s,t,i}+P^{M\_Surplus}_{s,t,i}+P^{M\_Sen}_{s,t,i}+P^{M\_Rec}_{s,t,i} \quad (56)$$

The cost of sending/receiving power is calculated through (57):

$$C^{R\&S}_{s,t,i}=\rho^{Rec}_{t,i}P^{Rec}_{s,t,i}+\rho^{Sen}_{t,i}P^{Sen}_{s,t,i} \quad (57)$$

The flowchart of the proposed model is shown in Fig. 3. The proposed framework is modeled as Mixed Integer Linear Programming (MILP) and has been solved under GAMS and MATLAB software on a Core i7, 3.5 GHz processor with 12 GB of RAM.

5. Case study

The input data and case studies have been introduced in this section.

5.1. Input data

In this paper, the energy management of islanded networked MGs has been investigated to minimize the operation cost of the system. The proposed method is based on the modified MGC system [15], which is updated for four MGs [14]. It is assumed that some part of the insensitive loads is cut to maintain the reliability of the MG and increase its stability. The minimum and maximum amounts of DR are −20% and 20%, respectively. According to [19], the penalty cost (a_{IL}) is higher than the marginal cost of CDGs. The maximum amount of power exchange is considered 1500 kW. The onshore wind turbine Vestas V100 IEC IIB is considered according to [28]. The electricity prices are taken from the South Australian Energy Market Operator and are shown in Fig. 4.

Also, the wind speed, sun irradiation, and electric load can be found in [29–31]. The characteristics of microturbines, fuel cells, storage systems, and renewable generation are presented in Tables 2,3,4, and 5, respectively.

5.2. Results and discussion

To evaluate the efficiency of the proposed model, three cases are examined:

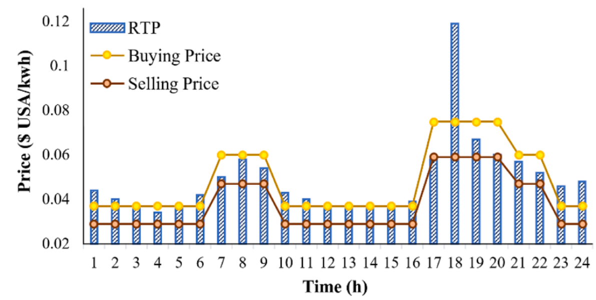


Fig. 4. Day-ahead profiles of electricity prices.

(i) *Case 1 (uncoordinated operation strategy):* Each MG performs an autonomous operation scheduling and individually minimizes its costs using decentralized energy management. In this case, all MGs are disconnected from the upstream network and operated as an islanded mode.
(ii) *Case 2 (hybrid energy management without adjustable power):* In this case, the operation scheduling of an island networked MG system has been investigated using hybrid energy management without considering adjustable power. The MGC operates in disconnected mode, while the connection between the MGs in MGC is established.
(iii) *Case 3 (hybrid energy management considering adjustable power)*: In this case, we evaluate the proposed hybrid energy management strategy. We consider the adjustable power concept to study the transactive energy among the MGs. Also, MGs can modify their primary scheduling in the rescheduling step. The results of the transactive energy among MGs are shown in Fig. 5. Fig. 5a and b shows the amount of transactive energy among MGs at the lower-level considering the PBDR program. Also, the amount of transactive energy among MGs without the PBDR program has been presented in Fig. 5c and d.

The positive values show the surplus power, while the negative values are the shortage power of MGs. It should be noted that the surplus/shortage powers have been considered as generation/load in the MGC. As we can see, the amount of transactive energy in case 3 is more

Table 2
Parameters of MTs in each microgrid and MGC [32].

Parameters	Microturbine characteristics MT1	MT2	MT3	CMT
η (%)	29.5	31.1	28.9	29.5
$\underline{P}^{MT}$ and $\overline{P}^{MT}$ (kW)	0, 190	0, 320	0, 240	0, 950
SUC^{MT} and SDC^{MT} ($)	0.22, 0.1	0.2, 0.12	0.21, 0.09	0.18, 0.16
O&M cost ($ /kWh)	0.016	0.009	0.011	0.012

Table 3
Parameters of FCs in each microgrid [32].

Parameters	Fuel cell characteristics FC_1 (MCFC)	$FC_{2\&3}$ (PAFC)
η (%)	52.2	38.1
$\underline{P}^{FC}$ and $\overline{P}^{FC}$ (KW)	0, 300	0, 400
SUC^{FC} and SDC^{FC} ($)	0.33, 0.22	0.32, 0.2
O&M cost($ /kWh)	0.045	0.036

Table 4
BESS parameters in each microgrid and MGC [24,33,34].

Parameters	Lead acid battery energy storage systems $BESS_1$	$BESS_2$	$BESS_3$	$CBESS$
$K^{ES}_{O\&M}$ ($ /kWh)	0.002	0.002	0.002	0.002
E^{ES}_{R} (kWh)	2800	2600	2400	3200
E^{ES}_{INIT} and& E^{ES}_{END} (kWh)	570 and 570	530 and 530	490 and 490	640 and 640
$\overline{P}^{ES.Dis}$ and& $\overline{P}^{ES.Chr}$ (kW)	700	650	600	800
$\overline{SOC}$ and& $\underline{SOC}$ (%)	80 and 20	80 and 20	80 and 20	80 and 20
$\eta^{ES.Dis}$ and& $\eta^{ES.Chr}$(%)	92	92	92	92

Table 5
Value of parameters [28,35–37] ($ USA).

Value	Parameters	Value	Parameters
1.7$/GJ	C_{ng}	2 MW	Rated power of wind turbine
9.78 KWh/m^3	L_{ng}	3 m/s	Cut-in wind speed
0.12$/KWh	ρ^{DS}	22 m/s	Cut-out wind speed
0.6$/KWh	ρ^{DE}	12 m/s	Rated wind speed
3% per month	η^{L}	30%	η^{PV}
0.08$/KWh	a^{IL}	2.16 m^2	S^{PV}
0.016$/KWh	$K^{PV}_{O\&M}$	0.015$/KWh	$K^{WT}_{O\&M}$

than case 2 because of adjustable power. The results of Fig. 5 show that the adjustable power enhances the internal power trading. The total hourly transactive energy between MGs and MGC in the case studies for different conditions has been presented in Fig. 6.

When the PBDR program has been implemented, the total daily transactive energy in cases 2 and 3 is −1298 kWh and 1005 kWh, respectively. It means that MGs in case 2 import energy from MGC. Also, when the MGs cannot participate in the PBDR program, the total daily amount of transactive energy in cases 2 and 3 is −2090 kWh and 575 kWh, respectively. However, the results of Fig. 6 show that by the PBDR program, the amount of surplus energy of MGs is enhanced. Unlike MGs 1 and 3, the MG2 has surplus power at the most of time slots. Therefore, MGs 1 and 3 can utilize the surplus power of MG2 as a back-up to supply the required energy. Fig. 7 shows the amount of load shedding and wasted energy for the case studies.

In the uncoordinated operation, MGs are not able to transact energy together. Therefore, if MGs have surplus power, they will suffer from the

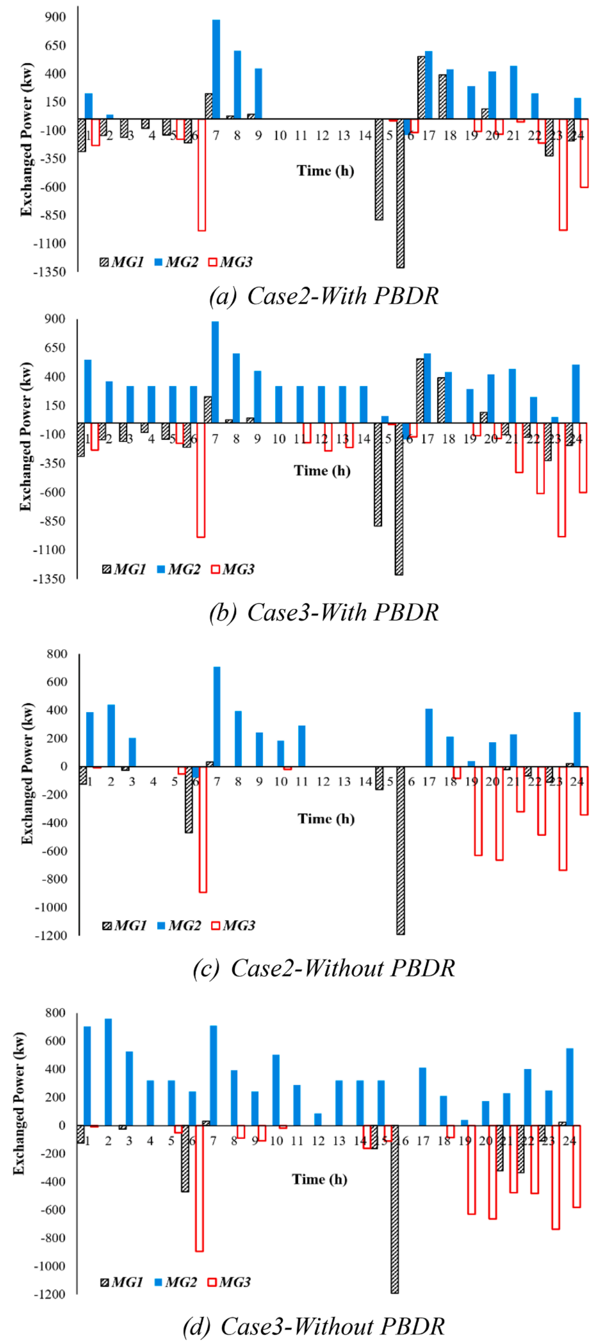


Fig. 5. Exchanged power scheduling results in microgrids in cases 2 and 3.

waste of energy [16], and if they have a power shortage, they will suffer from load shedding. Both wasted energy and load shedding increase the cost of energy scheduling. Therefore, the connection among MGs (cases 2 and 3) reduces the operating costs compared to uncoordinated mode. The results of adjustable power considering the PBDR program is presented in Table 6.

According to Table 6, EMS-MGC informs the EMS-MG2 to increase the output power of MT-MG2 because the cost function of MT-MG2 is lower than other sources, and it can generate more energy. Therefore, using adjustable power, EMS-MGC reduces the total cost of the system and the shortages in other MGs and MGC. To prevent the wasted energy at time slots 21 and 22, EMS-MGC sends the reduction signals to fuel cells in MGs1 and 3. Since the generation costs of fuel cells are higher than CMT and MTs, the reduction signals have been sent to the fuel cells. The total cost of the studied system in different case studies is shown in

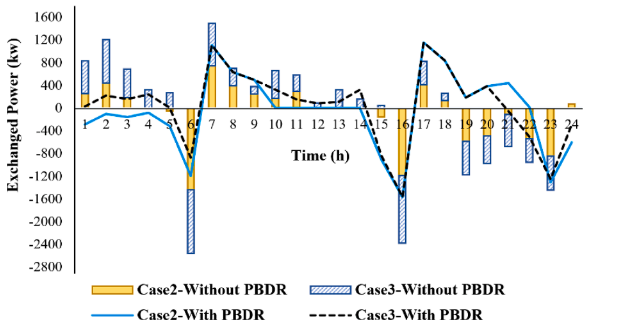


Fig. 6. The sum of the exchanged power scheduling results in the three microgrids in cases 2 and 3.

Table 7.

When MGs participate in the PBDR program, they can shift their load demands from peak periods to off-peak periods. Therefore, the power generation of units with high marginal cost has been decreased. Also, the amount of load shedding has been decreased. Therefore, the total cost of the system is decreased by the PBDR program in the case studies. It should be noted that the cost of MGs in the proposed model is less than cases 1and 2. In case 1, the MGs cannot exchange energy together, and each MG should supply the required energy locally by its sources. In case 3, the adjustable powers help to improve the transactive energy among MGs, and compared to case 2, the total cost of the system is reduced. The results of the energy scheduling of BESSs, CDGs, and load shedding in case studies are shown in Fig. 8.

During off-peak periods, the generation power of CDGs in case 1 is more than cases 2 and 3 because MGs cannot transact energy together, and each MG should supply the required energy by its local resources. The total generation of CDGs in cases 1, 2, and 3 is 29,982 kWh, 29,792 kWh, and 29,923 kWh, respectively. Therefore, the amount of load shedding, emission of greenhouse gasses, wasted energy, and total cost in case 1 is more than other case studies. Also, the minimum load shedding belongs to case 3. The performance of battery energy storage systems in the proposed model for different conditions is shown in Fig. 9a and b. According to Figs. 8 and 9, BESSs stored surplus power during off-peak periods and discharged it during peak periods. As shown in Fig. 9, the PBDR program has a significant impact on the performance of CBESS.

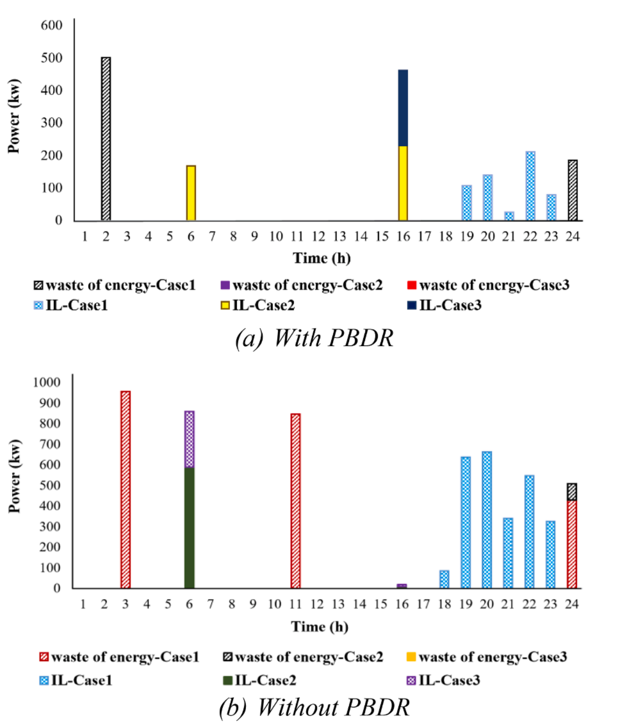


Fig. 7. Results of load shedding and waste of energy in cases 1 to 3.

Table 6
Bounds for adjustable amount in each MG of networked MGs system with consideration PBDRP.

Time (h)	$\Delta P_{2.1}^{adj}$ (KWh)	$\Delta P_{3.1}^{adj}$ (KWh)	$\Delta P_{1.2}^{adj}$ (KWh)	$\Delta P_{2.2}^{adj}$ (KWh)	$\Delta P_{3.2}^{adj}$ (KWh)
1	320	0	0	0	0
2	320	0	0	0	0
3	320	0	0	0	0
4	320	0	0	0	0
5	320	0	0	0	0
6	320	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	320	0	0	0	0
11	320	−172	0	0	0
12	320	−240	0	0	0
13	320	−212	0	0	0
14	320	0	0	0	0
15	63	0	0	0	0
16	0	0	0	0	0
17	0	0	0	0	0
18	0	0	0	0	0
19	0	0	0	0	0
20	0	0	0	0	0
21	0	0	−101	0	−400
22	0	0	−125	0	−400
23	52	0	0	0	0
24	320	0	0	0	0

If MGs participate in DR programs, the MGC can utilize a battery energy storage system with a lower capacity to reduce investment costs. Due to the lack of MGC connection to the upstream network, CBESS has been used more to maintain stability and increases system reliability in the islanded mode. The maximum value of CBESS-SOC in Fig. 9a is 0.587, and the energy capacity of CBESS is 3200 kWh. The energy capacity of new storage with two iterations through Eq. (58) is equal to 2076.35 kWh with 800 kW charge/discharge power, and the minimum initial/final energy 415.27 kWh. The number of iterations continues until the SOC_{new} is set to the maximum value (0.8). The charge status of MGC new battery energy storage in case 3 with the PBDR program is shown in Fig. 10.

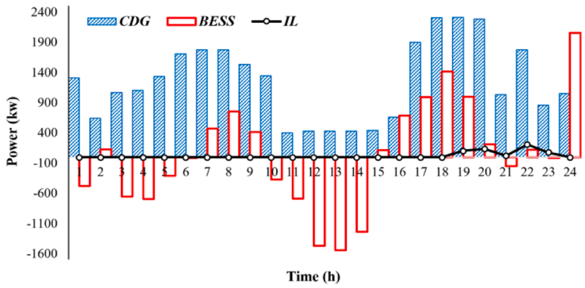
$$\begin{cases} E_{R,New}^{ES} = E^{ES} - \underline{SOC}\left(E_{R,old}^{ES} - E^{ES}\right) \\ E^{ES} = \left(\dfrac{SOC_{\max,old}.E_{R,old}^{ES}}{\overline{SOC}}\right) \end{cases} \tag{58}$$

6. Conclusions and future research challenge

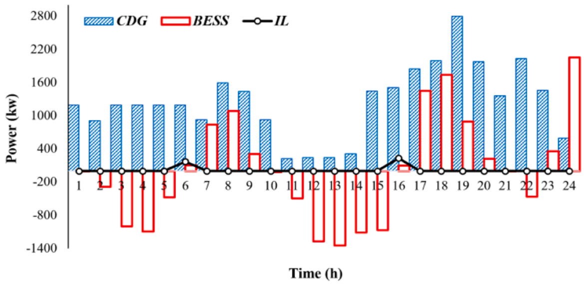
This paper proposes a two-level optimization framework for the day ahead scheduling of islanded networked microgrids with high penetration of renewable energy sources. To show the superiority and efficiency of the proposed model, three cases are compared with each other. In the proposed model, a hybrid energy management system is used that consists of local optimization, global optimization, and re-local optimization. The objective of the proposed model is the cost minimization

Table 7
Operating costs of the studied system in different conditions.

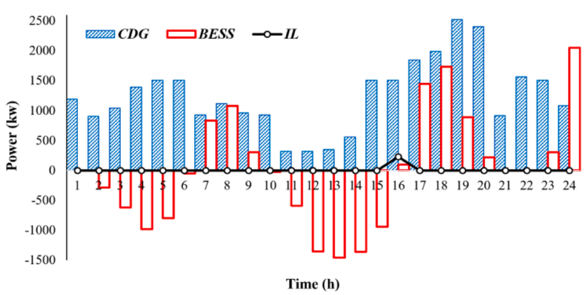
DR status	Case 1	Case 2	Case 3
With PBDRP	2934.26$	2819.40$	2759.51$
Without PBDRP	3209.60$	3029.40$	2965.33$



(a) Case1-With PBDRP



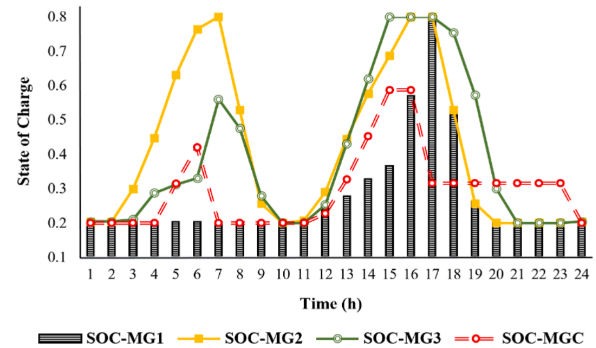
(b) Case2-With PBDRP



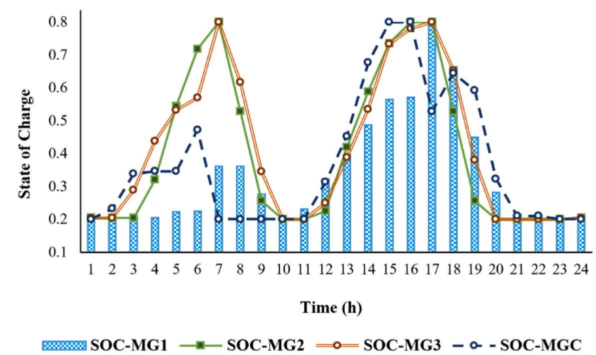
(c) Case3-With PBDRP

Fig. 8. (a) Summation of power scheduling of BESS, CDG, and interruptible load in case 1 (b) power scheduling of BESS, CDG, and interruptible load in case 2 (c) power scheduling of BESS, CDG, and interruptible load in case 3.

of the MGs and the system. Besides, the adjustable power ranges have been defined to control the surplus/shortage energy of microgrids by MGC and improve the transactive energy in the system. Also, control and coordination between surplus and shortage powers are achieved through power exchange by system-level devices and power exchange among MGs. By the adjustable power concepts: 1) the generation power of cheaper CDGs has been increased to reduce the total cost of the system. 2) The shortage powers of MGs and MGC have been decreased using the surplus power of MGs. 3) The amount of involuntary load shedding has been decreased. 4) Preventing the wasted energy in islanded mode. According to the simulation results, the proposed model has better technical and economic performances. The simulation results show that the proposed model reduces the amount of wasted energy and load shedding of the system. The proposed model can be applied to the practice setting where a virtual power plant (VPP) provides energy services for a certain geographical area consist of several MGs [38]. The MGs send their shortage/surplus powers to the VPP. The VPP defines the adjustable power amounts to provide better transactive energy among MGs. Also, it is noteworthy that the proposed model is applicable to multi-energy systems, where the heating and electric networks are integrated [39]. In these systems, the MGC should define two electric and thermal adjustable powers. The efficiency of the proposed model on multi-energy systems will be investigated in future works.



(a) Case3-With PBDRP



(b) Case3-Without PBDRP

Fig. 9. State of charge battery energy storages in case 3.

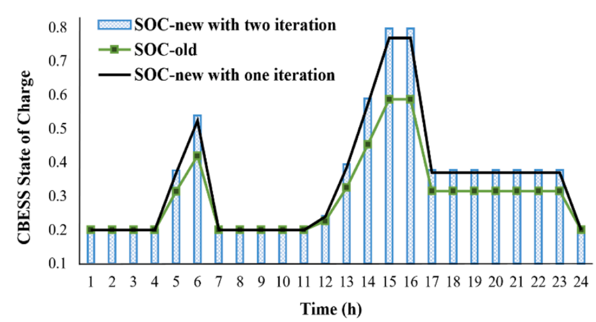


Fig. 10. State of charge community battery energy storage in case 3.

Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property.

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CRediT authorship contribution statement

Ali Jani: Conceptualization, Data curtion, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Hamid Karimi:** Conceptualization, Data curtion, Formal analysis, Project administration, Supervision, Validation. **Shahram Jadid:** Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

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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