Electrical Power and Energy Systems 118 (2020) 105760

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new isolated renewable based multi microgrid optimal energy management system considering uncertainty and demand response

Seyed Ehsan Ahmadi, Navid Rezaei*

Department of Electrical Engineering, University of Kurdistan, Sanandaj, Iran

ARTICLE INFO

Keywords:
Networked microgrids (NMGs)
Isolated structure
Demand response program (DRP)
Microgrid marginal pricing (MGMP)
Energy management system (EMS)

ABSTRACT

This paper proposes a novel energy management system (EMS) for an isolated structure of networked microgrids (NMGs). The interconnected microgrids consist of the cyber-physical connections for information and power exchanges. A bi-level EMS is presented in which the outer-level EMS is aimed to exchange the required information and power between the interconnected microgrids, and the inner-level EMS is intended for energy scheduling of each on-fault microgrid in case of separation from other microgrids. This paper focuses on the operation of interconnected microgrids. A step-wise demand response program (DRP) is also considered in the energy management to attain the cost-effective operation. Furthermore, a new pricing model based on microgrid marginal pricing (MGMP) is introduced for the power exchanges between the interconnected microgrids. To cope with the uncertainties of the renewable energy sources and loads, some scenarios are generated using the scenario-based analysis. Also, a backward scenario reduction method is used to reduce the number of the scenarios. Besides, a mixed integer linear programming (MILP) is applied to the stochastic optimization problem of the NMGs. The proposed model is implemented on a test system with five NMGs. The simulation is run over a 24-hour scheduling time horizon. Both cases without and with demand response program (DRP) are compared in the numerical results. The results of the simulation demonstrate that using the proposed DRP in the energy management increases the performance of the generation units and decreases the total operational cost of the proposed NMGs. Also, the voltages of the buses converge to their rated values.

1. Introduction

1.1. Motivations

Environmental concerns and rising energy consumption today increase the usage of distributed energy resources, energy storages (ESs) and demand response programs (DRP). Besides, renewable energy sources (RES) play an important role in clean energy generation [1]. Although controlling many these resources presents difficult challenges in the safe and efficient operation of the network, these challenges are managed by the concept of microgrid [2]. Microgrid is a distribution system consisting of distributed generations (DGs), ESs and responsive loads. Indeed, microgrids are operated as an interconnected or isolated network. From the upstream grid perspective, the microgrid is a controllable system that is operated as a controllable load or a power source. In grid-connected mode, the microgrids send or receive power from the main grid and other microgrids in the system. However, factors such as major disruption to the main grid, decreasing the power quality of the main grid according to the certain standards, or maintenance programs cause to isolate the microgrid from the main grid [3–5].

Given the uncertainties in DER, the availability of ESs and responsive loads along with RES-based DGs is a proper solution for achieving higher reliability and ensuring balance between generation and load demand in the microgrids. This issue not only delays the increase of the generation capacity, but also reduces system operating costs and greenhouse gas emissions. Furthermore, deploying a microgrid can facilitate the implementation of the efficient DRP [6,7].

According to recent studies, the interconnection of the microgrids as a networked structure improves system performance and reliability in order to take advantage of significant features of networked microgrids (NMGs) [8,9]. In this regard, the operators of the microgrids can reduce their operating costs and customers can also benefit from a more cost-effective and reliable power source. Notably, the NMGs have a preferable economic dispatch and islanding control than the single microgrid system [10,11]. Furthermore, the optimal implement of the distributed energy resources in each microgrid, and the exchanged power to the upstream grid or other microgrids which cannot meet the demand of

* Corresponding author.
E-mail address: n.rezaei@uok.ac.ir (N. Rezaei).

https://doi.org/10.1016/j.ijepes.2019.105760
Received 7 September 2019; Received in revised form 1 December 2019; Accepted 4 December 2019

Nomenclature

Acronyms

DG distributed generation
DRP demand response programs
EMS energy management system
ES energy storage
MGMP microgrid marginal price
MILP mixed integer linear programming
NMGs networked microgrids
PV photovoltaic
RES renewable energy sources
WT wind turbine

Indices

index for microgrids
b index for buses
t index for tie-lines
d index for DRP
w index for steps of DRP curve
g index for DGs
n index for RES
e index for ESs
h index for scheduling time horizon
s index for scenarios

Sets

S set for scenarios
W set for steps of DRP curve
D_m set of responsive loads in mth microgrid
T_m set of tie-lines in mth microgrid
L_m set of loads in mth microgrid
G_m set of DGs in mth microgrid
N_m set of RES in mth microgrid
E_m set of ESs in mth microgrid

Parameters

$LP_{b,h,s}$ active demand at bth bus at hour h for scenario s
$LQ_{b,h,s}$ reactive demand at bth bus at hour h for scenario s
$DR_{d,h,s}^{\min}$ minimum load reduction of dth DRP at hour h for scenario s
$DR_{d,h,s}^{w}$ maximum load reduction of wth step of dth DRP at hour h for scenario s
$TLP_{m,h}$ total active demand in mth MG at hour h
$PG_g^{\max}$ maximum allowed active output of gth DG
$QG_g^{\max}$ maximum allowed reactive output of gth DG
$PG_g^{\min}$ minimum allowed active output of gth DG
$QG_g^{\min}$ minimum allowed reactive output of gth DG
RP_g active ramp limit of gth DG
RQ_g reactive ramp limit of gth DG
$PE^{\max}$ maximum allowed active power exchange
$QE^{\max}$ maximum allowed reactive power exchange
$PS_e^{ch,\max}$ maximum charging limit of eth ES
maximum discharging limit of eth ES
$PR_{n,h,s}$ active power output of nth RES at hour h for scenario s
$SOC_e^{\min}$ minimum state of charge of eth ES
$SOC_e^{\max}$ maximum state of charge of eth ES
EC_e capacity of eth ESs
α_g, β_g generation cost parameters of gth DG
r_b line resistance between buses b and $b+1$
x_b line reactance between buses b and $b+1$
ε maximum allowed voltage deviation
$\pi_{t,h}$ power exchange price of tth tie-line at hour h
λ_d^w offered price in step wth of dth DRP
η^{ch} charging efficiency of ESs
η^{dch} discharging efficiency of ESs
γ_s probability of sth scenario
σ coefficient of power exchanges
ψ depreciation factor of ESs

Variables

$FG_{m,h}(\cdot)$ generation cost function of DGs in mth microgrid at hour h
$FD_{m,h}(\cdot)$ function of the selling electricity in mth microgrid at hour h
$PF_{b,h,s}$ active power flow from bus b to $b+1$ at hour h for scenario s
$QF_{b,h,s}$ reactive power flow from bus b to $b+1$ at hour h for scenario s
$V_{b,h,s}$ voltage magnitude at bus b at hour h for scenario s
$\upsilon_{b,h,s}$ additional variable of voltage magnitude at bus b at hour h for scenario s
$PD_{d,h,s}$ offered load reduction of dth DRP at hour h for scenario s
$PD_{d,h,s}^{w}$ offered load reduction in wth step of dth DRP at hour h for scenario s
$PE_{t,h,s}^{up}$ active power exchange of tie-line t from lower microgrid to upper microgrid at hour h for scenario s
$PE_{t,h,s}^{do}$ active power exchange of tie-line t from upper microgrid to lower microgrid at hour h for scenario s
$QE_{t,h,s}^{up}$ reactive power exchange of tie-line t from lower microgrid to upper microgrid at hour h for scenario s
$QE_{t,h,s}^{do}$ reactive power exchange of tie-line t from upper microgrid to lower microgrid at hour h for scenario s
$PG_{g,h,s}$ active power output of gth DG at hour h for scenario s
$QG_{g,h,s}$ reactive power output of gth DG at hour h for scenario s
$PS_{e,h,s}^{ch}$ charging value of eth ES at hour h for scenario s
$PS_{e,h,s}^{dch}$ discharging value of eth ES at hour h for scenario s
$SOC_{e,h,s}$ state of charge of eth ES at hour h for scenario s
$TPG_{m,h}$ total generation of DGs in mth MG at hour h
TOC_m total operation cost of mth MG
$\mu_{g,h,s}^{uc}$ commitment state of gth DG at hour h for scenario s
$\mu_{g,h,s}^{su}$ start-up state of gth DG at hour h for scenario s
$\mu_{g,h,s}^{sd}$ shot-down state of gth DG at hour h for scenario s
$\mu_{d,h,s}^{dr}$ state of dth DRP at hour h for scenario s
$\mu_{e,h,s}^{ch}$ charging state of eth ES at hour h for scenario s
$\mu_{e,h,s}^{dch}$ discharging state of eth ES at hour h for scenario s
$\mu_{t,h,s}^{up}$ power exchange state of tie-line t from lower microgrid to upper microgrid at hour h for scenario s
$\mu_{t,h,s}^{do}$ power exchange state of tie-line t from upper microgrid to lower microgrid at hour h for scenario s

their consumers, are the significant features of the NMGs structure [12].

The concept of the NMGs cannot be widely applied without implementing an active energy management system (EMS) to achieve the efficient and the reliable control process [13]. According to the latest researches, the purpose of the NMGs energy management is to minimize the operating costs such as the fuel costs, the maintenance costs and the cost of the purchasing energy from the main grid while enhancing its reliability and environmental performance. EMS is used to optimize the performance of dispatchable DGs such as microturbines (MTs), ESs, demand side management throughout the network and power

Table 1
Compare the references reviewed on the energy scheduling of the multi-microgrids.

Reference	Uncertain Parameter		Energy Management System						
	RES-based	Load demand	Centralized	Decentralized	Distributed	Hybrid / Proposed	Deterministic	Stochastic	DRP
[19]	*	*			*			*	
[20]				*			*		
[21]						*	*		
[22]					*		*		
[23]		*		*				*	
[24]	*	*	*					*	
[25]	*	*				*		*	
[26]	*			*				*	
[27]	*			*				*	*
[28]	*	*	*					*	*
[29]	*	*	*					*	*
[30]	*	*				*		*	*
[31]				*			*		*
[32]				*			*		*
[33]	*	*	*				*	*	
[34]	*	*				*		*	*
This Paper	*	*				*		*	*

Reference	Energy Management System	Modelling Strategy		Operation Constraints				Programming Approach		Connection Status of the NMGs
	Storage Systems	Commitment States	Dist. Flow	Power Exchange Price	24-Hour scheduling	Linear (MILP)	Nonlinear (MINLP)	Isolated single MG from the system	Isolated NMGs from the main grid	Connected MG(s) to the main grid
[19]	*	*			*		*	*		
[20]	*	*	*		*	*				*
[21]	*	*			*	*				*
[22]			*				*			*
[23]	*		*				*			*
[24]	*				*		*			*
[25]	*				*		*			*
[26]			*	*		*				*
[27]	*				*		*			*
[28]	*						*			*
[29]	*	*			*	*				*
[30]	*				*	*				*
[31]	*				*	*				*
[32]	*				*		*			*
[33]	*				*		*			*
[34]	*		*	*	*		*			*
This Paper	*	*	*	*	*	*			*	

exchanges among the microgrids [14,15]. On the other hand, extending the usage of the RES in the microgrids has not only increases the uncertainties but also creates new uncertainty parameters in the operation of the NMGs. Hence, previous approaches based on deterministic modeling in the studies of the NMGs are no longer applicable to counteract the uncertainties. For this reason, new models based on probabilistic approaches are developed to examine the EMS in advanced networks under various uncertainties [16–18].

1.2. Literature review and approach

Many studies have been accomplished on the operation scheduling approaches of the NMGs. In [19], a resilience-oriented strategy has been presented for the optimal operation of the NMGs by considering feasible islanding in normal mode and supplying of critical loads in emergency. Also, the uncertainties of the RES-based DGs and loads have been considered in the optimization method. However, such approach has been studied only a single isolated microgrid and the potential interactions between the microgrids has been neglected.

In [20], the characteristics of two kinds of the decentralized economic dispatch framework of a distribution network with multi-microgrids have been compared. The proposed decentralized framework contains the uncertainties of RES generation and load consumption in a deterministic approach. Also, this framework can solve economic problems by centralized optimization. In [21], a nested energy management strategy has been proposed for day-ahead scheduling of NMGs. Compared to conventional EMS, the operation cost of the NMGs with proposed strategy is more cost-effective. The analysis of uncertainties in both RES outputs and loads were not taken into the account. In [22], a Software-Defined Networking (SDN) architecture has been introduced which is able to achieve fast power support between MGs, changing isolated local microgrids to the networked structure to assess more resiliency and efficiency. However, in studies [20–22], the deterministic approach has been considered and no attention has been paid to the uncertainty parameters.

In [23], a decentralized economic dispatch method has been addressed, when the distribution system operator (DSO) participate with microgrid central controllers (MGCCs) in the NMGs to optimize the energy management of the distribution system. However, in the above-mentioned references, the impact of DRP on the microgrid energy scheduling were neglected. In [24], integrated operation management of multi-microgrid system with stochastic predictive control has been defined. A joint probabilistic constraint of the power exchanges between the microgrids and the main grid is also addressed. In [25], a hierarchical stochastic EMS is proposed for the operation of interconnected microgrids. The power reference values to be exchanged between the microgrids and between the microgrids and the main grid are calculated with the local EMS. It should be noted that the studies in [19–25], the prices for the power exchanges between the microgrids have not been considered.

In [26], a decentralized EMS for the optimal operation of the NMGs in a distribution system has been presented. In the grid-connected mode, the operators of the distribution system and the microgrids have been considered as self-sufficient entities with objectives functions in order to minimize their own operating costs. Although the price for the power exchange has been considered in [26], no explanation has been provided on how to calculate this price. Also, the generation cost of the DG unit is assumed to be constant and the power exchange price is assumed to be twice the generation cost.

Several studies have been investigated the DRP in the networks containing single and multi-microgrids. In [27], a theoretical framework has been proposed for the optimization of investment and operation of a microgrid as a two-period stochastic programming program. The ES, RES-based units and DRP are also considered in the proposed microgrid. However, only a single microgrid has been connected to the main grid and the structure of the interconnected microgrids has been neglected. In [28], the probabilistic analysis of the optimal load dispatch has been proposed in a multi-carrier NMG to study the impact of the uncertain parameters of the RES units and loads on the optimal operation of the microgrids. Also, a new time-based demand side management has been considered to modify the load curve and prevent the inordinate energy consumption in peak hours. In [29], a local resource-triggered survivability-oriented DRP has been presented to minimize the load shedding and reduce of the usage of the RES units. The proposed DRP is triggered by market price signals. The uncertainties of RES and load are also considered via a robust optimization method. In [30], an optimal scheduling problem has been presented for the NMGs under the uncertainties of the RES and loads in a proposed EMS. Two DRPs based on time of use (TOU) and real time pricing (RTP) have been incorporated into the optimization problem. Also, the optimization model has been solved applying a metaheuristic algorithm. In [31], the energy exchange among interconnected microgrids and the corresponding impacts on costs of the microgrids have been studied. Also, a bargaining-based energy trading market is designed, where the interconnected microgrids are the decision makers for the value of energy exchange and the related payments. In [32], the cooperation between the interconnected microgrids has been studied in which each microgrid exchanges the energy with other microgrids in a distribution network. Also, an incentive mechanism using Nash bargaining theory is applied to coordinate the energy exchanges. However, in studies [31] and [32], the deterministic approaches have been applied and the uncertainties of the RES-based units and load consumptions have been ignored.

In [33], the scheduling problem of networked microgrids has been presented. An efficient strategy has been applied to control local operation of each microgrid. The amount of the required energy from the main grid and active power output of the batteries during the power exchanges between the microgrids are the main goals of the operation problem. However, the impact of demand response programs on the operation of the networked microgrids has not been mentioned. Also, the distribution system load flow and the voltage constraints associated with the buses have not been applied. In [34], optimal operational of a reconfigurable distribution system with multi-microgrid has been presented. The DRP and ESs are included in scheduling problem of the distribution system in an uncertain environment. The costs of the exchanging powers between Distribution System Operator (DSO) and microgrids have been calculated according to the difference between the transmitted power from the microgrids to the DSO and from the DSO to microgrids and day-ahead wholesale market electricity price. However, in studies [33] and [34], no specific equation has been considered for the price of the exchange power and the same day-ahead wholesale market electricity price has been used to calculate the costs of the exchanging powers. Also, the structure intended for the interconnected microgrids are connected to the main grid and the active powers are exchanged between the microgrids and the DSO.

The comparison between multiple research studies on the energy scheduling of the multi-microgrids is summarized in Table 1. As it is clear from Table 1, the innovative and extensive approach of this paper can be demonstrated.

After a comprehensive assessment of the literature on the scheduling approaches of the NMGs studies, due to the best of our knowledge, it has been recognized that no research has been dedicated to proposing an isolated structure for the NMGs in which the microgrids are disconnected from the main grid. On the other hand, the DRP in the isolated structure of the NMGs has not been considered. Disconnecting an active distribution system from the main grid is a situation that may occur in a power system. On the other hand, in addition to the possibility of isolating the NMGs from the main grid, it can be assumed that microgrids are the real islands which are connected through the tie lines. In practical, there are such structures in which there are no upstream grids. Certainly, such structures of isolated NMGs requires accurate consideration. In this regard, an active distribution system can

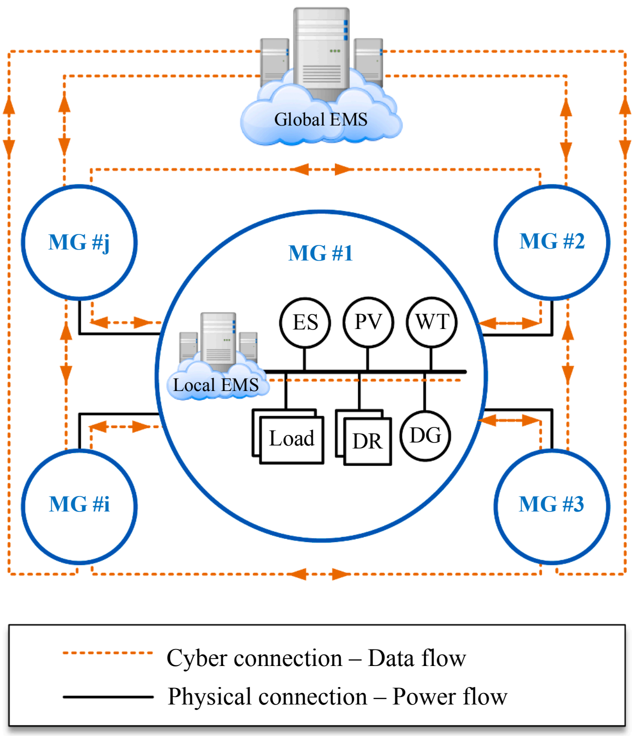

Fig. 1. Proposed structure of energy management for NMGs.

take the advantages of the NMGs, especially when a fault occurs in the isolated NMGs. In the meantime, the microcosm can receive support from other microcontrollers. In this case, the on-fault microgrid can receive the power support from other normal operated microgrids.

In order to fill this gap out, this paper presents the optimal scheduling of the isolated NMGs in the cases with and without the DRP. The proposed structure for the NMGs is optimized using the stochastic approach and investigated with the uncertainties of the RES-based units and loads through a novel bi-level EMS based on distributed concept. The bi-level EMS of the NMGs consist of the cyber-physical connections for exchanging the power support and the required information. The outer-level EMS is allocated for coordinating the DG outputs and the power exchanges among the microgrids in the interconnected status. Also, the inner-level EMS is conceived for each on-fault microgrid to schedule the optimal operation of the isolated zone in the networked system. The cyber communications are strongly connected in both levels of the EMS to exchange the required data in operation modes.

The dispatchable DGs, the RES units, the ESs and the DRP are presented in each microgrid to assess a comprehensive model of the NMGs. Also, a new pricing model for the power exchange between the NMGs is proposed in which the prices are estimated considering the microgrid marginal pricing (MGMP). Besides, the equations of the stochastic optimization problem are efficiently linearized. In summary, the main contributions of this paper can be highlighted as the following:

- A bi-level EMS is presented for the isolated structure of the NMGs. The outer-level EMS is proposed to exchange the required information and power support in the interconnected status of the microgrids and the inner-level EMS is intended for energy scheduling of each on-fault microgrid in case of separation from other microgrids.
- A step-wise DRP is proposed for each microgrid to coordinate the DG generations and load consumptions and to assess a thorough model of the NMGs. The proposed DRP contains different offered prices to investigate the load reductions in each microgrid.
- A novel power exchange pricing model is introduced to control the power exchanges in an isolated NMGs. In this paper, the cost of the exchanged power among two MGs is calculated according to their MGMP.

The reminder of the paper is outlined as follows. In Section 2, the energy management model of the NMGs is described. In Section 3, the probabilistic model of uncertainty, the power exchange pricing model and optimization problem of the NMGs are introduced. In Section 4, the proposed model of the isolated NMGs is simulated and illustrative implementation is given in detail. Finally, this study is concluded with some points in Section 5.

2. Energy management model of the NMGs

The proposed energy management for an isolated structure of the NMGs considering of DG units, RES-based units, ESs, active and reactive loads and DRP is illustrated in Fig. 1. In the interconnected status, the microgrids are connected radially via both cyber connections for exchanging required information and physical connections through the tie-lines between the central microgrids and the lower microgrids for exchanging the power support.

The energy management model is characterized by a bi-level EMS with independent function in each level. The outer-level EMS is devised for the information and power exchanges among the interconnected MGs. When the NMGs are isolated from the upstream grid, the outer-level EMS is activated. In this case, the global energy management is applied to achieve the global optimal solution of the operation problem of the interconnected microgrids. In fact, the global energy management guarantees the optimal scheduling of the NMGs from technical and economic viewpoints. In the interconnected status of the microgrids, the inner-level EMS is idle. The inner-level EMS is intended for energy scheduling of each on-fault microgrid. When a fault occurs in the NMGs, the inner-level is activated and the local energy management schedules the operation of the on-fault zone. Thus, no power exchanges among the on-fault zone and other interconnected microgrids. In the interconnected status of the microgrids, the inner-level EMS is inactive. It is worth mentioning that the cyber connections between the microgrids are strongly interconnected and no isolating is formed in the information exchange. In this paper, studies on the isolated operation of the on-fault microgrids using the local energy management in the inner-level have not been presented.

In the interconnected status of the isolated NMGs, in contrast to the networked systems being operated with a decentralized method, in which the microgrids apply the local measurements, the microgrids of the networked systems containing a proposed bi-level energy management method can share their data with other microgrids. It means that the NMGs with the proposed methods in this paper not only utilize local measurements, but also are able to send and receive required information. As a result, this kind of energy management realizes the reliability, the stability and the global optimization such as the centralized measurements methods [35,36].

3. Model description

In this section, the model and the optimization problem of the NMGs for a 24-hour time horizon operation are described. The reason for choosing a 24-hour time horizon operation is to investigate the impact of the different uncertainties of the RES-based units and the load consumptions within some scenarios on the DG units, the ESs and the and responsive loads.

3.1. *Scenario-based probabilistic model of uncertainty*

Uncertainty is used to support decisions based on actual measurements in accordance with climatic conditions. Hence, estimations of uncertainty should reflect the measurement process in a realistic way

[37]. There are several ways to deal with the uncertainties in a probabilistic approach. In this paper, scenario-based analysis (SBA) is applied to generate the number of scenarios and backward scenario reduction method is used to reduce them. More details on the scenario reduction methods can be found in [38].

The SBA is a common strategy for dealing with uncertainty parameters [39]. In this method, the Probability Density Function (PDF) curve of the uncertainty parameter is divided into several levels. The PDF is the density of a continuous random variable. Using the PDF, the probability of the uncertainty variable in each level is calculated. Each level is in accordance with a scenario and assume that scenarios $S = 1, 2, \dots, i, \dots, k$ have probabilities $\gamma_1, \gamma_2, \dots, \gamma_i, \dots, \gamma_k$. The mean of the upper and the lower limits of the level i is addressed as x_i. Therefore, the expected value of the output variable $z$is calculated as follows:

$$z = \sum_{i \in S} \gamma_i x_i \tag{1}$$

It should be noted that more scenarios increase the accuracy of the results, but the volume of computations also increase [39,40]. Power loads, WT and PV generations are variable, and their data is almost unclear. For example, the variable consumption of a residential customer generally depends on the presence of family members at the time of using several power units with a relatively short longevity throughout the day. Also, the WT output is modeled based on the wind speed at its installation site and the output power of the PV depends on the amount of solar radiation.

Ideally, regarding predictive errors, loads and RES-based generations should not be considered as definite parameters in planning and operation of a microgrid. Stochastic approach is modeled as a normal Gaussian PDF, where the mean is equal to the predicted value. In most cases, the forecasted value is considered as the standard deviation of PDF. The description of the normal Gaussian PDF is as follows:

$$f(x|m, \vartheta^2) = \frac{1}{\sqrt{2\pi\vartheta^2}} \exp\left(-\frac{(x-m)^2}{2\vartheta^2}\right) - \infty < x < + \infty \tag{2}$$

where m is the mean of the input forecasted variable, ϑ^2 is the variance and ϑ is the standard deviation of the input forecasted variable [41]. In this paper, as shown in Fig. 2, the normal PDF is divided into nine segments with different probability levels [42].

3.2. Pricing model of power exchange

For the proposed pricing model of the power exchanges, the microgrid marginal price (MGMP) has been considered. In order to formulate the MGMP, it is assumed that each microgrid is operated independently. In this regard, the generation of the DGs and the consumption of loads in each microgrid are concentrated in a local bus. This means that there is a balance between the DG unit generations and the load consumptions in each microgrid. The loss of the power lines and the constraints of RES-units are not considered in the proposed model.

In the pricing model, it is assumed that the cost of the selling electricity to consumers is equal to the cost of the generating electricity from DGs in each microgrid [30]. The cost function of the selling electricity is defined as $FD_{m,h}(TLP_{m,h})$ of the total active demand in mth microgrid. Also, the cost function of generating electricity is also determined as $FG_{m,h}(TPG_{m,h})$ of the total active power generation, in which the cost function $FG_{m,h}(\cdot)$ represents the actual electricity generation costs.

Clearly, to maintain system stability, the amount of power generation has been equalized to the amount of power consumption in each microgrid. The objective function for the system operator is to minimize the cost function of the generating electricity and maximize the cost function of the selling electricity. Therefore, the formulation of this model is presented as the following simple optimization problem.

$$\max FD_{m,h}(TLP_{m,h}) - FG_{m,h}(TPG_{m,h})$$

$$s.\ t.\ TPG_{m,h} - TLP_{m,h} = 0 \tag{3}$$

The Lagrangian function of this problem is evaluated as follows in Eq. (4):

$$\ell(TLP_{m,h}, TPG_{m,h}, \rho_{m,h}) = FD_{m,h}(TLP_{m,h}) - FG_{m,h}(TPG_{m,h}) + \rho_{m,h}.\,(TPG_{m,h} - TLP_{m,h}) \tag{4}$$

where $\rho_{m,h}$ illustrates the Lagrangian multiplier. The optimality condition is obtained by equalizing Lagrangian partial derivatives to be zero.

$$\frac{\partial \ell}{\partial TLP_{m,h}} \equiv \frac{dFD_{m,h}}{dTLP_{m,h}} - \rho_{m,h} = 0 \tag{5}$$

$$\frac{\partial \ell}{\partial TPG_{m,h}} \equiv -\frac{dFG_{m,h}}{dTPG_{m,h}} + \rho_{m,h} = 0 \tag{6}$$

$$\frac{\partial \ell}{\partial \rho_{m,h}} \equiv TPG_{m,h} - TLP_{m,h} = 0 \tag{7}$$

Therefore, Eq. (8) has been simply concluded from Eqs. (5)–(7):

$$\frac{dFD_{m,h}}{dTLP_{m,h}} = \frac{dFG_{m,h}}{dTPG_{m,h}} = \rho_{m,h} \tag{8}$$

The obtained value of $\rho_{m,h}$ is the MGMP of the mth microgrid at hour h. As mentioned previously, in the proposed model, the power exchange price between the mth microgrid and the nth microgrid is calculated with respect to the their MGMP. In this study, the power exchange price is formulated as follows in Eq. (9):

$$\pi_{t,h} = \sigma.\,\left(\frac{\rho_{m,h} + \rho_{n,h}}{2}\right) \tag{9}$$

where σ indicates the weighted coefficient of the power exchange. This coefficient is a number in the range of [1.5–3] according to the operating state [43].

3.3. Optimization formulations for NMGs

Formulations of stochastic optimization problem of NMGs are illustrated in Eqs. (10)–(39). According to the nonlinear nature of the NMGs equations, the nonlinear programming may fail to get an appropriate solution [44]. Therefore, the MILP model is applied to solve the optimization problem. More details of linearizing strategy can be found in [45].

3.3.1. Distribution network model

A radial network model extensively employed in the distribution system modeling are shown in Fig. 3. This modeling assigns an optimization formulation for each microgrid [46].

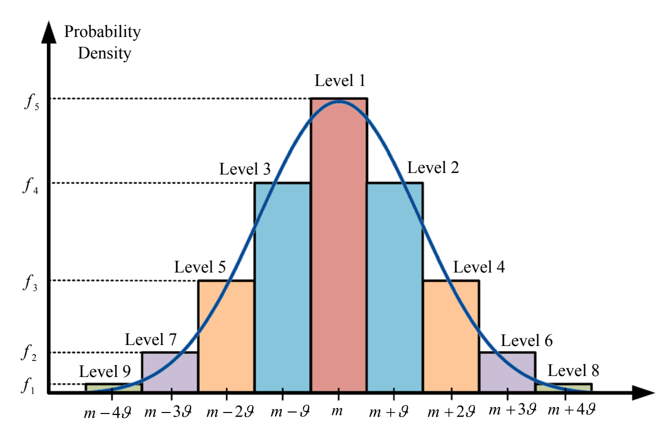

Fig. 2. Divided probability distribution function related to the standard deviation of prediction.

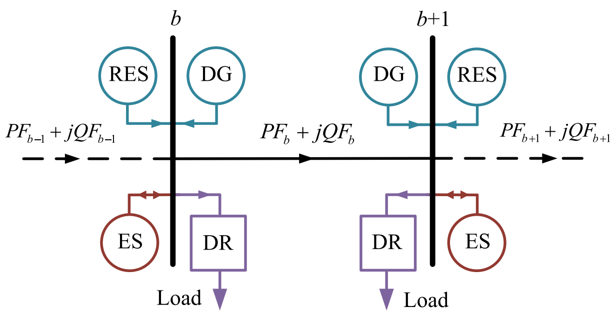

Fig. 3. Model of Radial distribution system.

The linearized power flow equations corresponding to bth bus of the distribution system is demonstrated as follows:

$$PF_{b+1,h,s} = PF_{b,h,s} + PG_{g,h,s} + PR_{n,h,s} + PS_{e,h,s}^{dch} - PS_{e,h,s}^{ch} - LP_{b,h,s} + PD_{d,h,s} \tag{10}$$

$$QF_{b+1,h,s} = QF_{b,h,s} + QG_{g,h,s} - LQ_{b,h,s} \tag{11}$$

$$\upsilon_{b+1,h,s} = \upsilon_{b,h,s} - 2(r_b PF_{b,h,s} + x_b QF_{b,h,s}) \tag{12}$$

$$(1-\varepsilon)^2 \leqslant \upsilon_{b,h,s} \leqslant (1+\varepsilon)^2 \tag{13}$$

where $\upsilon_{b,h,s} = V_{b,h,s}^2$.

3.3.2. DRP model

In addition to conventional resources in microgrids such as dispatchable DGs and RES-based units, DRP can also be investigated as the programable sources in the NMGs scheduling. In fact, the DRP is one of the influential sources to achieve the cost-effective operation [47]. In this regard, a step-wise DRP is presented in the energy management model to assign the demand reduction offers in the optimization problem. In this paper, the proposed DRP is modeled considering a step-wise price-demand curve as shown in Fig. 4. The step-wise DRP of the NMG is also formulated as follows in Eqs. (14)–(19).

$$DR_{d,h,s}^{\min} \leqslant PD_{d,h,s}^{w} \leqslant DR_{d,h,s}^{w} \quad , \forall\ w = 1 \tag{14}$$

$$0 \leqslant PD_{d,h,s}^{w} \leqslant DR_{d,h,s}^{w} - DR_{d,h,s}^{w-1} \quad , \forall\ w = 2, 3, \ldots, W \tag{15}$$

$$PD_{d,h,s} = \sum_{w=1}^{W} PD_{d,h,s}^{w} \tag{16}$$

$$DR_{d,h,s}^{\min}\mu_{d,h,s}^{dr} \leqslant PD_{d,h,s} \leqslant DR_{d,h,s}^{W}\mu_{d,h,s}^{dr} \tag{17}$$

$$DR_{d,h,s}^{\min} = \varkappa^{\min} LP_{b,h,s} \quad , \forall\ b \in d \tag{18}$$

$$DR_{d,h,s}^{w} = \varkappa^{w} LP_{b,h,s} \quad , \forall\ b \in d \ \ , w = 1, 2, \ldots, W \tag{19}$$

where $\varkappa^{\min}$ is the coefficient of the minimum allowed demand reduction and $\varkappa^{w}$is the coefficient of the adjusted demand reduction in wth step of DRP.

3.3.3. Constraints

The advanced power distribution networks containing the NMGs can be operated based on the following constraints:

3.3.3.1. DGs constraints. The following constraints guarantee that the DG outputs be in generation capacities. The commitment states of the DGs are incorporated into the generation limits by Eqs. (20) and (21).

$$PG_g^{\min}\mu_{g,h,s}^{uc} \leqslant PG_{g,h,s} \leqslant PG_g^{\max}\mu_{g,h,s}^{uc} \tag{20}$$

$$QG_g^{\min}\mu_{g,h,s}^{uc} \leqslant QG_{g,h,s} \leqslant QG_g^{\max}\mu_{g,h,s}^{uc} \tag{21}$$

The constraints demonstrated in Eqs. (22)–(25) are determined for the up/down ramp rate limits of the DGs. The start-up and shot-down states are considered in the constraints of DGs.

$$PG_{g,h-1,s} - PG_{g,h,s} = RP_g(1 - \mu_{g,h,s}^{su}) \tag{22}$$

$$PG_{g,h,s} - PG_{g,h-1,s} = RP_g(1 - \mu_{g,h,s}^{sd}) \tag{23}$$

$$QG_{g,h-1,s} - QG_{g,h,s} = RQ_g(1 - \mu_{g,h,s}^{su}) \tag{24}$$

$$QG_{g,h,s} - QG_{g,h-1,s} = RQ_g(1 - \mu_{g,h,s}^{sd}) \tag{25}$$

Also, the commitment states of the DGs are presented in Eqs. (26)–(27):

$$\omega_{g,h,s}^{su} + \omega_{g,h,s}^{sd} < 1 \tag{26}$$

$$\omega_{g,h,s}^{su} - \omega_{g,h,s}^{sd} - \omega_{g,h,s}^{uc} + \omega_{g,h-1,s}^{uc} = 0 \tag{27}$$

3.3.3.2. ES constraints. An ES can be activated in three various modes including charging, discharging and idle. In charging mode, the ES is operated as a local load and reserves the power. In discharging mode, the ES is operated as a local DG and returns the reserved power. In idle mode, the ES neither reserves the power nor returns the reserved power. The ES constraints are presented in Eq. (28)–(32). Charging and discharging states of ESs are also taken into the account in the ES constraints.

$$SOC_{e,h,s} = SOC_{e,h-1,s} + \frac{1}{EC_e}\left(\eta^{ch} PS_{e,h,s}^{ch} - \frac{1}{\eta^{dch}} PS_{e,h,s}^{dch}\right) \tag{28}$$

$$SOC_e^{\min} \leqslant SOC_{e,h,s} \leqslant SOC_e^{\max} \tag{29}$$

$$0 \leqslant PS_{e,h,s}^{ch} \leqslant PS_e^{ch,\max}\mu_{e,h,s}^{ch} \tag{30}$$

$$0 \leqslant PS_{e,h,s}^{dch} \leqslant PS_e^{dch,\max}\mu_{e,h,s}^{dch} \tag{31}$$

$$\mu_{e,h,s}^{ch} + \mu_{e,h,s}^{dch} \leqslant 1 \tag{32}$$

3.3.3.3. Power exchange constraints. In this modeling, the power exchange variable is divided into two positive variables in order to reduce the complexity of using the bi-directional power exchanges in the optimization problem. In this regard, the power exchange states are proposed for the power exchange variables. Eqs. (33)–(37) present the power exchange constraints.

$$-PE^{\max}\mu_{t,h,s}^{up} \leqslant PE_{t,h,s}^{up} \leqslant PE^{\max}\mu_{t,h,s}^{up} \tag{33}$$

$$-QE^{\max}\mu_{t,h,s}^{up} \leqslant QE_{t,h,s}^{up} \leqslant QE^{\max}\mu_{t,h,s}^{up} \tag{34}$$

$$-PE^{\max}\mu_{t,h,s}^{do} \leqslant PE_{t,h,s}^{do} \leqslant PE^{\max}\mu_{t,h,s}^{do} \tag{35}$$

$$-QE^{\max}\mu_{t,h,s}^{do} \leqslant QE_{t,h,s}^{do} \leqslant QE^{\max}\mu_{t,h,s}^{do} \tag{36}$$

$$\mu_{t,h,s}^{up} + \mu_{t,h,s}^{do} < 1 \tag{37}$$

3.3.3.4. Power balance constraints. The power balance between the generation and consumption is obligatory for assessing the dependable operation of the NMGs. In this reason, both active and reactive power balance constraints at mth MG of the NMGs at hour h for scenario s are illustrated as follows in Eqs. (38)–(41).

$$\sum_b LP_{b,h,s} + \sum_d PD_{d,h,s} = \sum_g PG_{g,h,s} + \sum_e PS_{e,h,s}^{dch} - \sum_e PS_{e,h,s}^{ch} + \sum_n PR_{n,h,s} + \sum_t (PE_{t,h,s}^{up} - PE_{t,h,s}^{do}) \tag{38}$$

$$\sum_b LQ_{b,h,s} = \sum_g QG_{g,h,s} + \sum_t (QE_{t,h,s}^{up} - QE_{t,h,s}^{do}) \tag{39}$$

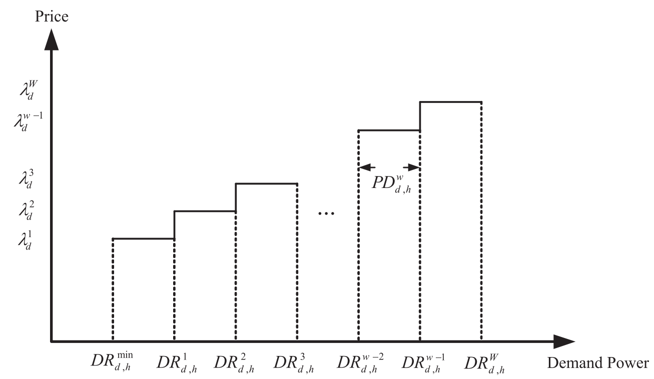

Fig. 4. The proposed step-wise demand response price-demand curve.

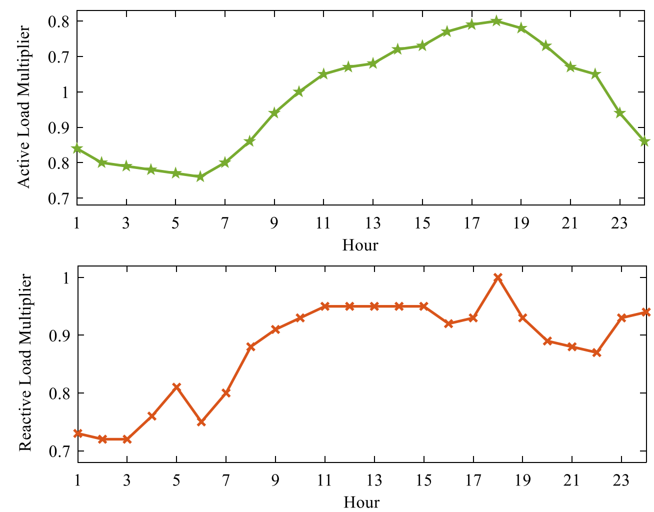

Fig. 6. Hourly forecasted multipliers of demands [48].

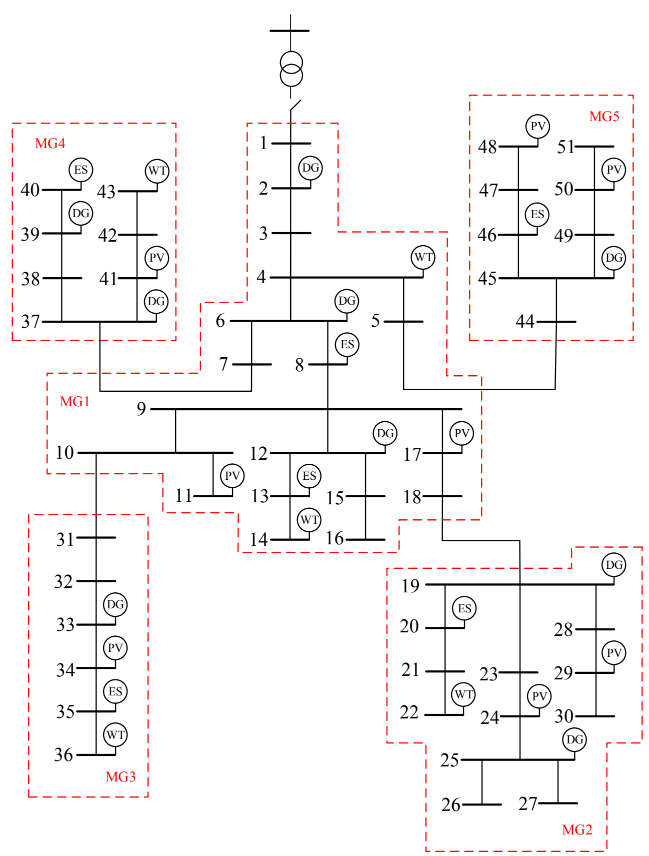

Fig. 5. Advanced distribution test system with five NMGs.

Table 3
Location and sizes of RES-based units.

MG	Location	Type	Capacity (MW)
MG1	Bus04	WT	0.5
	Bus11	PV	1.0
	Bus14	WT	2.5
	Bus17	PV	1.5
MG2	Bus22	WT	2.0
	Bus24	PV	1.5
	Bus29	PV	2.5
MG3	Bus34	PV	1.5
	Bus36	WT	1.0
MG4	Bus41	PV	2.0
	Bus43	WT	1.5
MG5	Bus48	PV	2.0
	Bus50	PV	1.5

Table 2
Loads and three-step DRP information.

MG	Total Active Loads (MW)	Total Reactive Loads (MVAR)	Buses of DRP	Offered DRP price ($/MW)		
				1st Step	2nd Step	3rd Step
MG1	18	7.2	9, 14, 16	5.6	6.3	7
MG2	12	4.8	23, 25	4.8	5.4	6
MG3	6	2.4	32	6.4	7.2	8
MG4	7	2.8	–	–		
MG5	8	3.2	45	7.2	8.1	9

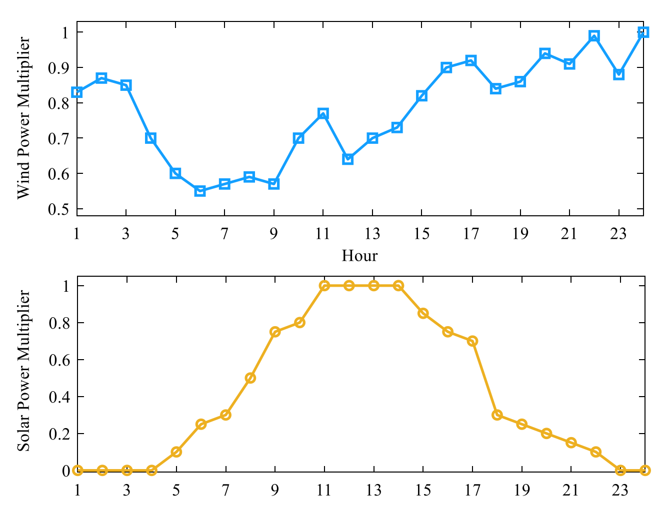

Fig. 7. Hourly forecasted multipliers of RES-based units [48].

Table 4
Location and sizes of DG units.

MG	Location	α($/MW)	β($)	PG^{max}	QG^{max}	RP	RQ
MG 1	Bus02	13.325	38.96	4	2	1.5	1.0
	Bus06	12.349	27.98	4	2	1.0	0.5
	Bus12	26.802	31.02	10	6	2.5	1.5
MG 2	Bus19	10.784	32.93	3	2	1.0	0.5
	Bus25	17.922	10.03	7	4	2.0	1.0
MG 3	Bus33	12.974	10.05	6	3	2.0	1.0
MG 4	Bus37	23.021	58.72	4	2	1.5	0.5
	Bus39	31.023	17.69	3	2	1.0	0.5
MG 5	Bus45	15.838	58.38	8	4	2.5	1.5

Table 5
Location and capacities of ESs.

MG	Location	Capacity (MW)	Max Charge/Discharge (MW)
MG1	Bus08	2.5	0.5
	Bus13	2.0	0.6
MG2	Bus20	3.0	0.4
MG3	Bus35	1.5	0.2
MG4	Bus40	2.0	0.5
MG5	Bus46	2.5	0.8

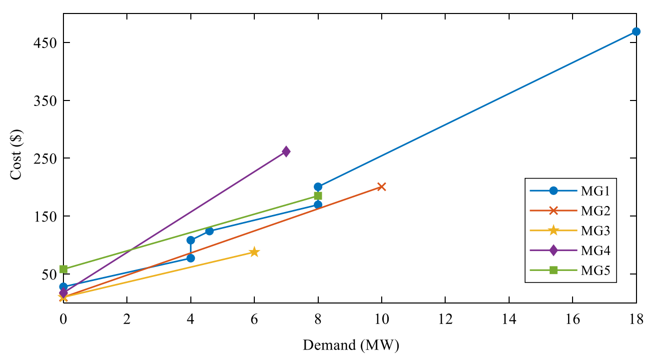

Fig. 8. Cost-demand curves of the MGs.

Table 6
MGMPs information.

	Min	Max	MGMP
MG1	10.08	18	26.802
MG2	6.72	12	17.922
MG3	3.36	6	12.974
MG4	3.92	7	31.023
MG5	4.48	8	15.838

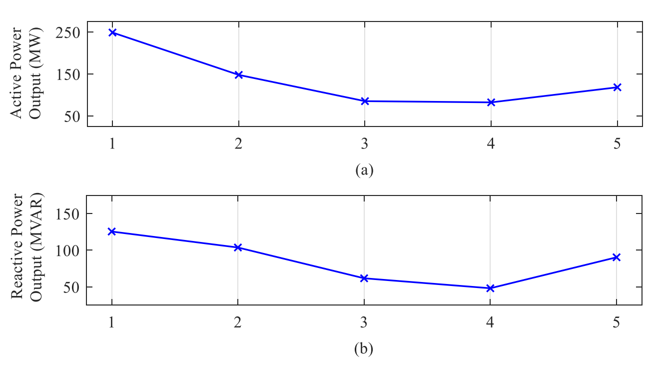

Fig. 9. Total active (a) and reactive (b) power of DGs in case without DRP.

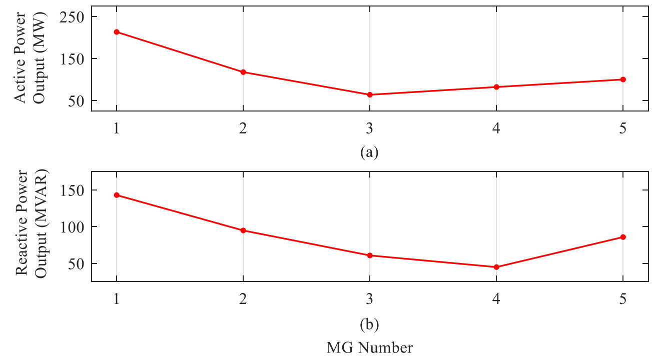

Fig. 10. Total active (a) and reactive (b) power of DGs in case with DRP.

$$\sum_b LP_{b,h,s} + \sum_d PD_{d,h,s} = \sum_g PG_{g,h,s} + \sum_e PS^{dch}_{e,h,s} - \sum_e PS^{ch}_{e,h,s} + \sum_n PR_{n,h,s} + (PE^{do}_{t,h,s} - PE^{up}_{t,h,s}) \tag{40}$$

$$\sum_b LQ_{b,h,s} = \sum_g QG_{g,h,s} + (QE^{do}_{t,h,s} - QE^{up}_{t,h,s}) \tag{41}$$

Eqs. (38) and (39) represent the active and the reactive power balance equations at central MG of the NMGs, respectively, while Eqs. (40) and (41) indicate the power balance equations of downstream MGs.

3.3.4. Objective function

According to the proposed energy management, it is assumed that the operator of the interconnected MGs is the operator of the entire available distribution system. In this paper, for the stochastic optimization model of the NMGs, the objective function is the minimization of the total operating costs in all proposed scenarios with their probabilities. The operating costs include the costs of the DG generations, power exchange, amortization of ESs and the DRP in the NMGs. Thus, the objective function is formulated as follow in Eq. (42).

$$\min \sum_h \left[\sum_s \gamma_s \left(\begin{array}{l} \sum_g (\alpha_g.\, PG_{g,h,s} + \beta_g.\, \mu^{uc}_{g,h,s}) \\ +\pi_t \sum_t (PE^{up}_{t,h,s} + PE^{do}_{t,h,s}) \\ +\psi \sum_e (PS^{ch}_{e,h,s} + PS^{dch}_{e,h,s}) \\ +\lambda^w_d \sum_d (PD_{d,h,s}) \end{array} \right) \right] \tag{42}$$

The first and the second parts of Eq. (42) illustrate the generation costs of the DG units. The generation parameters are efficiently linearized, where the second order terms of the DG cost functions are not taken into the account. Third and fourth parts represent the costs of active power exchanges among the interconnected microgrids. In fact, the proposed outer level EMS of the NMGs is identifier of the downward or upward directions of the power exchanges. Fifth and sixth sections show the amortization costs of charging or discharging of the ESs. To encourage the microgrids to have more self-sufficiency in their local generations, it is aimed that the proposed power exchange prices are more than the DG generation cost parameters.

3.4. Operating costs of mth MG of the interconnected MGs

The total operating costs of mth MG is presented as follows in Eq. (43) to obtain the operating costs of each microgrid individually. It should be noted that operating costs of mth microgrid are calculated after solving the optimization problem.

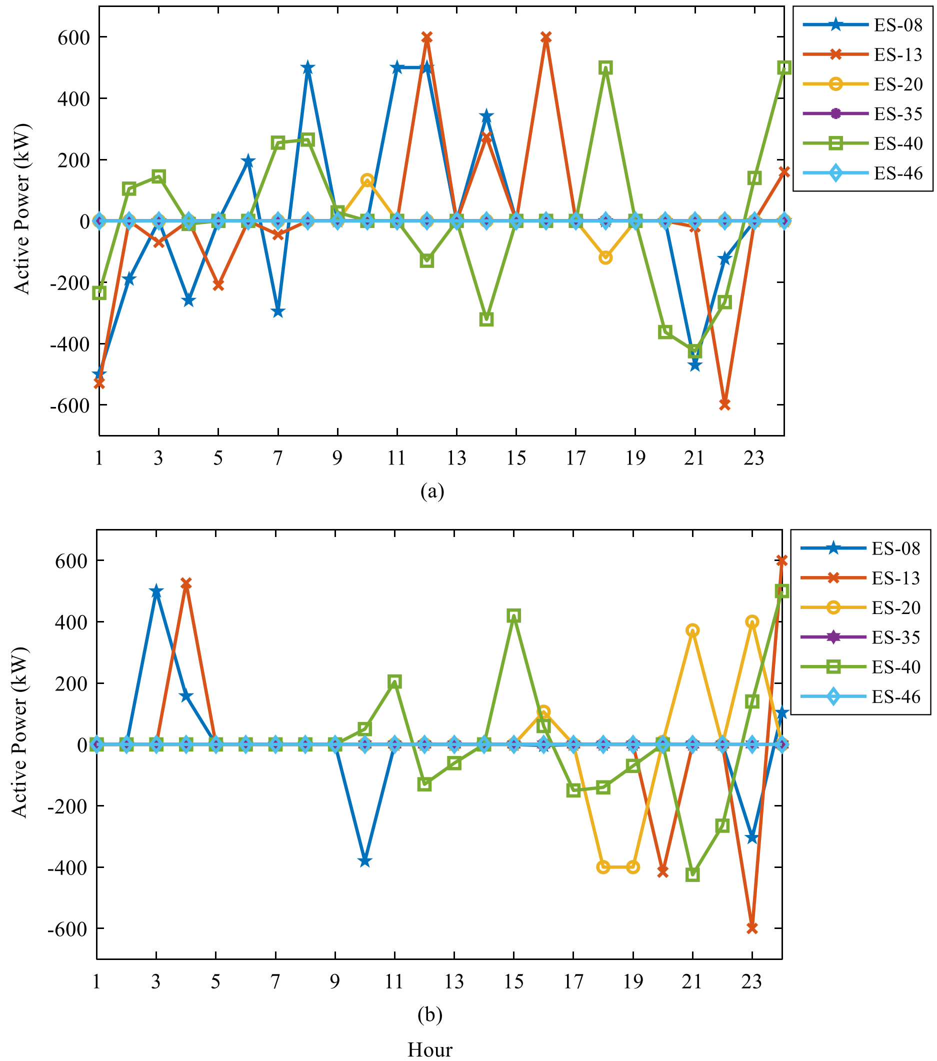

Fig. 11. Active power of ESs in cases without DRP (a) and with DRP (b).

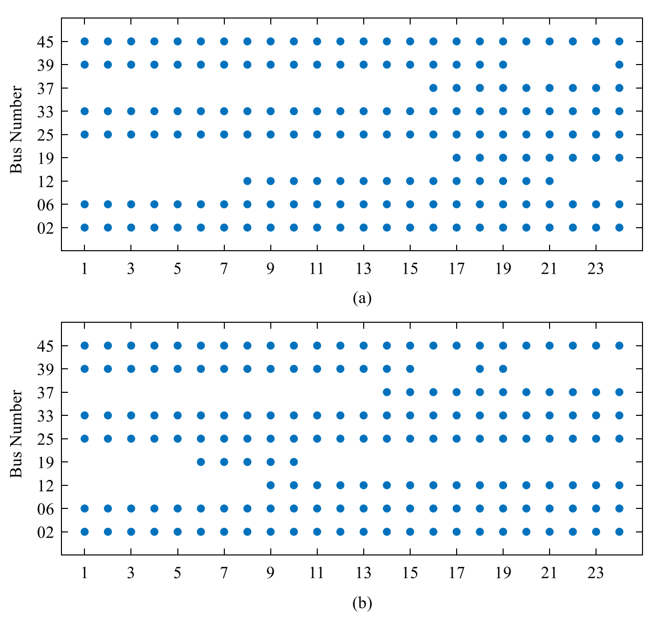

Fig 12. Commitment states of DG units in cases without DRP (a) and with DRP (b).

$$TOC_m = \sum_h \left[\sum_s \gamma_s \left(\begin{aligned} & \sum_{g \in G_m} (\alpha_g . PG_{g,h,s} + \beta_g . \mu^{uc}_{g,h,s}) \\ & + \pi_t \sum_{l \in T_m} (PE^{up}_{t,h,s} + PE^{do}_{t,h,s}) \\ & + \psi \sum_{e \in E_m} (PS^{ch}_{e,h,s} + PS^{dch}_{e,h,s}) \\ & + \lambda^w_d \sum_{d \in D_m} (PD_{d,h,s}) \end{aligned} \right) \right] \tag{43}$$

4. Illustrative implementations

The proposed model is simulated on a test radial network with five NMGs as shown in Fig. 5. The presented mathematical problem is verified over a 24-hour scheduling time horizon. The interconnected microgrids are operated in the isolated structure, which are disconnected from the upstream grid. Each microgrid contains dispatchable DGs, RES-based units such as WTs and PVs, ESs, both active and reactive loads and DRP in some selected buses. The total load and DRP information of the microgrids are shown in Table 2 and the corresponding multipliers of the hourly forecasted load consumption shown in Fig. 6. In this study, the three-step demand response price-demand curve is proposed. Furthermore, the value of the forecasted load in each bus is 1 MW for all microgrids. The locations and the capacities of RES-based units containing WTs and PVs generations are illustrated in Table 3 and the related multipliers of the hourly forecasted power

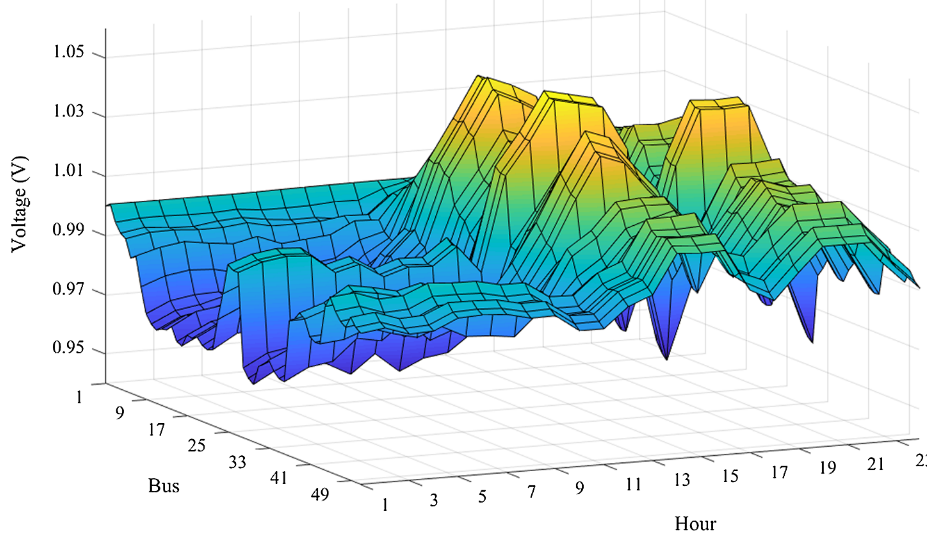

Fig. 13. Voltage of the buses in case without DRP.

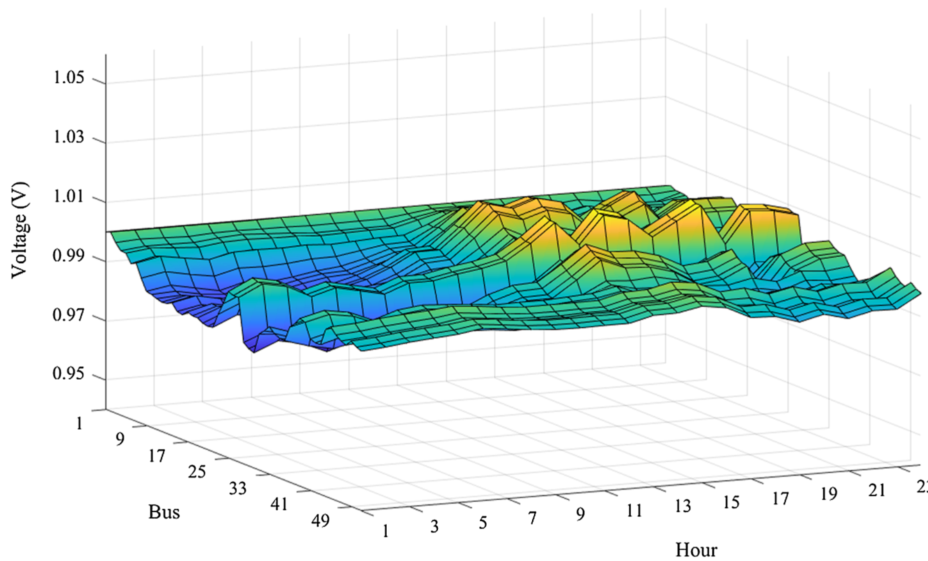

Fig. 14. Voltage of the buses in case with DRP.

Table 7
Minimum and maximum voltages of interconnected MGs in cases with and without DRP.

Case	Case 1: Without DR		Case 2: With DR	
MG	Minimum Voltage (V)	Maximum Voltage (V)	Minimum Voltage (V)	Maximum Voltage (V)
1	0.9541	1.0075	0.9800	1.0100
2	0.9500	1.0168	0.9773	1.0146
3	0.9570	1.0022	0.9829	1.0089
4	0.9740	1.0006	0.9887	0.9993
5	0.9848	1.0056	0.9913	1.0037

outputs are illustrated in Fig. 7. Besides, Table 4 indicates the locations and the sizes of the DG units. Also, the capacities and the charging/discharging limits of ESs are presented in Table 5. The cost-demand curve of each microgrid is presented in Fig. 8 which is applied for calculating the MGMPs. Table 6 shows the calculated MGMPs and the maximum and the minimum active demand in each microgrids to explain the details of the proposed power exchange prices.

Furthermore, in this study, the power base of the test system is set to be 10 MVA. $PG^{\min}$ and $QG^{\min}$ are set to be zero for all DG units. $\varkappa^{\min}$, $\varkappa^{1}$, $\varkappa^{2}$ and $\varkappa^{3}$ are set to be 0.2, 0.4, 0.6 and 0.8 for all responsive loads. $SOC^{\max}$ and $SOC^{\min}$ are set to be 0.9 and 0.2 for all ESs, respectively. Also, $\eta^{ch}$and $\eta^{dch}$are set to be 0.95 for all ESs. The line resistance and reactance of interconnected MGs are set to be 0.012 and 0.02 p.u., respectively. It is worth mentioning that all electricity prices and costs and are proposed in U.S. dollars. The optimization problem is solved using CPLEX solver under the GAMS 24.8.3 environment. All above information are for illustration and can be change according to the proposed case study.

Figs. 9 and 10 illustrate the total active (a) and reactive (b) power outputs of the DGs in a 24-hour time horizon of each MG in cases without and with DRP, respectively. According to the Figs. 9 and 10, MG1 generates more reactive power than its reactive load consumption over a 24-hour time horizon of operation. However, the reactive load consumption of the MG3 is lower than the MG4. It is because of that the MG3 sends the surplus power generated to the MG1 to balance the bus voltages of the NMGs. Generally, as it is clear and expected from Fig. 10, the total active and reactive DG generations of the MG1, MG2, MG3 and MG5 in case with DRP (a and b) have been decreased, while

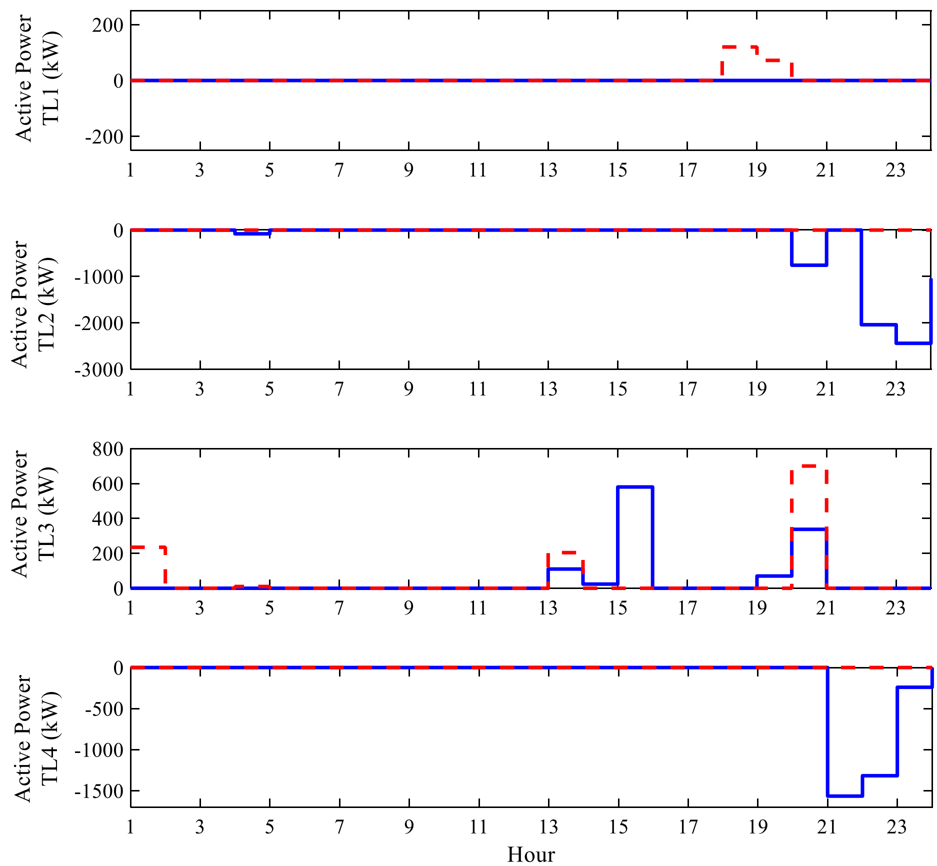

Fig. 15. Active power exchanges in 24 h of operation in cases without and with DRP.

Table 8
Operation costs of stochastic approach in cases without and with DRP.

MG	Case	Cost of DGs ($)	Cost of Buying Electricity ($)	Cost of Selling Electricity ($)	Cost of Charging and Discharging of ESSs ($)	Cost of DRP ($)	Total Cost ($)
MG1	Without DRP	6173.817	229.401	−89.972	5.668	0.000	6318.914
	With DRP	5250.707	49.636	−135.508	3.649	317.042	5485.526
MG2	Without DRP	3052.143	0.937	−0.077	0.933	0.000	3053.936
	With DRP	2484.532	5.369	0.000	1.449	181.167	2672.517
MG3	Without DRP	1358.154	0.000	−197.273	0.131	0.000	1161.012
	With DRP	1097.987	0.000	−49.636	0.000	120.778	1169.130
MG4	Without DRP	3194.411	89.035	0.000	3.263	0.000	3286.709
	With DRP	3184.259	130.139	0.000	3.371	0.000	3317.769
MG5	Without DRP	3247.016	0.000	−32.050	0.003	0.000	3214.969
	With DRP	2992.032	0.000	0.000	0.000	135.875	3127.907
NMGs	Without DRP	17030.596	319.373		2.643	0.000	17359.967
	With DRP	15016.258	185.144		9.998	754.861	15964.733

the DG generation amounts of MG4 in this case have been almost unchanged. It is because of that MG4 has not participated in the DRP.

The active power of ESs in cases without DRP (a) and with DRP (b) is shown in Fig. 11. As it is clear, in the cases without and with DRP, only ESs located at buses 8, 13, 20 and 40 save the active power and return it to the network, while other ESs are in idle mode. Also, the total amount of the charging power is equal to the total amount of discharging power in a 24-hour time horizon. It means that ESs have been returned the same amount of saved power to the network in 24 h operation. In fact, this is due to the equilibrium of state of the charge (SOC) percentages in the first and last hours of operation. Furthermore, the total amount of the charging/discharging active power in case with DRP is less than the case without DRP.

Fig. 12 shows the commitment states of the DG units in cases without DRP (a) and with DRP (b). As it is clear, DG units located at buses 2, 6, 25, 33 and 45 are constantly on-grid in both cases. These results are due to lower generation costs of the DGs located in MG1 at the buses 2 and 6 than the DG located at the bus 12. For the same reason, the DG located at the bus 25 is preferred over the DG located at the bus 19 in MG2. Also, the prices of the power exchange in the MG3 and MG5 are lower than the other microgrids. The only significant difference between the cases without and with DRP is that the DG unit located at buses 19 in case without DRP is only on-grid over the hours 17–24, while in case with DRP is only on-grid over the hours 6–10.

The voltage of the buses in cases without and with DRP are illustrated in Figs. 13 and 14, respectively. In both cases, the voltages are in the allowed deviation. Also, the minimum and maximum voltages of interconnected microgrids in cases with and without DRP are presented in Table 7. As it is clear from Table 7, the voltages are in the range of 1 p.u. As a result, the DRP plays an important role in the voltage control of the NMGs.

Fig. 15 indicates the exchanged powers among the interconnected

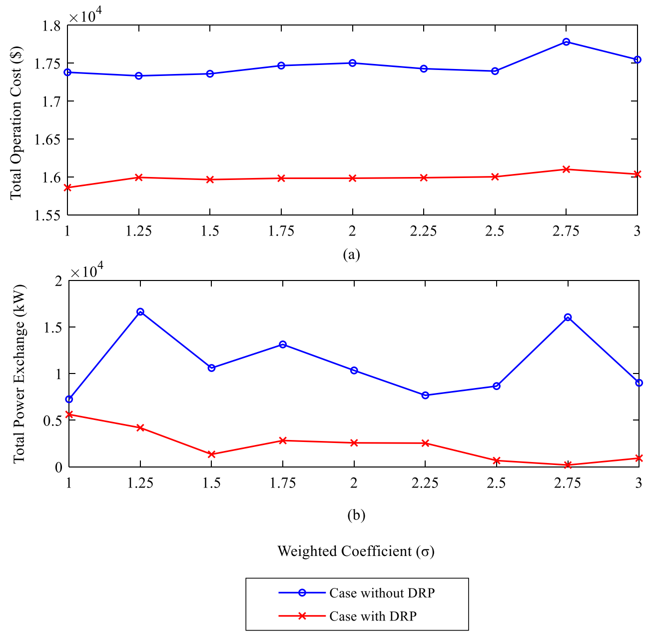

Fig. 16. Sensitivity analysis of total operation cost (a) and total power exchange (b) in terms of weighted coefficient of power exchange price for cases without and with DRP.

microgrids in the case without DRP shown by solid lines and the case with DRP shown by dash lines. It is assumed that TL1, TL2, TL3 and TL4 represent the tie-lines between the buses 18–19, buses 10–31, buses 7–37 and buses 5–44, respectively. Noticeably, the positive values demonstrate the power exchanges from centeral microgrid to other microgrids. Contrarily, the negative values show the exchanged powers from other microgrids to centeral microgrid. For example, in case without DRP at hour 20, in TL3 the active power is exchanged from bus 7 to bus 37, while in TL2 the active power is exchanged from bus 31 to bus 10. Obviously, MG2 in case without DRP and MG3 and MG5 in case with DRP have no exchange powers with the MG1.

According to the Eq. (43) and the objective function presented by Eq. (42), the operational costs of each microgrid and the NMGs are illustrated in Table 8. For the sake of a detailed analysis, the generation costs of the DG units, the power exchange costs and the amortization costs of charging or discharging of the ESs in each microgrid at a 24-hour time horizon operation are appraised, individually. Positive values represent the costs and the negative values represent the earnings.

As it is clear from Table 8, the total operational cost of the NMGs in case with DRP is $1395.234 less than the case without DRP. Furthermore, the total operation costs of DG units and the total costs of exchange powers in case with DRP are also $2014.338 and $134.229 less than the total costs in case without DRP, respectively.

The sensitivity analysis of the total operation cost (a) and total power exchange (b) in terms of weighted coefficient of the power exchange price for cases without and with DRP are shown in Fig. 16.

It can be seen in Fig. 16(a) that as the proposed weighted coefficient increases, the total operation cost enhances approximately for both cases without and with DRP. However, in Fig. 16(b), the proposed weighted coefficient increases, the total exchanged power changes irregularly. Furthermore, in the ranges [1.75–2.25], the total exchanged power changes linearly, such that as the price of power exchange increases, the total power exchange among the tie-lines decreases. This is the performance expected of the proposed pricing model. In some scientific papers that have studied the operation of the microgrids, the costs of power exchanges per hour have been estimated between 2 and 3 times the generation costs per hour [43].

5. Conclusions

In this paper, a bi-level EMS was considered for an isolated structure of the NMGs, in which the microgrids contained cyber-physical connections for data communications and power exchanges. The outer-level EMS was aimed to exchange the required information and power support between the interconnected microgrids, and the inner-level EMS was designed for energy scheduling of each on-fault microgrid in case of departure from interconnected microgrids. In the interconnected status, the microgrids was connected radially via the tie-lines. This paper only focused on the operation of interconnected microgrids. In order to enhance operation of the microgrids, a step-wise DRP was proposed in the energy management modeling. Furthermore, a novel pricing model of the power exchange between the microgrids was introduced in which the associated prices was calculated according to the marginal pricing in each microgrid. Besides, the stochastic optimization problem was formulated in a MILP format to insure the fast response and global optimal solution. On the other hand, the uncertainties of the RESs and loads were assumed using SBA modeling to provide the highly reliability and more accurate operation. The optimization problem was implemented on a distribution system with five NMGs. The simulation results illustrated that the proposed energy management with the implementation of DRP not only decreased the operational costs but also increased the performance of the NMGs. Compared to the case without DRP in a 24-hour time horizon operation, the total generation of DG units and the total power exchanges were reduced the case with DRP, while the total active power of the ESs were increased. Also, the voltages of the buses in the case with DRP were more favorable than the case without DRP and the minimum and maximum measures were close to their rated values. According to the mentioned results, it can be concluded that propose energy management strategy performed appropriately with taking into account the DRP in the isolated NMGs. According to the architecture of the proposed energy management, the operation of the on-fault microgrids with corresponding local EMSs in each MG can also be studied. Likewise, mesh framework can be applied in the physical connections to make the NMGs more reliable than the radial framework. In addition, the self-healing concepts can also be proposed in future researches to realize the interconnected capabilities in the isolated NMGs.

Declaration of Competing Interest

Author declares that there is no conflicts of interest.

References

[1] Chen C, Duan S, Cai T, Liu B, Hu G. Smart energy management system for optimal microgrid economic operation. IET Renew Power Gener 2011;5:258–67.
[2] Di Somma M, Graditi G, Heydarian-Forushani E, Shafie-khah M, Siano P. Stochastic optimal scheduling of distributed energy resources with renewables considering economic and environmental aspects. Renew Energy 2018;116:272–87.
[3] Rahman MS, Oo AMT. Distributed multi-agent based coordinated power management and control strategy for microgrids with distributed energy resources. Energy Convers Manage 2017;139:20–32.
[4] Rezaei N, Kalantar M. Stochastic frequency-security constrained energy and reserve management of an inverter interfaced islanded microgrid considering demand response programs. Int J Electr Power Energy Syst 2015;69:273–86.
[5] Rezaei N, Ahmadi A, Khazali AH, Guerrero JM. Energy and frequency hierarchical management system using information gap decision theory for islanded microgrids. IEEE Trans Indust Electron 2018:7921–32.
[6] Mohsenzadeh A, Pang C, Haghifam M. Determining optimal forming of flexible microgrids in the presence of demand response in smart distribution systems. IEEE Syst J 2018;12(4):3315–23.
[7] Arefifar SA, Yasser A-RM, El-Fouly TH. Optimum microgrid design for enhancing reliability and supply-security. IEEE Trans Smart Grid 2013;4(3):1567–75.
[8] Li Z, Bahramirad S, Paaso A, Yan M, Shahidehpour M. Blockchain for decentralized transactive energy management system in networked microgrids. Electr J 2019;32(4):58–72.
[9] Wang D, Qiu J, Reedman L, Meng K, Lai LL. Two-stage energy management for networked microgrids with high renewable penetration. Appl Energy 2018;226:39–48.
[10] Li Z, Shahidehpour M, Aminifar F, Alabdulwahab A, Al-Turki Y. Networked microgrids for enhancing the power system resilience. Proc IEEE 2017;105(7):1289–310.
[11] Han Y, Zhang K, Li H, Coelho EAA, Guerrero JM. MAS-based distributed coordinated

control and optimization in microgrid and microgrid clusters: a comprehensive overview. IEEE Trans Power Electron 2018;33(8):6488–508.
[12] Li Y, Zhang P, Yue M. Networked microgrid stability through distributed formal analysis. Appl Energy 2018;228:279–88.
[13] Wang Z, Chen B, Wang J, Begovic MM, Chen C. Coordinated energy management of networked microgrids in distribution systems. IEEE Trans Smart Grid 2015;6(1):45–53.
[14] Ahmadi SE, Rezaei N. Reliability-Oriented Optimal Scheduling of Self-Healing in Multi-Microgrids. 2018 Smart Grid Conference (SGC), Sanandaj, Iran; 2018; 1-6.
[15] Hayes BP, Prodanovic M. State forecasting and operational planning for distribution network energy management systems. IEEE Trans Smart Grid 2016;7(2):1002–11.
[16] Fang X, Hodge B, Du E, Kang C, Li F. Introducing uncertainty components in locational marginal prices for pricing wind power and load uncertainties. IEEE Trans Power Syst 2019;34(3):2013–24.
[17] Abrahamse W, Fong CC, Grigg CH, Silverstein B. Communication is key: how to discuss energy and environmental issues with consumers. IEEE Power Energy Mag 2018;16(1):29–34.
[18] Khazali AH, Rezaei N, Ahmadi A, Hredzak B. Information gap decision theory based preventive/corrective voltage control for smart power systems with high wind penetration. IEEE Trans Indust Inform 2018;14(10):4385–94.
[19] Hussain A, Bui V, Kim H. Resilience-oriented optimal operation of networked hybrid microgrids. IEEE Trans Smart Grid 2019;10(1):204–15.
[20] Zhou X, Ai Q, Yousif M. Two kinds of decentralized robust economic dispatch framework combined distribution network and multi-microgrids. Appl Energy 2019;253:113588.
[21] Hussain A, Bui V, Kim H. A Resilient and privacy-preserving energy management strategy for networked microgrids. IEEE Trans Smart Grid 2019;10(1):204–15.
[22] Ren L, Qin Y, Li Y, Zhang P, Wang B, Luh PB, et al. Enabling resilient distributed power sharing in networked microgrids through software defined networking. Appl Energy 2018;210:1251–65.
[23] Zhao Y, Yu J, Ban M, Liu Y, Li Z. Privacy-preserving economic dispatch for an active distribution network with multiple networked microgrids. IEEE Access 2018;6:38802–19.
[24] Bazmohammadi N, Tahsiri A, Anvari-Moghaddam A, Guerrero JM. Stochastic predictive control of multi-microgrid systems. IEEE Trans Indust Appl 2018;55(5):5311–9.
[25] Bazmohammadi N, Tahsiri A, Anvari-Moghaddam A, Guerrero JMA. hierarchical energy management strategy for interconnected microgrids considering uncertainty. Int J Electr Power Energy Syst 2019;109:597–608.
[26] Wang Z, Chen B, Wang J, Kim J. Decentralized energy management system for networked microgrids in grid-connected and islanded modes. IEEE Trans Smart Grid 2016;7(2):1097–105.
[27] Wang H, Huang J. Joint investment and operation of microgrid. IEEE Trans Smart Grid 2017;8(2):833–45.
[28] Amir V, Jadid S, Ehsan M. Probabilistic optimal power dispatch in multi-carrier networked microgrids under uncertainties. Energies 2017;10(11):1770.
[29] Park SH, Hussain A, Kim HM. Impact analysis of survivability-oriented demand response on islanded operation of networked microgrids with high penetration of renewables. Energies 2019;12(3):452.
[30] Nikmehr N, Najafi-Ravadanegh S, Khodaei A. Probabilistic optimal scheduling of networked microgrids considering time-based demand response programs under uncertainty. Appl Energy 2017;198:267–79.
[31] Wang H, Huang J. Bargaining-based energy trading market for interconnected microgrids. IEEE Int Conf Commun (ICC) 2015:776–81.
[32] Wang H, Huang J. Incentivizing energy trading for interconnected microgrids. IEEE Trans Smart Grid 2018;9(4):2647–57.
[33] Bazmohammadi N, Tahsiri A, Anvari-Moghaddam A, Guerrero JM. Optimal operation management of a regional network of microgrids based on chance-constrained model predictive control. IET Gener Transm Dis 2018;12(5):3772–9.
[34] Esmaeili S, Anvari-Moghaddam A, Jadid S. Optimal operational scheduling of reconfigurable multi-microgrids considering energy storage systems. Energies 2019;12(9):1766.
[35] Pourbabak H, Chen T, Su W. Centralized, decentralized, and distributed control for energy internet. Energy Internet 2019:3–19.
[36] Xu S, Pourbabak H, Su W. Distributed cooperative control for economic operation of multiple plug-in electric vehicle parking decks. Int Trans Electr Energy Syst 2017;27:2050–7038.
[37] Rabiee A, Soroudi A, Mohammadi-Ivatloo B, Parniani M. Corrective voltage control scheme considering demand response and stochastic wind power. IEEE Trans Power Syst 2014;29(6):2965–73.
[38] Heitsch H, Römisch W. Scenario reduction algorithms in stochastic programming. Comput Optimiz Applic 2003;24(2–3):187–206.
[39] Jordehi AR. How to deal with uncertainties in electric power systems? A review. Renew Sustain Energy Rev 2018;96:145–55.
[40] Kayal P, Chanda C. Optimal mix of solar and wind distributed generations considering performance improvement of electrical distribution network. Renew Energy 2015;75:173–86.
[41] Tabar VS, Jirdehi MA, Hemmati R. Energy management in microgrid based on the multi objective stochastic programming incorporating portable renewable energy resource as demand response option. Energy 2017;118:827–39.
[42] Ortega-Vazquez MA, Kirschen DS. Should the spinning reserve procurement in systems with wind power generation be deterministic or probabilistic?. 2009 Int Conference on Sustainable Power Generation and Supply, Nanjing; 2009; 1-9.
[43] Parhizi S, Khodaei A, Shahidehpour M. Market-based versus price-based microgrid optimal scheduling. IEEE Trans Smart Grid 2018;9(2):615–23.
[44] Shao C, Wang X, Shahidehpour M, Wang X, Wang B. An MILP-based optimal power flow in multicarrier energy systems. IEEE Trans Sustain Energy 2017;8:239–48.
[45] Guéret C, Prins C. Sevaux. Dash optimization limited: M. Applications of optimization with xpress-MP; 2002. p. 30–47.
[46] Baran ME, Wu FF. Network reconfiguration in distribution systems for loss reduction and load balancing. IEEE Trans Power Deliv 1989;4(2):401–1407.
[47] Rezaei N, Kalantar M. Smart microgrid hierarchical frequency control ancillary service provision based on virtual inertia concept: An integrated demand response and droop controlled distributed generation framework. Energy Convers Manag 2015;92:287–301.
[48] Wang Z, Chen B, Wang J, Begovic M, He Y. MPC-based voltage/VAR optimization for distribution circuits with distributed generators and exponential load models. IEEE Trans Smart Grid 2014;5(5):2412–20.