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Comparison of centralised and decentralised operational costs of multi-microgrid systems considering reliability and flexibility criteria

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ABSTRACT

The main purpose of formation of multi-microgrid (MMG) in both centralised and decentralised mode is to ensure the microgrid (MG) of providing load-generation balance. Minimizing operational costs and maximizing profit in MMGs have been key research topics in recent years. However, in the previous literature, an accurate and scientific comparison of centralised and decentralised MMGs has still remained as a research gap. Focusing on this gap is the main contribution of the current research; it is focused on comparison of centralised and decentralised MMGs from the operational cost viewpoint, including RESs (PV and WT), fossil fuel generators (FFG), and ESS. Moreover, the operational costs of centralised and decentralised MMGs considering reliability and flexibility criteria will be compared. The study will be done in a test power system with real specifications considering two possible scenarios. The simulations will be done in MATLAB platform using the MATPOWER package and Gurobi solver. The simulations results show that total daily operational cost of centralized MMGs is notably less than this cost in decentralized MMGs. Demand response become better when the MMGs are centrally scheduled. Also the reliability criterion of EENS is less, i.e., the power system becomes more reliable with centralized MMGs. Power losses in centralized MMGs decrease, but the CO2 emission increases.

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Introduction

The excessive increase in the number of greenhouse gases pollution from all human activities and their negative environmental impact such as global warming, shortage of fossil sources, etc., are some of the reasons for high penetration of renewable energy sources (RES) and electric vehicles (EVs) [1; 2]. The pressures of renewable electricity generation, penetration of EVs and increased electricity consumption are drivers to form microgrids (MGs). This technology used in several areas including the military, hospitals, and airports [3]. Modern distribution networks must satisfy the technical and security constraint and reliability of the distribution system, and on the other hand, it must observe optimal scheduling of MGs [4].

MG is a group of linked loads and RESs within clearly defined electrical boundaries that works as a single controllable essence that can operate in grid connected mode (connected to the upstream grid) or in an isolated mode (without support of the external grid) [5]. To take advantage of the MGs' faster speed in terms of power exchange, high resilience, reliability, and greater controllability, conventional distribution systems can be changed into multi-MG (MMG) systems [6; 7].

Each MG in the MMG system will have a different mixture of resources and consumers. Commonly, MMG system contains some independent generators and consumers which are directly connected to the MMG system. The main purpose of creating MMG is to increase the resilience, balance supply and demand, operate to deliver the best outcomes for locally connected loads and offer support and services to the wider systems etc. MMG in both centralised and decentralised modes tries to ensure the MG of providing load-generation balance [8]. Minimizing operational costs and maximizing profit in MMGs have been key research topics in recent years [9].

In [10], a stochastic method for energy management of residential MG is illustrated, in which demand response (DR) programs and energy storage system (ESS) are also considered. In addition, this research represents stochastic bidding strategy for MG participation in the day-ahead market. Reference [11] proposed an energy management model for a MG with considering optimal power flow (OPF). In [12; 13], the authors presented the demand-side energy management in smart grids. The authors represent a multi-agent-based, three-level, hierarchical energy management system for MGs in [14]. In [4], MG energy management in automated distribution network with considering consumers comfort index have been studied.

Minimizing the cost function of power generation is the most important optimized variable in the MG [15]. Authors of [16-18] tried to minimize the MGs cost function of power generation by optimally setting and sizing the RES by following an OPF, or through the introduction of self-adaptive mathematical model. Reference [19], applied cost function minimization of the power generation of the network by finding the optimal sizing of the ESS using the Grey Wolf optimization method. Research [20], modelled an optimization problem to the MG that reduces the cost as well as reduces the emissions of greenhouse gases whilst improving the reliability of the system. The structure of MMGs has been investigated in [21] to minimise the cost and emission in MMGs due to the stochastic behaviours of RESs and demands. The authors of [22] addressed the integration of an islanded MG into the electricity market and tried to minimise the total cost and find the optimal size and place of different RES components such as wind turbine (WT), photovoltaic (PV) etc.

In the existing literature, several researchers have worked on difference between centralised and decentralised cost function of generation by MMGs. In [23], the comparison of centralised and decentralised MMGs from the viewpoints of reliability, communications, scalability and resiliency has been studied. In [24], the energy management of centralised and distributed MMGs have been addressed, with the objective of maximising the profit from the MMG system. The authors of [25] proposed a centralized / decentralized (C/DC) MMGs control method to improve the operation of these MMGs in the presence of communication link fault. The authors of [26] presented an optimization algorithm for economic operation of MMGs in the presence of the uncertainties of renewable energy sources (RESs). In [27], a bilevel optimization approach for economic operation of MMGs with interruptible loads in local energy and reserve markets is proposed.

For the sake of clarity, a summary of the conducted papers is presented in the Table 1:

Table 1. A summary of the conducted papers.

Ref. No.	**The highlighting features**
Ref. [4]	The MG energy management in automated distribution network with considering consumers comfort index is studied.
Ref. [10]	A stochastic method for energy management of residential MG considering demand response (DR) programs and energy storage system (ESS) is presented.
Ref. [11]	An energy management model for a MG with considering optimal power flow (OPF) is proposed.
Ref. [12,13]	The demand-side energy management in smart grids is considered.
Ref. [14]	A multi-agent-based, three-level, hierarchical energy management system for MGs is studied.
Refs. [15-18]	Minimizing the MGs cost function of power generation by optimally setting and sizing the RES by following an OPF, or through the introduction of self-adaptive mathematical model is considered.
Ref. [19]	The optimal sizing of the ESS in MMGs using the Grey Wolf optimization method is studied.
Ref. [20]	Minimizing of the cost and emission in MMGs whilst improving the reliability is presented.
Ref. [21]	Minimizing of the cost and emission in MMGs due to the stochastic behaviours of RESs and demands is considered.
Ref. [22]	Addressing the integration of an islanded MG into the electricity market and to minimizing the total cost and finding the optimal size and place of different RES components are studied.
Ref. [23]	The comparison of centralised and decentralised MMGs from the viewpoints of reliability, communications, scalability and resiliency has been studied
Ref. [24]	The energy management of centralised and distributed MMGs studied, with the objective of maximising the profit from the MMG system.
Ref. [25]	A centralized / decentralized (C/DC) MMGs control method to improve the operation of these MMGs in the presence of communication link fault is presented.
Ref. [26]	An optimization algorithm for economic operation of MMGs in the presence of the uncertainties of renewable energy sources (RESs) is proposed.
Ref. [27]	A bilevel optimization approach for economic operation of MMGs with interruptible loads in local energy and reserve markets is proposed.

In the previous literature, an accurate and scientific comparison of centralised and decentralised MMGs with complete structure from the viewpoints of operational cost and reliability and flexibility criteria has still remained as a research gap. Focusing on this gap is the main contribution of the current research, as bellows:

- It is focused on comparison of centralised and decentralised MMGs from the operational cost viewpoint, including RESs (PV and WT), fossil fuel generators (FFG), and ESS.

- Moreover, the operational costs of centralised and decentralised MMGs considering reliability and flexibility criteria will be compared.
- The study will be done in a test power system with real specifications considering two possible scenarios. The simulations will be done in MATLAB platform using the MATPOWER package and Gurobi solver [28].

The rest of this paper is organized as follows: The methodology of the paper is explained in the *Methodology* section. Section of *Simulation results and discussion* provides the simulation results and discussion, and conclusion are presented in the *Conclusion* section.

Methodology

Optimization procedure

The related problem is formulated as an optimization problem to minimize the MMG operation cost subject to reliability and flexibility criteria and operational constraints. The problem is optimized for both centralized and decentralized MMGs. As mentioned, the MATPOWER package is used as the optimization tool in this research. MATPOWER is a package of free, open-source simulation available in MATLAB-language M-files and provides numerous case examples for solving steady-state power system simulation and optimization problems, such as power flow (PF), continuation power flow (CPF), extensible OPF, unit commitment (UC) and stochastic, secure multi-interval OPF/UC. The MATPOWER framework has been widely used for solving steady-state electrical power scheduling problems, analyse a power system, and balanced system problems, from power flow to optimal power flow analysis [29].

Centralized and decentralized MMGs

In centralized MMGs, all microgrids are controlled and scheduled from a single center called energy management system (EMS). All data regarding microgrids (ramp rate units, minimum up time, minimum down time, charge and discharge storage and type of load, etc.) are telecommunicated to the EMS to decide about scheduling orders. EMS based on all received data and the objective function of costs, schedules the day-ahead activities of units. This optimization procedure may aim at boosting the reliability, reducing costs, etc. This research work focuses on decreasing operational costs of a set of microgrids. In fact, in centralized MMGS, only one optimization is done by EMS to schedule the set of microgids, and all microgrids are connected via a shared bus to the upstream grid.

On the other hand, in decentralized MMGs, each microgrid separately schedules its activities to minimize its operational costs. In this model, microgrids directly exchange data with EMS to receive scheduling orders and there is no proxy agent. In this model, each microgrid is done a separate optimization, and the microgrid is directly connected to the upstream grid.

Mathematical modelling of the system

Main objective function:

As mentioned, in the related optimization problem, the objective is to minimize the operation cost of the MMG. Therefore, an objective function is defined as,

$$C_{MMG}^{Operational} = \sum_{i=1}^{I} C_{MGi} \tag{1}$$

The operational cost of each MG includes five terms and can be formulated as,

$$C_{MG} = C_G + C_{DER} + C_{ESS} + C_{FF} + C_{DR} \tag{2}$$

The cost of power purchased from the grid can be represented in (3).

$$C_G = \sum_{i=1}^{N_t} Price^G(t) \times P_G(t) \tag{3}$$

The cost of power generated from the distributed energy resources is represented in (4).

$$C_{DER} = C_{PV} + C_{WT} \tag{4}$$

C_{PV} is the cost of power generated from the PV arrays, illustrated in (5).

$$C_{PV} = \sum_{i=1}^{N_t} Price^G(t) \times P_{PV}(t) \tag{5}$$

The power generated by PV arrays depends on the cell temperature and the intensity of solar irradiance the maximum power points, which is determined by the following equation:

$$P_{PV}(t) = P_{PV,STC} \times \frac{G_T(t)}{1000} \times \left(1 - \gamma\left(T_j - 25\right)\right) \times N_{PV}(s) \times N_{PV}(p) \tag{6}$$

$$T_j = T_{amp} + \frac{G_T}{G_{T,STC}} \times (NOCT - 20) \tag{7}$$

C_{WT} is the cost of power generated from the wind farms, illustrated in (5).

$$C_{WT} = \sum_{i=1}^{N_t} Price^{WT}(t) \times P_{WT}(t) \tag{8}$$

The power generation of wind turbines depends on wind speed. Wind speed fluctuation can be instantaneous, hourly, daily, and seasonal. Therefore, the following equation is used to model the real power generated by the wind turbine.

$$P_{WT}(v) = \begin{cases} 0 & if\ \ v < V_{ci} \\ P_R(A + Bv + Bv^2) & if\ \ V_{ci} < v < V_r \\ P_R & if\ \ V_r < v < V_{co} \\ 0 & if\ \ V_{co} < v \end{cases} \tag{9}$$

Cost of using stored power in ESS will be calculated as (10):

$$C_{ESS} = \sum_{i=1}^{N_t} Price^{ESS}(t) \times P_{ESS}(t) \tag{10}$$

Cost of Traditional Fossil-Fuel Power Generation can be calculated as follow:

$$C_{FF} = a(P_{FF})^2 +\ b(P_{FF}) + c \tag{11}$$

As the final term, the cost of demand response is as (12), as bellow:

$$C_{DR} = \sum_{i=1}^{N_t} P_{DR,i,t}(t) \times M_{i,t} \tag{12}$$

The reliability criterion of expected energy not supplied (EENS) is used in this formulation to ensure the system reliability. The EENS value is implicitly extracted from demand response results. To make the proposed scheme flexible, its capability in deferent scenarios will be tested and verified.

Problem constraint

The objective function of (1) must be optimized with respect to the MMG operational constraint as follows:

The total amount of generated power is directly depending on total demand. Eq. (13) illustrates the balance between generation and demanded powers.

$$P_d = P_g \tag{13}$$

Inequality (14) illustrates the summary of the generation limits of the fossil-fuel sources.

$$P_i^{min} \leq P_i \leq P_i^{max} \tag{14}$$

where, P_i^{min} and P_i^{max} respectively represent the minimum and maximum amounts of power generation which is typically set to the rated power.

1) The constraints of power flow limits of transmission lines are as (15),

$$-S_{ij}^{max} \leq S_{ij} \leq S_{ij}^{max} \tag{15}$$

2) Voltage and angle limits of buses are as follows:

$$V_i^{min} \leq V_i \leq V_i^{max} \tag{16}$$

$$\delta_i^{min} \leq \delta_i \leq \delta_i^{max} \tag{17}$$

The constraints of state of charge of ESS, as follow:

$$SOC(t) = SOC(t-1) + charge \tag{18}$$

Finally, subject to the unit commitment constraints presented in [24] as Eqs. (2) to (16). For more clarity, the optimization process used in this paper solved by MATPOWER OPF is summarized as the following flowchart:

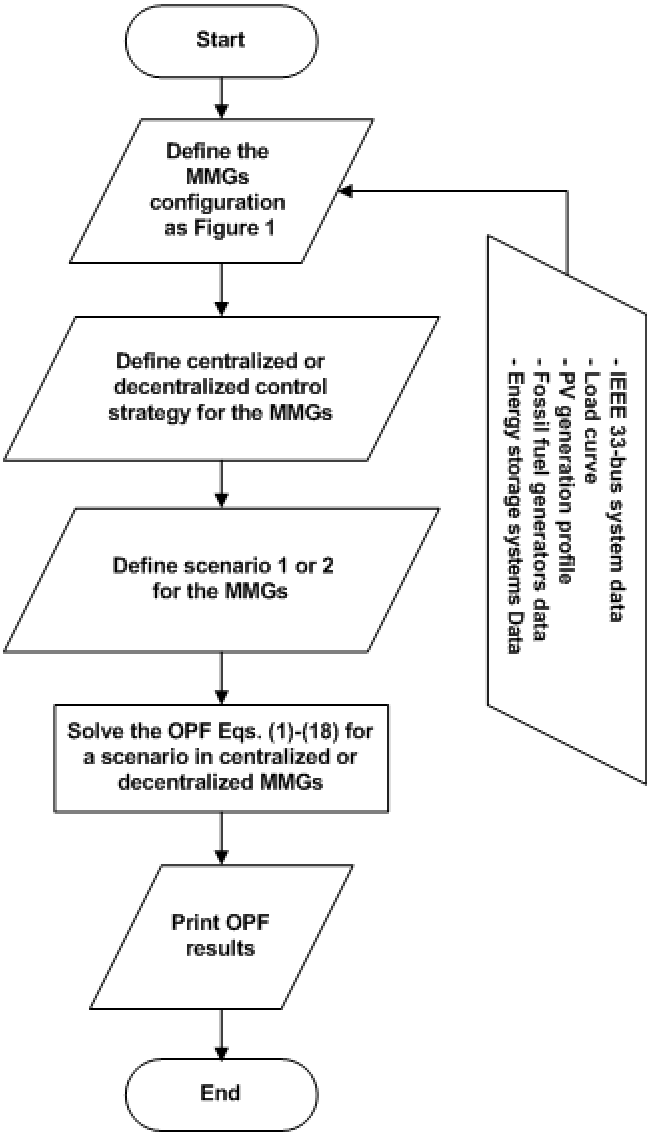

Figure 1. The flowchart of the optimization process

Simulation results and discussion

Problem modelling of the system

The used system in this project is the IEEE 33-bus radial distribution network [30] which consists of three MGs and is modelled as a balanced network system in MATPOWER. Consumer of each MG include regular loads (EVs in future) whose load demand is supplied from RESs, and FFGs located in the MG or purchasing power from the upstream grid. As represented in figure 1, three wind farms are installed in buses 15, 19 and 30. Three PV stations are located in buses 17, 21 and 32. In this project, each MG performs its optimal scheduling with the aim of minimizing operating cost. Two FFGs have been added to buses 8 and 10, two ESSs are installed at buses 2 and 33. Each microgrid can purchase power from the main grid (upstream grid) at the rate of 15 kwh/$ and sell to it at the rate of 11 kwh/$. Other details of the considered system are presented in the following sub-sections.

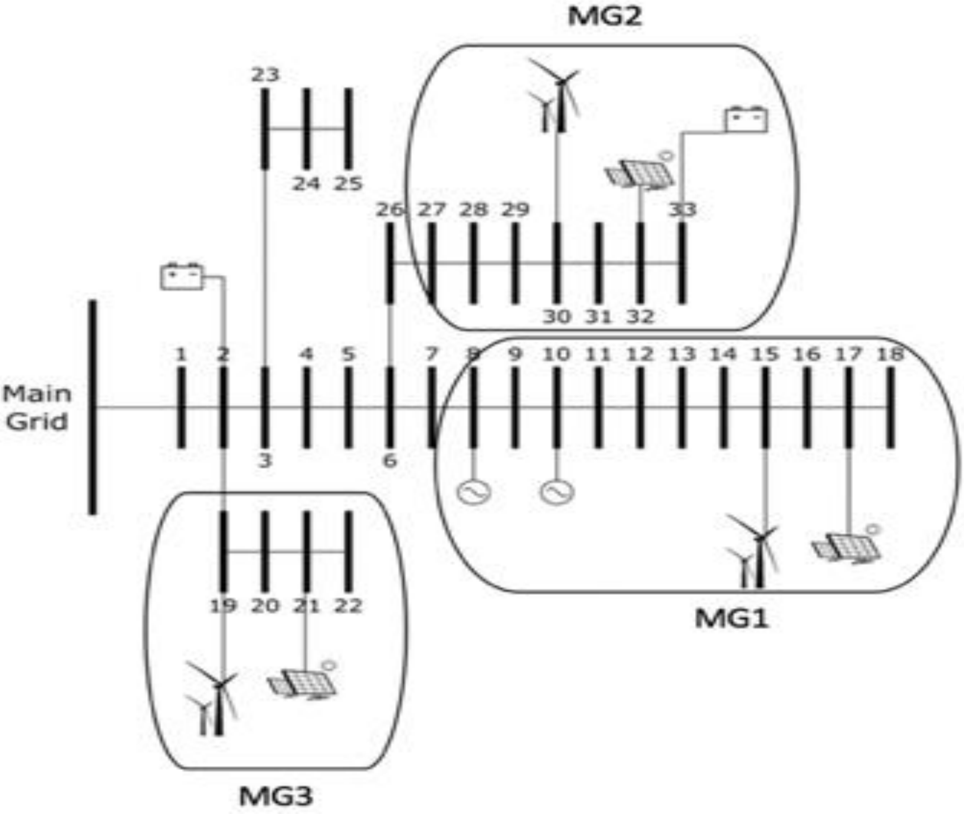

Figure 2. The modified IEEE 33-bus system distribution network structure

The system load curve

The nominal (mean value) loading of the mentioned IEEE system is 730 kW [30]. Totally, the daily load curve of this system is as shown in figure 2. The figure shows that the peak load with the value of 1400 kW appears at 18 O'clock.

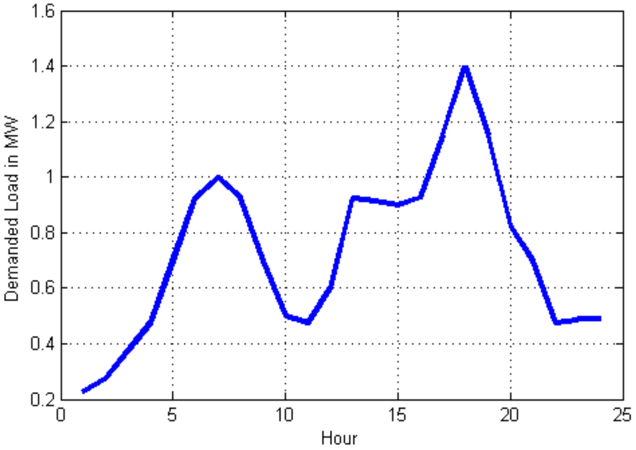

Figure 2. Daily load curve of IEEE 33-bus system

Wind farms power generation profile

Typical three wind farms electricity generation for a 24-hour period is represented in figures 3 to 5 [31].

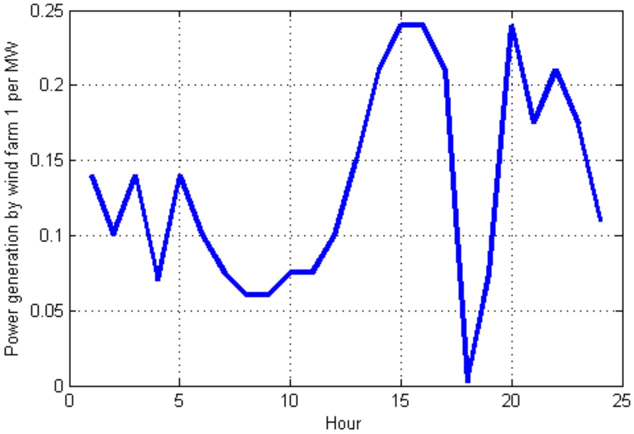

Figure 3. Power generation by wind farm 1

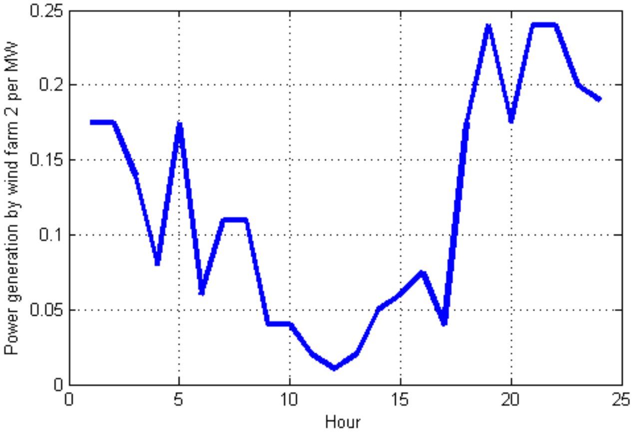

Figure 4. Power generation by wind farm 2

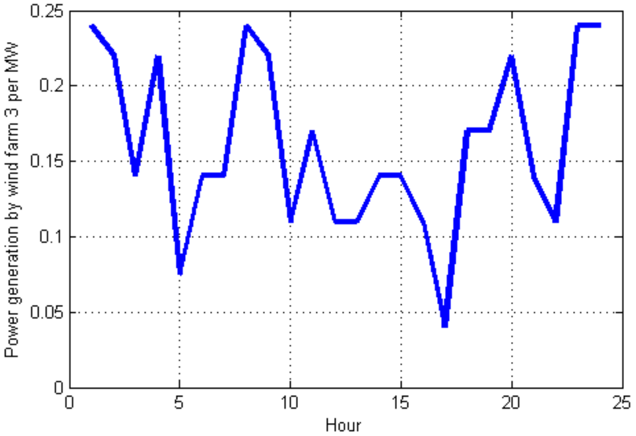

Figure 5. Power generation by wind farm 3

PV panel power generation profile

Typical three PV panels electricity generation for a 24-hour period is represented in figures 6 to 8 [31].

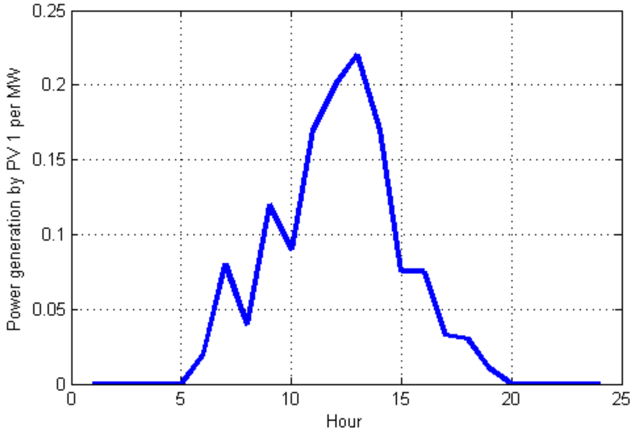

Figure 6. Power generation by PV 1

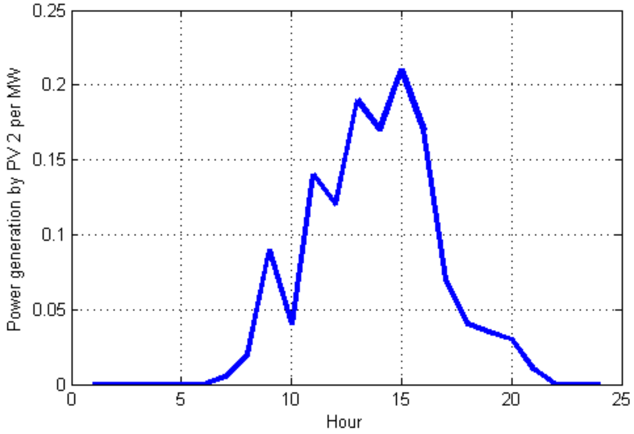

Figure 7. Power generation by PV 2

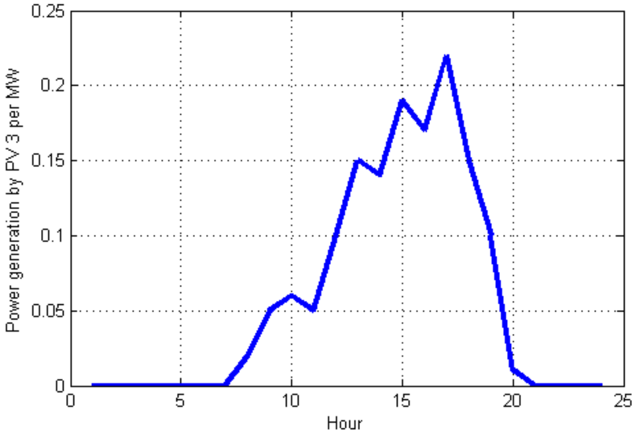

Figure 8. Power generation by PV 3

Fossil Fuel Generators (FFGs)

As shown in figure 1, two 1200 kW FFGs from the diesel type are respectively installed at buses 8 and 10 of the considered IEEE system. The production cost of these generators is 8 $/kwh. The start up and shut down costs of these FFGs are both 7 $.

Energy Storage Systems (EESs)

Two EESs as battery bank are installed at buses 2 and 33 of the considered system. The capacity of each EES is 3200 kwh. The charging and discharging efficiencies of them are both 95% and minimum and maximum charge levels are in respect 5% and 95%. The state of charge of ESS at the initial hour of system operation is 95%.

Implemented scenarios

For the centralised and decentralized MMGs, the problem is solved as a 24 hours unit commitment in the form of two scenarios by the MATPOWER package. These scenarios are selected to test the flexibility of the proposed model. These scenarios are as follows:

Scenario 1: The generation units of the MMGs are the combination of fossil fuel and renewable (hybrid system) and all units operate within their limits and MGs has unlimited exchange with upper grid.

Scenario 2: The generation units of the MMGs are only renewable energy sources to satisfy net-zero emission target and MG has unlimited exchange with upper grid.

The justification for selecting these specific scenarios is that they are more applicable in real MMGs; the real world MMGs are commonly hybrid or net-zero emission, that both of them are considered in this study.

In each scenario, the obtained results from simulations such as details of energy exchange and costs in the system, and the reliability criterion of EENS are calculated and presented in the following Tables.

At the first, the optimization problem of Eqs. (1)-(18) is solved for centralized MMGs for scenarios 1 and 2. The details of energy and money transactions are respectively presented in the tables 2 and 3. Similar simulation is done for decentralized MMGs are obtained results are as what provided in tables 4 and 5. Many points can be concluded from these tables. The most important point are summarized as follows:

- In scenario 1, with respect to costs in decentralized MMGs, the total daily operational cost of centralized MMGs is significantly decreased and is about 23% of the related cost in decentralized MMGs.

- In scenario 2, with respect to costs in decentralized MMGs, the total daily operational cost of centralized MMGs is decreased by 7% of the related cost in decentralized MMGs.
- Therefore, by centralized scheduling of MMGs, the total daily operational cost will be decreased.
- In both scenarios, less load is shed by demand response when the MMGs are scheduled centrally. Therefore, from the demand response viewpoint, centralized MMGs is more efficient than decentralized MMGs. In other words, centralized MMGs is more reliable with less value of the reliability criterion of EENS. This EENS reductions by centralized MMGs are in respect 9% and 15% in scenarios 1 and 2.
- Also, from the standpoint of power loss and related cost, the operation of centralized MMGs is better that the decentralized type. By centralized MMGs, the power loss and related cost decreased by 9% and 11% in scenarios 1 and 2, respectively.
- Of course based on the tables 2 and 4, the CO2 emission in centralized MMGs is more than this emission in decentralized MMGs. This is a negative point for centralized control and an emission penalty must be paid to the environment agencies. Here in this case study, this penalty is 11.1 k$ with decentralized MMGs that is 2.8 k$ more than its value with decentralized MMGs.

Totally, based what mentioned in the above bullets, the performance of centralized MMGs is more better than decentralized MMGs. This is due to, in centralized MMGs, operation of all microgirds is globally optimized during the period of 24 hours. On the other hand, in decentralized MMGs, the operation of micrigrids is locally optimized that is not global optimal.

Table 2. Details of energy and money transactions in the centralized MMGs, scenario 1

Terms	Powers (kwh) and emission (kg)	Cost / profit for MMGs
Power purchased from grid	-60,070.2 kwh (sold to grid)	660.8 k$ profit
Power generated by DERs	15,182 (10,412 WT, 4,770 PV) kwh	22.8 k$ cost
Using stored power in ESS	3,225 kwh	35.5 k$ cost
Fossil fuel power generation	57,600 kwh	576 k$ cost
Demand response	1,225.9 kwh	9.8 k$ cost
EENS	1,225.9 kwh	9.8 k$ cost
Power losses	875.65 kwh	9.6 k$ cost
CO2 emission of MMGs	3,686.4 kg	11.1 k$ cost
Total daily cost of MMGs = 13.8 k$		

Table 3. Details of energy and money transactions in the centralized MMGs, scenario 2

Terms	Powers (kwh) and emission (kg)	Cost / profit (k$) for MMGs
Power purchased from grid	-6,604.7 kwh (sold to grid)	73 k$ profit
Power generated by DERs	15,182 (10412 WT, 4770 PV) kwh	22.8 k$ cost
Using stored power in ESS	6,080 kwh	66.9 k$ cost
Fossil fuel power generation	0 kwh	0 k$ cost
Demand response	3,678.8 kwh	22.4 k$ cost
EENS	3,678.8 kwh	22.4 k$ cost
Power losses	823.11 kwh	40.5 k$ cost
CO2 emission of MMGs	0 kg	0 k$ cost
Total daily cost of MMGs = 102 k$		

Table 4. Details of energy and money transactions in the decentralized MMGs, scenario 1

Terms	Powers (kwh) and emission (kg)	Cost / profit (k$) for MMGs
Power purchased from grid	-41,265 kwh (sold to grid)	454 k$ profit
Power generated by DERs	12,146 (8,330 WT, 3,816 PV) kwh	18.2 k$ cost
Using stored power in ESS	2,096 kwh	23.1 k$ cost
Fossil fuel power generation	43,200 kwh	432 k$ cost
Demand response	1,336.2 kwh	10.7 k$ cost
EENS	1,336.2 kwh	10.7 k$ cost
Power losses	972 kwh	10.6 k$ cost
CO2 emission of MMGs	2,765 kg	8.3 k$ cost
Total daily cost of MMGs = 59.6 k$		

Table 5. Details of energy and money transactions in the decentralized MMGs, scenario 2

Terms	Powers (kwh) and emission (kg)	Cost / profit (k$) for MMGs
Power purchased from grid	3,002.2 kwh	33 k$ profit
Power generated by DERs	12,146 (8,330 WT, 3,816 PV) kwh	18.2 k$ cost
Using stored power in ESS	5,013 kwh	55.2 k$ cost
Fossil fuel power generation	0 kwh	0 k$ cost
Demand response	4,279.2 kwh	34.2 k$ cost
EENS	4,279.2 kwh	34.2 k$ cost
Power losses	923 kwh	10.1 k$ cost
CO2 emission of MMGs	0 kg	0 k$ cost
Total daily cost of MMGs = 108.9 k$		

Conclusion

This paper deals with a comparison of centralized and decentralized MMGs as two basic models of multi-microgrid (MMGs) energy management systems (EMSs). The RESs (PV and WT), fossil fuel generators (FFG) and ESS were included in MMGs. The operational costs of centralised and decentralised MMGs considering reliability and flexibility criteria were compared. The study was done in a test power system with real specifications considering two possible scenarios. The used scenarios verified the flexibility of the centralized MMGs. The simulation results revealed:

- Total daily operational cost of centralized MMGs is notably less than this cost in decentralized MMGs.
- Demand response become better when the MMGs are scheduled centrally.
- With centralized MMGs, the reliability criterion of EENS is less, i.e., the power system becomes more reliable.
- Power losses in centralized MMGs is less than these losses in decentralized MMGs.
- In comparison of decentralized MMGs, the centralized MMGs produce more CO2 emission.

Consequently, the energy management system of centralized MMGs is preferred in scheduling system of multi-microgrids (MMGs). For the interested readers, studying the impact of emerging technologies (e.g., hydrogen storage, pumped storage, advanced demand response programs) on MMGs performance can be an interesting research avenue.

Symbols and Parameters

CPF	Continuation Power Flow	RES	Renewable Energy Sources
DR	Demand Response	OPF	Optimal power flow
ESS	Energy Storage System	$Price^{PV}$	Price of generated power by PV arrays
EV	Electric Vehicle	$Price^{WT}$	Price of generated power by Wind turbine
FFG	Fossil Fuel Generator	$Price^{ESS}$	Price of stored power in ESS
MG	Microgrid	P_{PV}	Power generated by PV array
MMG	Multi-microgrid	P_{WT}	Power generated by wind turbine
a	Coefficient of the fossil fuel cost function	P_{ESS}	Power generated by ESS
b	Coefficient of the fossil fuel cost function	$P_{PV,STC}$	PV rated power in standard test condition
c	Coefficient of the fossil fuel cost function	P_r	Rated power
$C_{MMG}^{Operational}$	Total operational cost of MMG	P_{FF}	Power generated by fossil fuel generator
C_{MGi}	Operational cost of ith MG	$P_{DR,i,t}$	Power reduced by customer
C_G	Cost of power purchased from grid	P_d	Power demand
C_{DER}	Cost of power generated by distributed energy resources	P_G	Power generated
C_{ESS}	Cost of using stored power in ESS	T_j	jth solar cell temperature
C_{FF}	Cost of fossil fuel power generation	v	Wind speed
C_{DR}	Cost of demand response procedure	V_{ci}	Cut-in speed
C_{PV}	Cost of power generated from the PV arrays	V_{co}	Cut-out speed
$C_T(t)$	Solar irradiance at time t	V_r	Rated speed
$C_{T,STC}$	Rated solar irradiance in standard test condition	V_i^{min}	Minimum voltage at bus i
$M_{i,t}$	Amount of money that customer receives because of participation	V_i^{max}	Maximum voltage at bus i
$N_{PV}(p)$	Number of parallel PV modules	V_i	Voltage at bus i
$N_{PV}(s)$	Number of series PV modules	γ	Temperature coefficient of power
$NOCT$	Nominal rated cell temperature	δ_i^{min}	Minimum voltage angle at bus i
P_t^G	Power purchased from grid	δ_i^{max}	Maximum voltage angle at bus i
$Price_t^G$	Price for purchased power from grid	δ_i	Voltage angle at bus i

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