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Multi-microgrids energy management in power transmission mode considering different uncertainties

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ABSTRACT

Concepts of microgrids have become a key issue in smart grids today. Increasing the penetration of microgrids in the power grid causes the complexity of power management between them, to solve which a broader concept called multi-microgrids systems is proposed. A multi-microgrids system also uses different sources of complementary power and effectively coordinates the energy exchange between the microgrids and the main grid to improve the stability, reliability, and energy efficiency of the system. Dividing distribution systems into a number of microgrids will enable us to make greater use of future distribution systems. In this research, an energy management system for controlling interconnected microgrids is expressed to manage power exchanges between both microgrids and each microgrid with the main grid. Multilayer neural networks have also been used to predict the uncertainty parameters of the problem. Finally, the proposed method is performed on a multi-microgrids system connected to the upstream grid with the presence of renewable and non-renewable resources and various operating scenarios are implemented on it. The simulation results show the presented energy management efficiency in reducing the system costs and the effect of the presence of demand response programs in reducing the cost of the operating of multi-microgrids systems.

1. Introduction

1.1. Literature review

Owing to the increasing need for energy as well as concerns about climate change, the interest in using renewable resources (RES) has been significantly considered [1]. Among RESs, solar cells and wind turbines are the most common and economical sources. Regardless of the benefits of using renewable energy, these clean sources add a lot of uncertainties to the power system, which makes it more complicated to operate [2]. Currently, several solutions have been proposed to overcome this uncertainty with the aim of increasing reliability and improving its energy management. One of the solutions to this problem is to decentralize the control of distribution systems into a set of small-scale zones called microgrid (MG) [1,3,4]. However, one of the challenges of MG operators is energy management in them [5].

The connection between MGs in Multi-microgrids system (MMG) and as a result, the energy exchange between them provides a special potential to reduce the operating cost of MGs and can lead to a reduction in the amount of required load interruption [6,7]. When these MGs are connected to each other, each of them can exchange power with themselves or with the utility grid. Interconnected MMGs allow MGs to meet their energy demand from their RESs or cheaper sources by distributing energy between MGs. Therefore, the cost of fossil-fueled generation could be reduced [2]. In [8], it shows the advantages of using the interconnected MGs against several MGs separately. In this article, it is stated that due to the different types of energy sources and the unique characteristics of the load in each MG, the MG alliance can realize the power complementary among MGs, which leads to the reduction of the operation cost of MMG.

MMGs are divided into 3 categories based on their structure type, which are: 1) radial topology, 2) daisy-chain topology, and 3) mesh topology. The description of each MMG structure is provided in [2]. In general, from the radial structure to the mesh structure, the level of cooperation and interaction increases, which leads to more solution space for the optimal energy management, which certainly makes the algorithm design more complex and challenging. In this paper, a mesh structure is used. By creating a ring between MGs connected together, this structure has improved the interaction between MGs and consequently the operation performance and also reduced operational costs effectively [9,10]. The used structure is more complex than the previous

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Nomenclature

Indices

m, n Index of MGs, with $m, n = 1, 2, ..., M$
t Index of periods, with $t = 1, 2, ..., T$
BS Index of battery storage
DG Index of diesel generators
gas Index of the type of pollution (CO_2, SO_2, NO_X)

Parameters

a_m, b_m, c_m Coefficients of the power generation cost of the m-th DG
C_m^{DG} Cost of power generation by the m-th DG
A_{PV} Area of each solar panel
$Ecaps_{BS}$ Total capacity of the BS-th battery
n_{PV} Number of solar panels
N_{PV}^T Temperature coefficient of the solar cell
$NOCT$ Nominal operating temperature of the solar cell
$P_{DG,t}$ The DG generation power at the hour t
$P_{DG}^{\min}/P_{DG}^{\max}$ The Minimum/maximum of the generation power of DG
P_{PV} The amount of production power of photovoltaic system
P_{WT} The amount of wind farm production power
R_{DG}^{Up}/R_{DG}^{Dn} The ramp-up/ramp-down limit of the m-th DG
$PB_{m,t}$ The battery power at the moment t
$P_{BS,ch,t}/P_{BS,dch,t}$ The charged/discharged power of the BS-th battery at hour t
$P_{ch}^{\max}/P_{dch}^{\max}$ The maximum charged/discharged power of the BS-th battery at hour t
$PG_{m,t}$ The exchange power between the m-th MG and the upstream network at hour t
$PM_{m,n,t}$ The exchange power between the m-th MG and the nth MG at hour t
$PR_{m,t}$ The total generated renewable power of the m-th MG at hour t
$SOC_{BS,t}$ State of charge for the BS-th battery at hour t
$SOC_{\min}/SOC_{\max}$ The minimum/maximum state of charge for the battery
T^{ref} Reference temperature
$\eta_{BS,ch}/\eta_{BS,dch}$ Charging/discharging efficiency of the BS-th battery
η_{PC} The air conditioning efficiency of the PV panel
η_{PV}^r The PV panel reference efficiency

Binary variables

$U_{DG,t}$ On/off status of the DG-th diesel generator at hour t
$U_{ch,t}$ "1″ if the BS-th battery is charging at hour t, "0″ otherwise.
$U_{dch,t}$ "1″ if the BS-th battery is discharging at hour t, "0″ otherwise.

Positive variables

$X_{DG,t}^{on}/X_{DG,t}^{off}$ Number of hours the DG-th diesel generator remains on/off
$UT_{DG}^{on}/DT_{DG}^{off}$ Minimum on/off time of the DG-th diesel generator

two structures; So that each interconnected MG's scheduling is not only affected by its local power supply and demand, but also influenced by other MGs connected to the MMG. In the field of MMG power control strategies in two islanded and grid-connected modes, extensive research has been done so that integrated power transmission to MGs is not disturbed. In grid-connected mode, reference [11] presents a multi-objective nonlinear control scheme for parallel operation of MGs under asymmetric grid faults. This design provides a multi-objective control that simultaneously eliminates active/reactive power fluctuations at the point of common connection (PCC), overcurrent protection, and reactive power injection. In [12], a new approach for realizing Seamless transitions for three/single-phase MMG is presented, which can improve power supply reliability. An unintentional islanding transition control strategy is proposed in [13]. The proposed strategy reduces the three-phase unbalance and effectively maintains voltage and frequency stability during the unintentional islanding period. However, the problem with this paper is that the state transition is not obvious.

Energy management in MGs is a planning method to coordinate resources on both supply and demand sides to realize power interaction and share surplus energy of RESs among adjacent MGs [4]. According to the latest research, the purpose of energy management in interconnected MMGs is to minimize operating costs such as fuel costs of diesel generators (DGs), unit maintenance, and power purchase costs from the utility grid and adjacent MGs while improving its reliability, and environmental performance. Energy management system (EMS) is used to optimize the performance of distributed DGs, demand side management and exchange power between MGs [14].

There are different models of EMS in MMG, which are: 1) centralized 2) decentralized 3) hybrid 4) nested EMS. In [6], a detailed description of each type of EMS is provided.

In this research, centralized EMS has been used, and all MGs have sent the data of generation resources and the amount of shortage and surplus power to the central EMS (CEMS), and the central unit determines the next day's planning and the amount of exchange power for each MG base d on this. In [15], a bi-level EMS for an islanded structure of networked MGs is presented, which the outer-level EMS is aimed to exchange the required information and power between the interconnected MGs, and the inner-level EMS is intended for energy scheduling of each on-fault MG in case of separation from other MGs. In this reference, the constraints of the units are well described, but the possibility of exchanging each microgrid with the upstream network is not considered. Also, scenario-based method (SBA) has been used to predict uncertainty parameters, which have a lot of computational limitations in problems with big data, which are more tangible with increasing the size of MMG. In [16], presents the bi-level programming for analyzing competitive situations of hierarchical decision-making between an Energy Services Provider representing several MGs. In this paper, an energy service provider (ESP) unit is used as an intermediary between the retail and wholesale markets. In decentralized EMS, Stackelberg game rules are used for two-level programming. The problem of the article mentioned is its single-period review and some constraints of diesel generators such as ramp-up and ramp-down are not considered in it. Also, the curtailment bids should be replaced by considering the parameters of the cost functions as random or stochastic variables with known probabilities.

In [17], different types of demand response programs (DRP) for Optimal Operation of MMG system are classified and each of them is fully described. DR. programs are classified into two categories: price-based demand response (PBDR) and incentive-based demand response (IBDR) [1,17,18]. PBDR programs use shifting load strategies, while IBDR programs generally use curtailing load strategies. The main aim of the DRP is to adapt the users' power consumption with respect to time-varying market prices. With DRP, the MGs with the ability of load shifting will adjust their consumption regarding the power market prices to minimize the operation cost [18]. It should be noted that for the simulation of this paper, the PBDR demand response program of the real-time pricing program section was used, the results of which can be seen in the third scenario.

In the problem of optimal operation of MMG, we are faced with three important sources of uncertainty, which are: 1- Uncertainty in the output power of RESs, 2- Uncertainty in the load demand, and 3- Uncertainty in the price of exchange power. In [19], solves the uncertainty parameters by generating scenarios based on past values using the Monte Carlo method. Each scenario comprises of a vector of DER output powers, load consumption and market prices, with a probability of occurrence. Then, to reduce the computational complexity while maintaining the accuracy of the results, the Fast-Forward scenario reduction has been used. The numerous scenarios of Monte Carlo Simulation increase the computation time and make the algorithm unprofitable for the complex operation and planning procedures. The limited number of scenarios could also reduce the accuracy of the results [20]. Furthermore, the Monte Carlo method does not consider the correlation between the parameters. We use MLP neural network to overcome this problem.

Table 1 compares the results of various research studies on the energy management of multi-microgrids. It is obvious that the innovative and extensive method described in this paper can be proven.

1.2. Contributions of current study

In general, the main contribution of this article can be summarized as follows:

1) Maximizing the use of RESs and minimizing the emission of environmental pollutants from non-renewable energy sources
2) Fair implementation of MMG operation and weight allocation considering the importance of MG load and avoiding power intermediation by MG operators
3) Optimum use of storage systems and analysis of their presence in reducing operating costs
4) The participation of loads and investigating the impact of its presence in reducing the operation cost of MGs by creating different scenarios
5) A multilayer EMS has been used to reduce the computational burden on the CEMS and the possibility of transmission the power of each MG with neighboring MGs and the upstream network
6) The remaining of this paper is organized as follows: In Section 2 problem formulation is presented. Section 3 provides simulation results. Finally, conclusions are presented in Section 4.

2. Problem formulation

2.1. First level: local optimization

At this level, each MG minimizes its operation cost based on the prices of the power received from the upstream network and adjacent MGs, as well as the cost of its other units as represented in Eqs. (1)-(17) [22].

Consider a small-scale MMG system with m MGs denoted by the set $m \triangleq \{1, 2, \ldots, M\}$, is used. Each studied MG has a wind turbine (WT) and a solar array (PV), an ESS unit and a DG unit along with the local load that can participate in DRP. A prominent point is that the energy exchange between any two connected MGs and each MG with the upstream network can be achieved directly without an intermediary, where each vertex $m, n \in M$ represents a MG. The constraints used in the problem are as follows:

2.1.1. Diesel generator and environmental constraints

The operation of diesel generators is always associated with limitations, which include:

$$P_{DG}^{\min} U_{DG,t} \leq P_{DG,t} \leq P_{DG}^{\max} U_{DG,t} \tag{1}$$

$$\left(X_{DG,t-1}^{on} - UT_{DG}^{on}\right)\left(U_{DG,t-1} - U_{DG,t}\right) \geq 0 \tag{2}$$

Table 1
Comparing the references reviewed in the proposed research area.

References	Diesel Generator	Wind Turbine	Solar	Storage Systems	Emissions	Power Exchange Price	DRP	Avoiding Power Intermediation	Deterministic (forecasting)	Stochastic	Exchanging the Power of each MG with the main grid	Centralized EMS	Decentralized EMS
[4]		✓	✓	✓		✓	✓			✓			✓
[6]	✓			✓		✓			✓		✓	✓	
[15]		✓	✓	✓			✓			✓		✓	✓
[17]	✓			✓		✓	✓			✓	✓		
[21]	✓	✓	✓	✓		✓				✓	✓	✓	
This paper	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	

$$X_{DG,t}^{on} = (1 - U_{DG,t-1})U_{DG,t} + U_{DG,t}U_{DG,t-1}\left(1 + X_{DG,t-1}^{on}\right) \quad (3)$$

$$\left(X_{DG,t-1}^{off} - DT_{DG}^{off}\right)\left(U_{DG,t} - U_{DG,t-1}\right) \geq 0 \quad (4)$$

$$X_{DG,t}^{off} = (1 - U_{DG,t})U_{DG,t-1} + (1 - U_{DG,t})(1 - U_{DG,t-1})\left(1 + X_{DG,t-1}^{off}\right) \quad (5)$$

$$P_{DG,t} - P_{DG,t-1} \leq \left(1 - U_{DG,t}(1 - U_{DG,t-1})\right) * R_{DG}^{Up} + U_{DG,t}(1 - U_{DG,t-1})P_{DG}^{\min} \quad (6)$$

$$P_{DG,t-1} - P_{DG,t} \leq \left(1 - U_{DG,t-1}(1 - U_{DG,t})\right) * R_{DG}^{Dn} + U_{DG,t-1}(1 - U_{DG,t})P_{DG}^{\min} \quad (7)$$

$$C_{em}^{DG} = em_{cost_{gas}} \times em_{value_{gas}} \times P_{DG,t} \times U_{DG,t} \quad (8)$$

Eq. (1) shows Minimum and maximum generation power of the DG. The minimum off/on time and the on/off time of the DGs are expressed in Eqs. (2), (4), (3) and (5), respectively [23]. Also, Eqs. (6) and (7) indicate ramping-up and down limitations of DGs, respectively [6,24,25].

Thermal units, especially units fueled by coal, diesel, diesel and even natural gas, in terms of production energy, emit CO_2, NO_X and SO_X harmful gasses. To reduce the emission of these gasses, a parameter named *C_emission* is defined in Eq. (8), which considers the cost of emission of these 3 gasses in the model. The values of the parameters used in this equation are given in the Table 2. Also, the cost of power generation by DG is obtained by Eq. (9) [26,27]. The coefficients used in this equation are shown in Table 3.

$$C_m^{DG} = a_m \times b_m P_{DG,t} + c_m (P_{DG,t})^2 \quad (9)$$

2.1.2. Batteries

All ESS constraints are formulated as follows:

$$SOC_{BS,t} = SOC_{BS,t-1} + \left(\left(\eta_{BS,ch}P_{BS,ch,t} - P_{BS,dch,t} / \eta_{BS,dch}\right)\Delta t\right) / E_{cap_{BS}} \quad (10)$$

$$SOC_{\min} \leq SOC_{BS,t} \leq SOC_{\max} \quad (11)$$

$$0 \leq P_{BS,ch,t} \leq P_{BS,ch,t}^{\max} U_{BS,ch,t} \quad (12)$$

$$0 \leq P_{BS,dch,t} \leq P_{BS,dch,t}^{\max} U_{BS,dch,t} \quad (13)$$

$$U_{BS,ch,t} + U_{BS,dch,t} \leq 1 \quad (14)$$

$$PB_{BS,t} = P_{BS,ch,t} - P_{BS,dch,t} \quad (15)$$

Eq. (10) specifies the SOC of the battery [21,28]. The maximum/minimum limits of SOC, charging and discharging power of the battery are specified in Eqs. (11)-(13), respectively. Eq. (14) is for not to occur charging and discharging the battery at the same time. Also, the battery power at hour t is calculated from Eq. (15) [29,30].

2.1.3. Exchange power

The most basic task of MG is to maintain the economic balance of supply and demand by adjusting the supplied power and managing the demand side [4]. The Load and generation equivalence has shown in Eq. (16). Generally, a positive sign indicates buying power, whereas a negative sign indicates selling power.

$$P_{DG,t} + PG_{m,t} + PR_{m,t} - PB_{m,t} - Ldr_{m,t} + PM_{m,n,t} = 0 \quad (16)$$

Table 2
The cost and amount of gas produced by diesel generators.

gas	$em_{cost_{gas}}$ [\$/kg]	$em_{value_{gas}}$ [kg/kWh]
NO_X	9.324	0.000198
SO_X	2.1978	0.0000036
CO_2	0.03108	0.0007182

2.1.4. Preventing intermediation

One of the problems that we must pay attention to during operation is that MGs buy/sell their shortage/surplus power in the operation process and do not engage in power mediation to achieve more profit. If this is not prevented, the profit of one or more MGs will improve at the same time as the profit of the rest of the MGs deteriorates, which means that the mentioned MG has bought power cheaper and sold it more expensively to other MGs. To prevent this, conditions must be provided so that no MG in MMG buys and sells power simultaneously from/to adjacent MGs or the upstream network. To achieve this, we divide each of the parameters $PG_{m,t}$ and $PM_{m,n,t}$ into two positive components, and then by multiplying each of them into a binary variable, we control the power exchanges.

2.1.5. Objective function

The objective function of this level is to minimize the total operating cost of each MG, which is calculated as Eq. (17).

$$Z_m = Min\left(\sum_{t=1}^{T} \text{Cost}\right) = Min\left\{C_m^{DG} + C_{em}^{DG} + C_m^{BS} + C_m^{Grid} + C_m^{MG}\right\} \quad (17)$$

2.2. Second level: global optimization

At this level, the multi-microgrid EMS unit minimizes the overall operation cost by considering the objective functions of each MG and satisfying the constraints [22]. For this purpose, the overall objective function of MMG is considered in the form of coefficients of the objective functions of each MG and based on the importance of the load of that MG, in the form of Eq. (18).

$$Z_T = Min\left(\sum_{m=1}^{M}\left\{W_m \times \left[\frac{Z_m^* - Z_m}{Z_m^*}\right]\right\}\right) \quad (18)$$

Where W_m is the weight of the m-th objective function and Z_m is the m-th MG objective function and Z_m^* is the solution of the model considering the m-th function as the objective and the rest of the functions as constraints.

Fig. 1 shows the MMG optimal operation strategy used in this paper, which consists of two layers.

3. Simulation result

In this part, the proposed model has been implemented on an MMG system and the impact of different exploitation operations on it has been investigated. For this purpose, an MMG system consisting of 3 microgrids connected to each other is considered, as shown in Fig. 2. To make the results closer to the real results, the real data of the Canadian state of Ontario have been used for simulation.

The considered MMG includes three units of DG, WT, PV, and storage in buses No. 9, 10, and 11, and all three MGs are connected to the upstream network through bus number 2 (PCC). MG loads are connected to bus numbers 6, 7, and 8. Data related to DGs and energy storage sources are given in Table 3 and Table 4, respectively. Also, the considered WTs in the first, second and third MGs have a rated capacity of 1000, 1000, and 2000 kW, respectively, and the value of the cut-in, rated and cut-off speed of the WTs is equal to 3, 11, and 25 m/s, respectively.

In this structure, three photovoltaic power plant units have been used, with the number and specifications of solar panels inserted in Table 5.

To estimate the amount of the load of each microgrid, the amount of RES generation and the price of power exchanges between MGs and the main grid, the MLP neural network has been used in the MATLAB environment. For this purpose, to forecast energy price data as well as load profile data from the ONTARIO market for three continuous years (from January 1, 2019 to July 30, 2021) have been collected with a time

Table 3
. Programmable DGs information.

MG	a_m [$]	b_m [$/kW]	c_m [$/kW^2$]	$P_{DG}^{max}[kW]$	$P_{DG}^{min}[kW]$	$IS[h]$	$\min_t[h]$	SUP [$]	SDP [$]
MG1	0.0019	0.00047	0.000024	500	50	0	4	15	5
MG2	0.0023	0.0005	0.000026	900	90	2	2	45	10
MG3	0.002	0.00048	0.000025	700	65	0	4	45	10

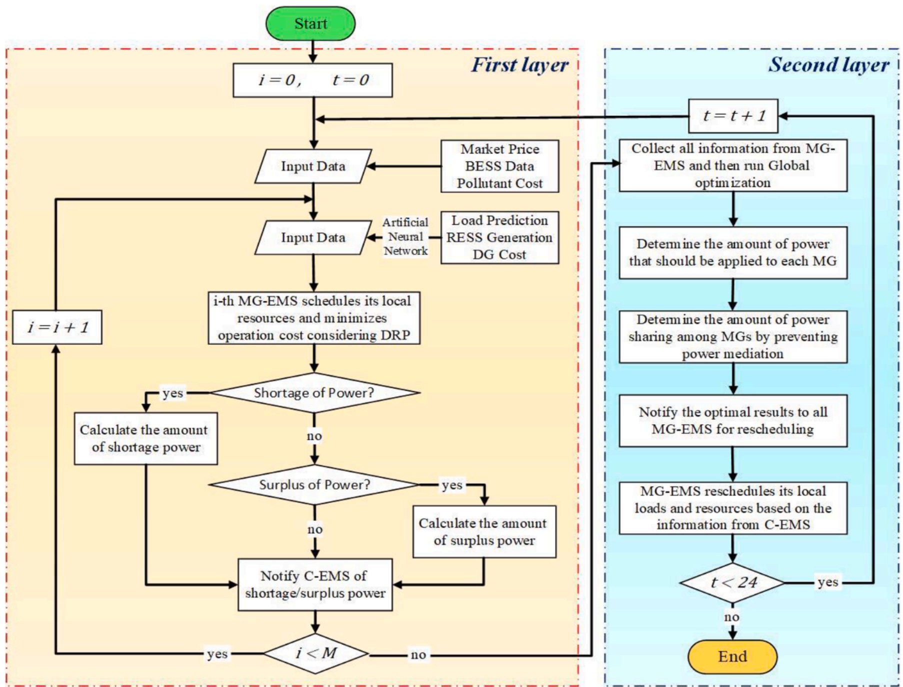

Fig. 1. Flowchart of optimal operation proposed strategy of the MMG system.

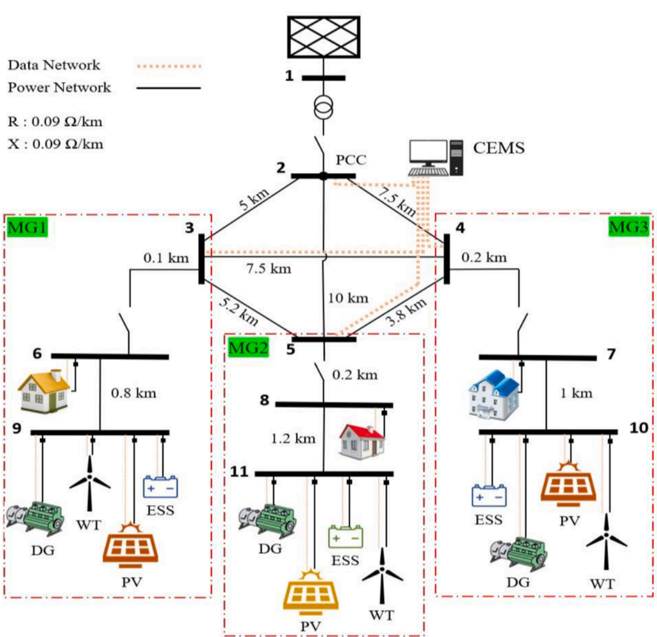

Fig. 2. Schematic representation of the MMG system used with 3 MGs.

interval of one hour. The optimization problem is implemented in GAMS 25.1.2 software using CPLEX solver and MATLAB on a PC with an Intel Core i7, 2.6 GHz CPU and 8 GB of RAM. The input and output data are transferred using GAMS/MATLAB interface.

Table 4
Storage units information [28].

MG	$Ecap_{ESS}[kW]$	$P_{dch}^{max}[kW]$	$SOC_{min}[\%]$	$SOC_{max}[\%]$	$\eta_{ch,dch}[\%]$
MG1	600	100	20	90	90
MG2	1000	170	20	90	90
MG3	600	100	20	90	90

To prove the effectiveness of the proposed method for modeling different uncertainties, the prediction of different parameters has been done for July 30, 2021. For example, the comparison of different parameters for actual and predicted data of the load, solar radiation, ambient temperature and wind speed for MG2 is shown in Fig. 3, which clearly shows the advantage of using MLP neural network to predict data with uncertainty. As can be seen, all the parameters of the neural network have performed well and have been able to follow the behavior of the real data to a large extent. In order to show the efficiency of this method, the well-known measure of the root mean square error (RMSE) for the predicted data mentioned in Table 6 is compared.

The power generation of renewable resources (wind and solar) utilized in the simulated MMG, according to the microgrid, is shown in Fig. 4. As predicted in the previous section, Fig. 5 indicates the pricing of MGs and the upstream network on the specified day.

To operate the proposed MMG, 3 different scenarios have been considered as follows, and in the end, the results are compared and summarized.

Table 5
Solar panels information.

MG	n_{PV}	$A_{pv}[m^2]$	$\eta^r_{PV}[\%]$	$\eta_{PC}[\%]$	$N^T_{PV}[^\circ C^{-1}]$	$T^{ref}[^\circ C]$	$NOCT[^\circ C]$
MG1	700	1.28	15.8	100	3.7×10^3	25	43
MG2	3000	1.28	16.1	100	3.7×10^3	25	43
MG3	1500	1.28	17.8	100	3.7×10^3	25	43

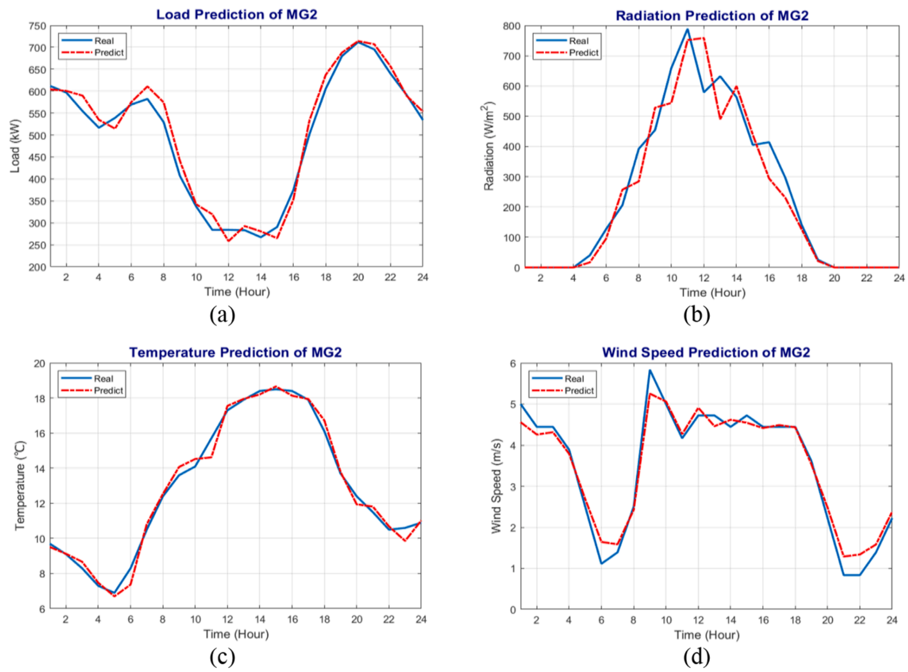

Fig. 3. Profiles of (a) load, (b) solar radiation, (c) ambient temperature, and (d) wind speed of the MG2 of MMG for actual and predicted data.

Table 6
Prediction error criteria of different data with MLP neural network.

MG	RMSE error criteria		
	MG1	*MG2*	*MG3*
Load	0.026	0.019	0.015
Solar radiation	0.045	0.043	0.046
Tempreture Ambient	0.0044	0.0048	0.0449
Wind Speed	0.072	0.061	0.058

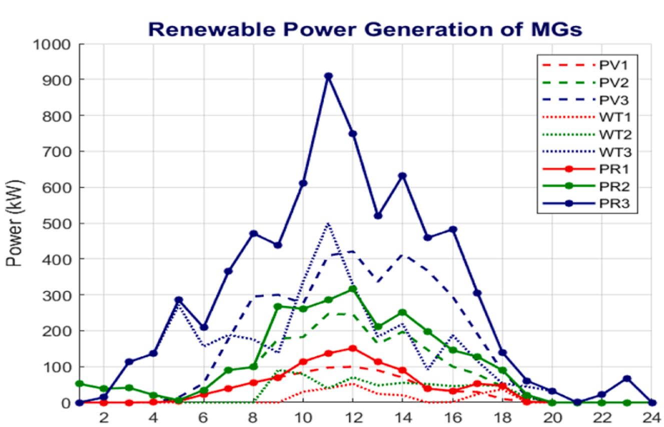

Fig. 4. The generation power of RES by type of source and MG in the proposed MMG ($P_R = P_{PV} + P_{WT}$).

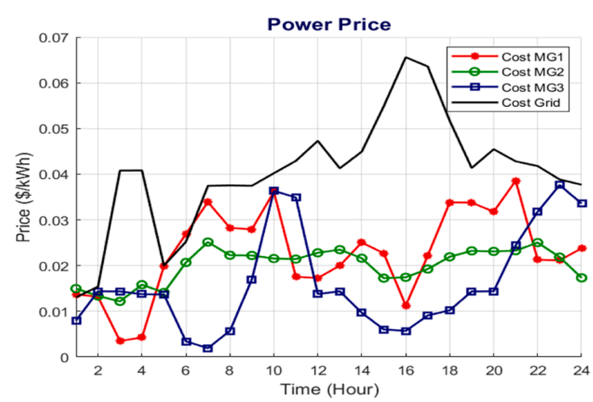

Fig. 5. Power price of MMG system and upstream network.

3.1. First scenario: operation of MMG in connected mode and ability to exchange power between MGs and DRP (with a maximum contribution of 20%)

The purpose of this scenario is to investigate the impact of the operation mode and DRP on the mentioned MMG. The load of MGs after applying DRP in MMG is shown in Fig. 6. As it can be seen in this figure, in MMG, for a better exchange of power between MGs, three areas with different load profiles in the province of Ontario, Canada have been used, so that the peak load of MG1 is in the middle of the day, MG2 in the early and late hours of the night, and MG3 is in the middle of the day and early night. Another point that we can learn from this load profile is that MG1 meets a shortage of power in most hours and MG2 meets an excess

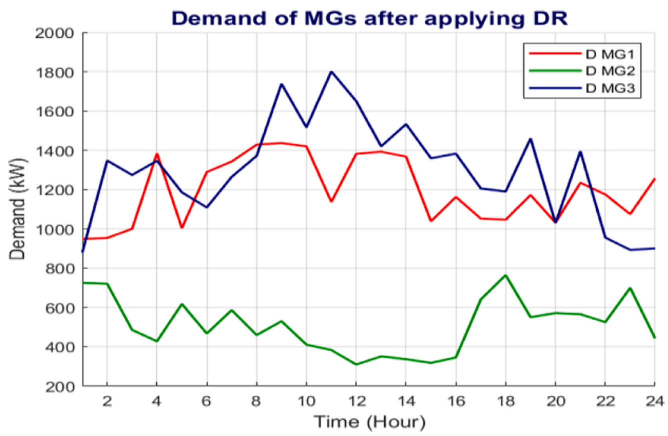

Fig. 6. The load of MMG microgrids after applying DRP.

of generation power in most hours. According to the load profile, as we expected, because MG1 is meeting a lack of generation, according to Fig. 7, its diesel generator produces its maximum capacity in most hours in order to meet the requirement of load-production equality in addition to reducing its operating cost. Also, the generation power of the MG2 diesel generator is reduced due to excess generation between 10:00 and 17:00 (due to a significant reduction in the load).

The exchange power of MGs with the upstream network and with together is shown in Fig. 8.a and b, respectively. As can be seen from these figures because the load of the MGs must be supplied in the early hours of the day and night, and the two diesel generators of MG1 and MG2 do not generate power at 00:00, so they cannot supply the load in the early hours of the morning, and the production of RESs is at zero. Therefore, MGs buy from the upstream network considering that the purchase price from the upstream network is lower compared to the rest of the hours. From 11:00 to 17:00, because MG2 has surplus generation power and the price of power purchased from MG2 is lower than the upstream network, so the MG1 buys some of the power it needs from MG2 during these hours and also in two hours from the same interval, i. e., 10:00 and 14:00 h, when the price of MG2 power is relatively lower than other hours, MG1 charges its own batteries from the same purchased power, which can be seen in Fig. 9. Also, as can be seen from this diagram, the battery located in MG2 takes two consecutive charges and two consecutive discharges due to its load and renewable generation power diagram, which was accompanied by a decrease in generation around 4:00 to 5:00, so that it is forced to buy from the upstream network should not be used to minimize its operating cost.

The analysis of the exchange power of MG3 is such that from 5:00 to 8:00 due to the increase in RES generation, its load is supplied by these

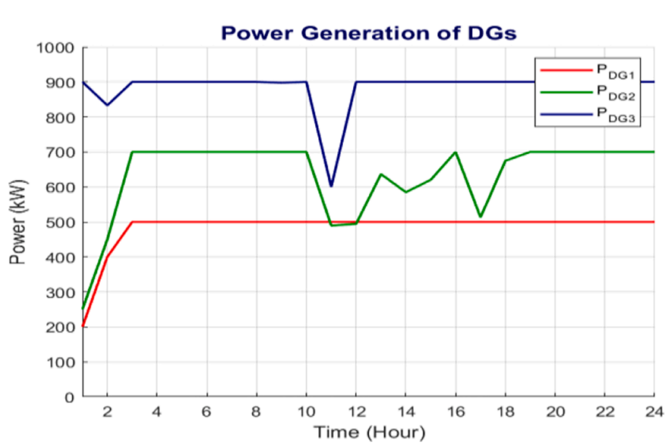

Fig. 7. Generation power of diesel generators according to MG.

sources and the third diesel generator until 9:00, which is one of the peak load points of MG3, and the purchase is made from the upstream network again. It is possible, but after that, due to the significant increase in renewable production and the passing of the peak load, a purchase from the upstream network is not made until 18:00, when renewable generation decreases. Then we have two local peak loads at 19:00 and 21:00 h, which are again supplied by purchasing from the upstream network, and from 22:00 h onward, when the load drops sharply and renewable generation at 23:00 h, MG3 sells power to MG1.

In general, the operating cost of MGs in the first scenario is according to Table 7. The reason for the lower operating cost of MG2 compared to the other two microgrids is that MG2 is faced with surplus generation power during most hours, which sells this surplus power to the upstream network and adjacent MGs, which lowers its operating cost.

3.2. *Second scenario: operation of MMG with and without the storage system*

In this scenario, we are going to compare the operation of MMG with and without the storage system. For this, the input data of DGs are applied as shown in Table 3 with initial powers of 250, 350, and 450 kW. Other problem input information is given in the previous section.

The generation power of DGs in two modes with and without storage is shown in Fig. 9.a and b, respectively. The use of storage causes the adjustment of the peak load from high consumption hours to low consumption hours, which consequently reduces the need to generate diesel generator resources; as expected, the operation in the mode with storage has lower diesel generator generation than the mode without storage, which can be seen in Fig. 9. As expected, in the mode of operation without storage, DGs generate more power, which becomes one of the effective factors in increasing the cost of operating MMG without the presence of storage.

As can be seen from Fig. 10, the use of storage increases/decreases the need to purchase from the upstream network during the hours when the price of purchasing power from the network is low/high. This statement can be easily seen by putting together Figs. 4 and 10; so that in the case with storage, MG1 and MG3 buy more power from the network in hours 00:00 - 10:00 when the network price is relatively low, and also in hours 14:00 - 20:00 when the network is high, MG1 buys less and the power purchased by MG3 from the network reaches zero.

In general, to compare the benefits of operation MMG with and without the use of storage, the price of both operation modes by MG is given in Table 8.

3.3. *Third scenario: operation of MMG in different DRP mode (with a maximum contribution of 40%)*

As for the last scenario, we are going to investigate the impact of the participation of different DRPs in the operation of MMG. For this, the input data of the diesel generator are shown in Table 3. Programmable DGs information with the initial power of 300, 100, and 700 kW, and the load of each of the MGs is applied before applying DRP is shown in Fig. 11. Other information required for this scenario is given in the first scenario. To investigate the impact of demand response on the operation cost of MMG, we consider 5 different operating modes with and without DRP with a maximum participation coefficient of 0.1, 0.2, 0.3, and 0.4.

The operating cost of MGs for different maximum load response coefficients is given in Table 9. As we can see, as the load participation in DRP increases, the operating cost decreases.

4. Conclusion

Currently, several solutions have been proposed to overcome this uncertainty with the aim of increasing reliability and improving energy management. One of the solutions to this problem is to decentralize the control of distribution networks in a set of small-scale areas (microgrid).

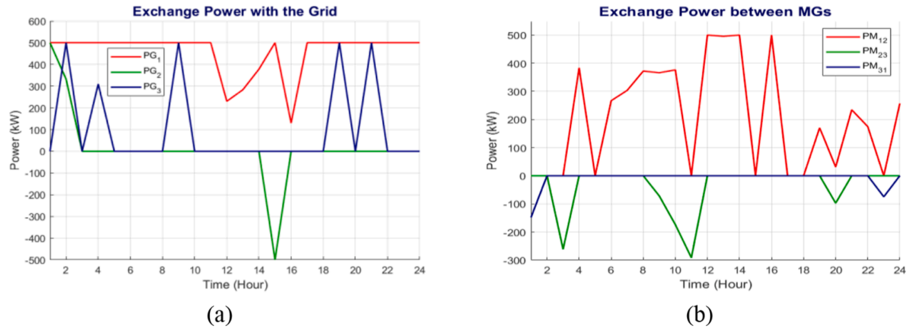

Fig. 8. Exchange power (a) MGs with the upstream network, and (b) between MGs with each other in the proposed MMG in the first scenario.

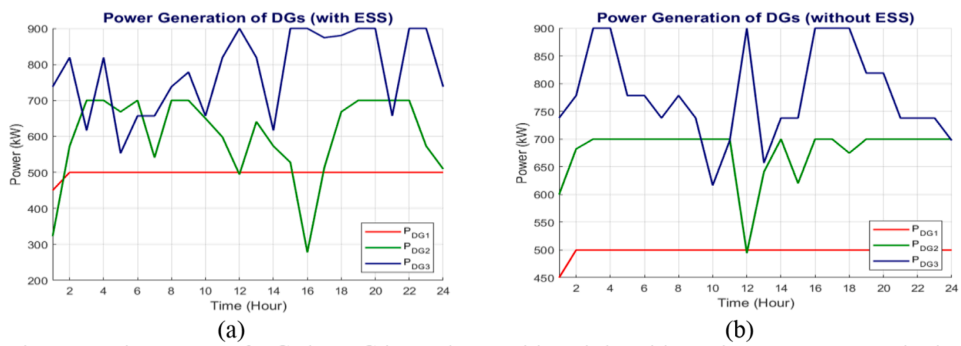

Fig. 9. The generation power of DGs by MG in mode (a) with and (b) without the storage system in the second scenario.

Table 7
The operation cost of MGs in the first scenario [$].

	MG1	MG2	MG3	MMG
Operation Cost	708.66	164.57	627.83	1500.06

Table 8
Operation cost of MGs in the second scenario [$].

Operation mode	MG1	MG2	MG3	MMG
With storage	717.43	146.39	606.25	1470.07
Without storage	681.85	142.22	595.94	1420.01

The connection of MGs as an interconnected network structure can provide many benefits, such as effective use of RES in the network, reducing the operation cost and compensating for the low flexibility caused by the high penetration of the use of RESs. However, one of the biggest challenges in using this structure is ensuring optimal energy management in it. In this paper, a two-layer EMS is used for optimal operation of MMG systems. The benefit of this approach is that MGs can more effectively manage their local resources and loads to reduce their operating cost through power exchanges between themselves and the upstream network. To prove the effectiveness of the proposed method in this study, an MMG with real conditions and considering all sources of uncertainty has been used. Three different scenarios were investigated in this simulation, and the advantages mentioned on it were analyzed. It

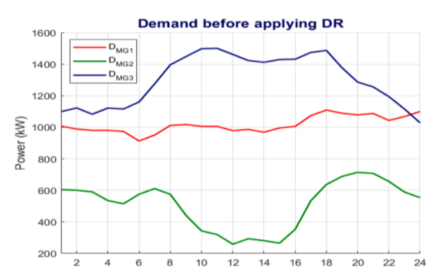

Fig. 11. The amount of load of MMG microgrids before applying DRP in the third scenario.

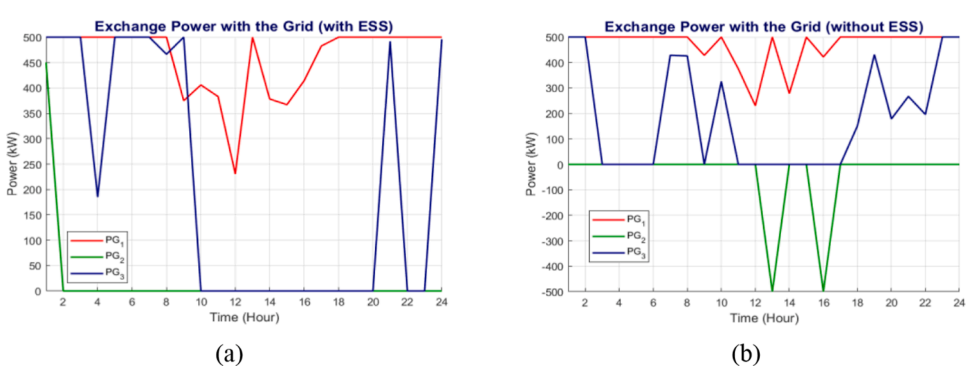

Fig. 10. Exchange power of MGs with the upstream network in mode (a) with and (b) without storage system in the second scenario.

Table 9
The effect of different coefficients of the maximum load participation of MGs in DRP in the third scenario.

MG	Operation Cost [$]			
	MG1	*MG2*	*MG3*	*MMG*
0	629.04	134.15	621.79	1384.98
0.1	620.01	130.00	616.48	1366.49
0.2	589.19	112.35	610.31	1311.85
0.3	566.62	92.64	606.33	1265.59
0.4	561.09	58.97	577.85	1197.91

was also proved that the operating cost of the connected MMG with the storage system is lower than the operating mode without the storage system. In the last scenario, the impact of load participating in the operation of MMG and reducing its cost was investigated. Also, in this study, actions were taken to prevent intermediation and additional selling or buying of power in transmission mode so as not to cause an unfair increase/decrease in operating costs and losses of MG(s) rights.

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.

Data availability

No data was used for the research described in the article.

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