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Quantifying the Impact of Different Parameters on Optimal Operation of Multi-Microgrid Systems

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***Abstract*—The multi-objective optimal power management of multi-microgrid systems is solved in this paper. Minimizing the total cost and emission of the system are considered as the objective functions. The multi-objective particle swarm optimization algorithm is applied on a multi-microgrid system that consists of four microgrids each includes diesel generators, wind turbines, photovoltaic units, battery, and local loads. The multi-microgrid system can exchange power with the electricity grid. Moreover, the adjacent microgrids in the multi-microgrid system can share power with each other. The impact of the variation of battery charging and discharging efficiency, the electricity price, the capacity of diesel generators and renewable-based units, the maximum exchangeable power between the multi-microgrid system and the electricity grid and the power sharing among adjacent microgrids on day-ahead units' scheduling of multi-microgrid are evaluated through sensitivity analysis in simulation results.**

Keywords—multi-microgrid systems, power management, sensitivity analysis, multi-objective optimization

I. Introduction

The recent increase in the energy demand in addition to environmental issues lead to the penetration of distributed energy resources (DERs) and especially renewable-based generators [1]. Microgrids (MGs) were suggested for supporting different advantages, including reliability, sustainability, and cost-effectiveness, to aggregate DERs and loads with distribution networks [2]. Recently, multi-microgrids (MMGs) are proposed to deal with the concern of the communication and energy transaction among MGs [3].

One challenging subject in the literature is the energy management of MMGs. Research has been conducted to solve the optimal energy management problem of MMG systems from different viewpoints [4-19]. A chance-constrained model was proposed in [4], however, the efficiency of the model is not studied on the emission of greenhouse gases. In [5], the impact of the presence of renewable energy sources (RESs) on the performance of the islanded MMG systems was investigated while the cost allocation among MGs and the emission of greenhouse gases are not considered. A cooperative energy planning was proposed in [6] to model the communication among MGs. A framework for managing the energy transfer among MGs was presented in [7]. However, the efficiency of the cooperation of MGs was not examined.

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Authors in [8] suggested a cooperative game for short-term energy planning of the MMG systems. However, emission index was not considered in the model.

An optimal energy-management scheme was proposed in [9] for a hybrid MMG system while applying a cooperative game. Authors in [10] applied an energy trading method based on the cooperative game. To determine the best association among microgrids in MMG systems a cooperative game was presented in [11]. A single-objective problem considering cost minimization as the objective function was studied.

"A two-stage stochastic programming" approach was suggested in [12] for MMG management. The objectives were to maximize the reliability and to minimize the emission of the system. Authors in [13] suggested a two-stage stochastic optimization scheme while considering capital and operational costs for optimal designing and operation of MMG systems. A "software-defined networking system" was proposed in [14] to improve the energy exchange among MGs. The total cost of the MMG system was reduced by applying the suggested approach. A chance-constrained approach was employed in [15] for optimal day-ahead scheduling of an MMG system considering emission index. However, optimal bidding strategy and demand response program were not studied.

For solving the problem of optimal day-ahead scheduling of an MMG system, a robust decentralized energy-management framework was proposed in [16]. A two-stage probabilistic optimization approach was suggested in [17] for day-ahead scheduling of MMG systems to minimize the total operational cost. A coordinated energy-management scheme was presented in [18] for optimal operation of MMG systems and a variable weighted multi-objective function was applied. In [19], the purpose-oriented shuffled complex evolution (POSCE) algorithm was suggested to deal with the problem of energy management of MMG systems for both faulted and normal operation modes.

In this paper, a multi-objective PSO algorithm is applied to investigate the day-ahead scheduling of units in renewable-based MMG systems. The objective functions are minimizing the emission and the operational cost of the system. To analyze the impact of different parameters of the MMG system on the operation of the system, sensitivity analysis in the operation of MMG system is carried out. The validity of the suggested algorithm in solving the problem of day-ahead scheduling of units in a renewable-based MMG system is

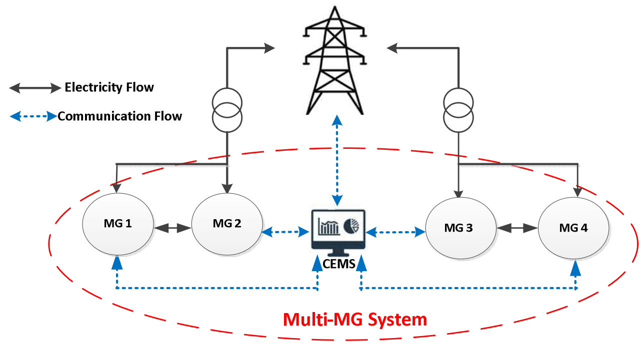

Fig. 1. Structure of multi-microgrid system that includes four interconnected microgrids, and is able to exchange power with the main electricity grid.

verified by implementing the algorithm on the grid connected MMG system of Fig. 1.

The studied MMG system of Fig. 1. consists of four MGs each including one diesel generator (DG), one RES-based unit, energy storage devices (ES), and local load. RES-based units in MG1 and MG3 are photovoltaic (PV) units. In MG2 and MG4 wind turbine (WT) is considered as the RES-based unit. Each MG can exchange power with the main electricity grid based on the electricity price. Moreover, power sharing up to 1 MW between MG1 and MG2 as well as between MG3 and MG4 is considered.

The main contribution of this paper is outlined as follows:

1. Solving the problem of optimal day-ahead scheduling of units in renewable-based MMG systems while considering economic-emission indices.
2. Investigating the impact of different parameters on the optimal operation of MMG systems through sensitivity analysis.

II. Problem Formulation

In this section a model is presented for the day-ahead scheduling of units in the renewable-based MMG system of Fig. 1.

A. Objective Functions

1. Minimizing the Operational Cost

The first objective function that should be minimized in the considered problem of power management of an MMG is the total operational cost. The operational cost consists of the cost of DGs in each MG and the cost of power exchange between the MMG and the electricity grid, which is modeled as (1). The central energy management (CEMS) unit of the MMG purchases power from the electricity grid in low-price hours while it sells power to the electricity grid during the high-price hours. In this way, the operational cost decreases, and this results in the increase of the profit from the difference of selling and buying price of electric energy:

$$F_1 = \min\left(Cost_{opr}\right)$$
$$= min\left(\sum_{n=1}^{N_p}\left\{\sum_{t=1}^{T}\left\{Cost_{DG}^{n,t} + P_{EX}^{n,t}B_{EX}^{t}\right\}\right\}\right) \quad (1)$$

where $Cost_{opr}$ is the operational cost of MMG, N_p is the number of MGs in the MMG system, T is the horizon of operation which is considered equal to 24 h in this paper and $Cost_{DG}^{n,t}$ is the hourly operational cost of DGs as dispatchable units in \$. $P_{EX}^{n,t}$ is the shared power of n^{th} MG with the electricity grid in MW and the positive values of $P_{EX}^{n,t}$ represent purchasing energy from the electricity grid while the negative values represent selling energy to the grid. B_{EX}^{t} is the electricity price in the market in \$/MWh. $P_{EX}^{n,t}B_{EX}^{t}$ shows the income (if $P_{EX}^{n,t}$ is negative) and cost (if $P_{EX}^{n,t}$ is positive) from power exchanging with the electricity grid.

By using the following equation, the operational cost of fossil fuel-based units is achieved:

$$Cost_{DG}^{t} = \alpha \times (P_{DG}^{t})^2 + \beta \times P_{DG}^{t} + \gamma \quad (2)$$

where $Cost_{DG}^{t}$ is the hourly operational cost of fossil fuel-based units in \$, P_{DG}^{t} represents the hourly output power of the fossil fuel-based units in MW. α, β, and γ are the cost function coefficients of the fossil fuel-based units, respectively, in \$/MW^2, \$/MW, and \$.

2. Minimizing the Emission

The second considered objective function is to minimize the total emission of the units in the MMG system. The considered model of the environmental objective function is as the following:

$$F_2 = \min(Emission)$$
$$= min\left(\sum_{n=1}^{N_p}\sum_{t=1}^{T}\left\{P_{DG}^{n,t}E_{DG}^{n,t} + P_{EX}^{n,t}E_{EX}^{t}\right\}\right) \quad (3)$$

where $Emission$ is the value of emission from MMG, $E_{DG}^{n,t}$ represents the emission factor in kg for each MWh of the produced power of fossil fuel-based units, E_{EX}^{t} shows the emission of each MWh received power from the electricity grid in kg. $P_{DG}^{n,t}E_{DG}^{n,t}$ is the value of emission in kg resulted from the output power of fossil fuel-based units while $P_{EX}^{n,t}E_{EX}^{t}$ is the value of emission in kg resulted from purchasing power from the electricity grid.

When the power is delivered to the electricity grid from the MMG system (i.e., $P_{EX}^{n,t}$ is negative,) the emission term of the electricity grid is zero and no emission is produced. Additionally, the ES device, PV units and WTs produce no emission.

B. Technical Constraints

The first technical constraint in the problem of optimal operation of MMG systems is the power balance constraint of (4) which deals with the balance of the amount of demanded load and the hourly total generated power of DGs, the stored power in ESs, the forecasted power of renewable based units as well as the shared power among MGs, and the exchanged power with the main electricity grid. The power balance equation can be formulated as follows:

$$P_{DG}^{n,t} + P_{Batt}^{n,t} + P_{EX}^{n,t} + P_{WT}^{n,t} + P_{PV}^{n,t} + \sum_{\substack{m=1 \\ m\neq n}}^{N_p} P_{nm}^{t}$$
$$= P_L^{n,t} \quad (4)$$
$$m,n = 1,2,3,4 \quad t = 1,2,\ldots,24$$

where $P_L^{n,t}$ is the hourly demanded load of each MG in MW, $P_{WT}^{n,t}$ and $P_{PV}^{n,t}$ are the estimated hourly power of WT and PV units of each MG in MW, respectively. $P_{Batt}^{n,t}$ represents the battery charging (negative values) and discharging (positive values) values in each MG in MWh. $\sum_{\substack{m=1 \\ m\neq n}}^{N_p} P_{nm}^t$ is the amount of transferred power among MGs in which P_{nm}^t shows the hourly transferred power between the n^{th} and m^{th} MG in MW. The positive values of P_{nm}^t show the power delivering from the n^{th} MG to the m^{th} MG while the negative values represent the power delivering from the m^{th} MG to the n^{th} MG.

All the generated and stored powers as well as the transferred power to the electricity grid should satisfy the following power limit constraints which are applied for all MGs and time intervals:

$$P_{DG,min}^{n} \leq P_{DG}^{n,t} \leq P_{DG,max}^{n} \tag{5}$$

$$-P_{nm,max} \leq P_{nm}^{t} \leq P_{nm,max} \tag{6}$$

$$-P_{EX,max}^{n} \leq P_{EX}^{n,t} \leq P_{EX,max}^{n} \tag{7}$$

$P_{DG,min}^n$ and $P_{DG,max}^n$ represent the minimum and maximum generated power of DG units in MW, respectively. $P_{nm,max}$ represents the maximum exchangeable power between the n^{th} and the m^{th} MG in the MMG system in MW. $P_{EX,max}^n$ shows the maximum exchangeable power of the n^{th} MG with the electricity grid in MW.

The following battery-related constraints should also be considered for all MGs and time intervals:

$$P_{Batt,min}^{n} \leq P_{Batt}^{n,t} \leq P_{Batt,max}^{n} \tag{8}$$

$$BL_{Batt,min}^{n} \leq BL_{Batt}^{n,t} \leq BL_{Batt,max}^{n} \tag{9}$$

$$BL_{Batt}^{n,t} = BL_{Batt}^{n,t-1} - \left(\eta_{Batt} \times P_{Batt}^{n,t}\right) \; if \; P_{Batt}^{n,t} < 0 \tag{10}$$

$$BL_{Batt}^{n,t} = BL_{Batt}^{n,t-1} - \left(\frac{P_{Batt}^{n,t}}{\eta_{Batt}}\right) \; if \; P_{Batt}^{n,t} > 0 \tag{11}$$

$P_{Batt}^{n,t}$ is the charging and discharging power of the battery in MW. Negative $P_{Batt}^{n,t}$ shows charging while positive values represent discharging of the battery. $P_{Batt,min}^{n}$ and $P_{Batt,max}^{n}$ are respectively the minimum and maximum hourly charging/discharging power values of the battery of n^{th} MG in MW. $BL_{Batt}^{n,t}$ is the energy level stored in the battery. $BL_{Batt,min}^{n}$ and $BL_{Batt,max}^{n}$ are the minimum and the maximum stored energy levels in the battery of each MG in MWh, respectively. η_{Batt} is the battery efficiency during charging and discharging.

III. Application of The Implemented Multi-Objective PSO Algorithm

A powerful metaheuristic algorithm, namely particle swarm optimization (PSO) algorithm is applied for solving the multi-objective optimization problem of optimal power management of MMG systems. PSO algorithm is efficient for solving optimization problems due to its stability, accuracy, simple formulation and implementation, and fast response [20, 21].

The modular structure of the implemented methodology is illustrated in Fig. 2. The input module consists of hourly input parameters, including the output power of PV units and WTs, load, and electricity price. The optimization module is the PSO optimization algorithm for solving the considered multi-objective economic-environmental framework. Optimal scheduling of DG units' operation, charging and discharging of batteries, the power sharing among MGs and the power exchange between the MMG system and the electricity grid are included in the output module.

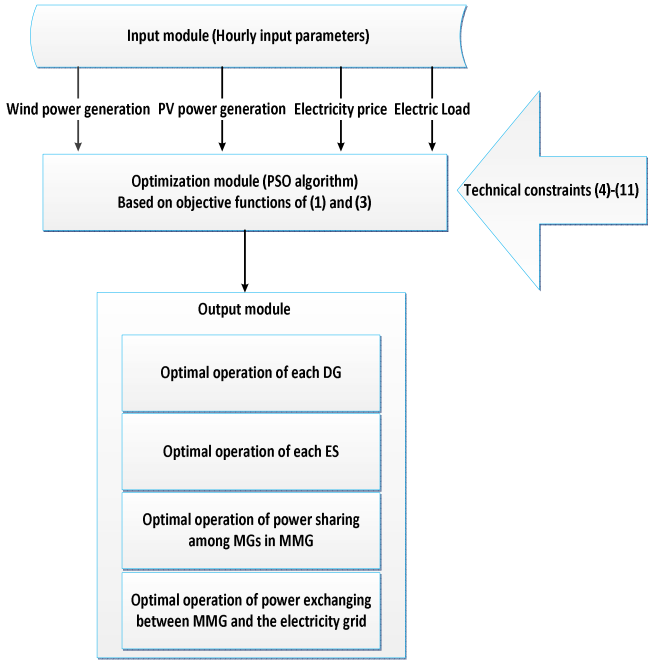

Fig. 2. Flowchart of the modular structure of the implemented methodology for solving the problem of day-ahead scheduling of units in renewable-based multi-microgrid systems.

IV. Simulation Results

The simulation results of the proposed approach for solving the problem of optimal power management of MMG systems are presented in this section. The objective functions of minimization of the total cost and the emission are considered simultaneously to solve the multi-objective optimal power management of an MMG system. To analyze the impact of the variation of different parameters of the MMG system on the operation of the system, sensitivity analysis in the operation of the considered MMG system is carried out.

The problem is solved in MATLAB while the population size and the maximum number of iterations in the proposed PSO algorithm are considered equal to 50 and 200, respectively.

The parameters related to the DGs, PV and WT, the batteries' parameters, the range of the maximum exchangeable power of each MG, and the emission coefficient of each unit are tabulated in Tables I to IV, respectively. It is assumed that the initial charge of batteries is $E_{int,Batt} =$ 0.375MWh. The rated power of PV units of MG1 and MG3 are 0.3 MW while the rated power of WTs of MG2 and MG4 equals 0.45 MW. The forecast values of electricity price, load demand, output power of PV, and WT units in the 24-h day-ahead are taken from [22].

In Figs. 3-10 the Pareto optimal solutions for day-ahead optimal power management of MMG with different values for economic and environment indices in different scenarios are represented.

In Fig. 3, the impact of the efficiency of battery charging and discharging on the optimal power management of MMG systems is shown. It is observed that by increasing this efficiency, the maximum achievable profit of the MMG system (the last point in the left side) increases significantly.

TABLE I. PARAMETERS OF DIESEL GENERATOR UNITS

MG	$P_{DG,Min}$ (MW)	$P_{DG,Max}$ (MW)	α (\$/MWh^2)	β (\$/MWh)	γ (\$)
1, 2	0	1.285	0.0345	44.5	26.5
3, 4	0	2.47	0.0435	56	12.5

TABLE II. PARAMETERS OF ENERGY STORAGE

MG	$P_{Batt,Min}$ (MW)	$P_{Batt,Max}$ (MW)	$BL_{Batt,Min}$ (MWh)	$BL_{Batt,Max}$ (MWh)	$E_{int,Batt}$ (MWh)	η_{Batt}
1,2,3, 4	-0.4	0.4	0.24	1.2	0.375	0.75

TABLE III. EXCHANGED POWER WITH THE ELECTRICITY GRID

MG1 $P^1_{EX,Max}(MW)$	*MG2* $P^2_{EX,Max}(MW)$	*MG3* $P^3_{EX,Max}(MW)$	*MG4* $P^4_{EX,Max}(MW)$
2.5	3.5	4	7

TABLE IV. EMISSION COEFFICIENTS

$E_{DG}(kg/MWh)$	$E_{Grid}(kg/MWh)$
725	927

The maximum achievable profit is 9000\$ when battery efficiency equals 75% and it increases to 11000\$ with an ideal battery with 100% charging and discharging efficiency. The reason is that by the increase of the battery efficiency the operator of the MMG system can purchase more power during the hours that the electricity price is lower and sell this stored power to the main electricity grid in high-price hours to increase the profit of the system operation. In other words, the increase in the battery efficiency results to a lower power loss during charging and discharging of the battery and consequently there will be more power for exchanging with the electricity grid and the achievable profit of the MMG system increases. Additionally, according to Fig. 3, the variation of the battery charging and discharging efficiency does not have a significant impact on the minimum produced emission (the last point in the right side) since the batteries do not have a direct relation with the emission value according to (3).

The impact of the variation of the maximum exchangeable power of MGs with the electricity grid on the power management of MMG systems is shown in Fig. 4. As is observed in Fig. 4, by changing the value of the maximum exchangeable power of MGs of the MMG with the electricity grid, the maximum achievable profit of the MMG system changes significantly. In this case, the value of the change of the minimum emission is not considerable due to the high pollution factor associated with the exchanged power with the electricity grid. According to Fig. 4, for the change of +20% and +10%, of the maximum exchangeable power with the electricity grid, the maximum value of the achievable profit increases by 10% and 5%, respectively. With the change of -20% and -10% of the maximum exchangeable power with the electricity grid, the maximum value of the achievable profit decreases by 5% and 2%, respectively.

In Fig. 5, the impact of the variation of the demanded load on the power management of MMG systems is shown. It is observed that, the variation of the demanded load leads to a significant change of the operational cost (the achievable profit) and the emission. With the increase of the value of the demanded load of the MMG system by 10% and 20%, the maximum achievable profit decreases by 30% and 45%, respectively, and the minimum produced emission increases by 15% and 30%, respectively. While the decrease of the demanded load by 10% and 20% leads to the increase of the maximum achievable profit by 10% and 40%, and the reduction of the emission by 2% and 15%, respectively.

The impact of the variation of the electricity price on the power management of MMG systems is observed in Fig. 6. According to this figure, since the electricity price does not have any relation with the emission, the variation of the electricity price does not affect the emission value. However, when the electricity price increases by 10% and 20%, the maximum achievable profit increases by 22% and 40%, and when the electricity price decreases by 10% and 20%, the maximum achievable profit reduces by 17% and 30%, respectively.

In Fig. 7, the impact of the variation of the capacity of DG units on the power management of MMG systems is shown. It is observed that the change in the capacity of DG units does not have a significant effect on the emission value. The reason is that, to decrease the value of the emission, as little unit output power is used as possible. The variation of the capacity of DG units has significant impact on the maximum achievable profit in the operation of the MMG system. The increase of the DG unit capacity by 10% and 20% increases the maximum achievable profit by 12% and 40%, and the decrease of the DG unit capacity by 10% and 20% leads to the reduction of the maximum achievable profit in the MMG system by 25% and 45%.

In Fig. 8, the impact of the variation of the maximum limit of the exchangeable power among MGs on the power management of the MMG system is illustrated. It is noticed that, by the increase of the maximum limit of the exchangeable power among MGs by 50%, the maximum achievable profit increases by 12% and by the reduction of the maximum limit of the exchangeable power among MGs by 50% and 100% the maximum achievable profit reduces by 1% and 10%, respectively. However, the variation of the maximum limit of the exchangeable power among MGs does not have a considerable effect on the value of the emission.

The impact of the variation of the rated power of the PV units on the power management of the MMG system is shown in Fig. 9.

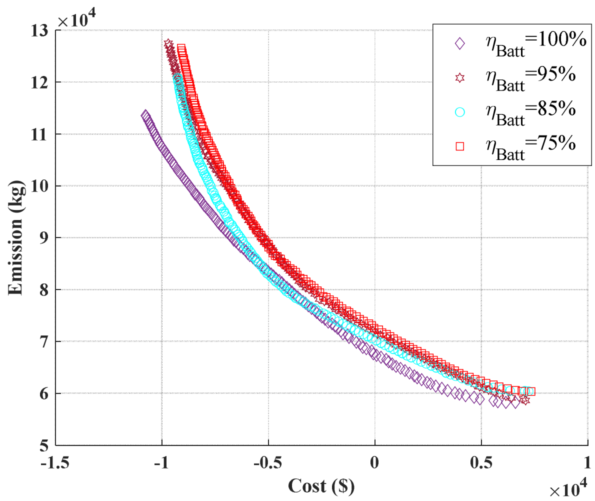

Fig. 3. Impact of the variation of the battery efficieny value on cost and emission indices in the power management of the multi-microgrid system.

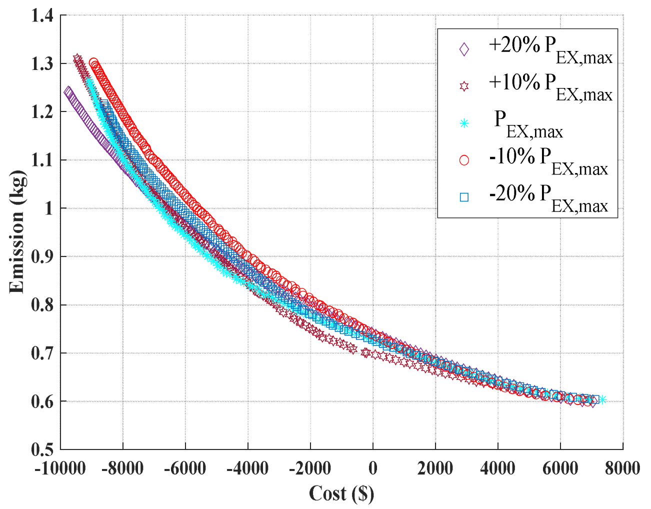

Fig. 4. Impact of the variation of the maximum exchangable power of microgrids with the electricity grid on cost and emission indices in the power management of the multi-microgrid system.

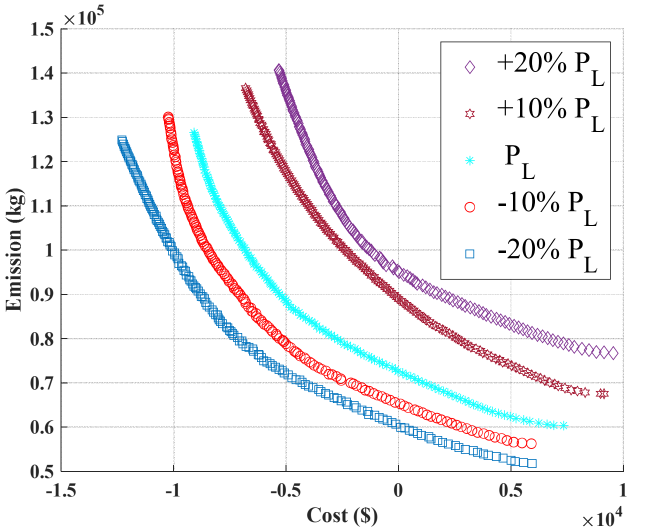

Fig. 5. Impact of the variation of the demanded load value of each microgrid on cost and emission indices in the power management of the multi-microgrid system.

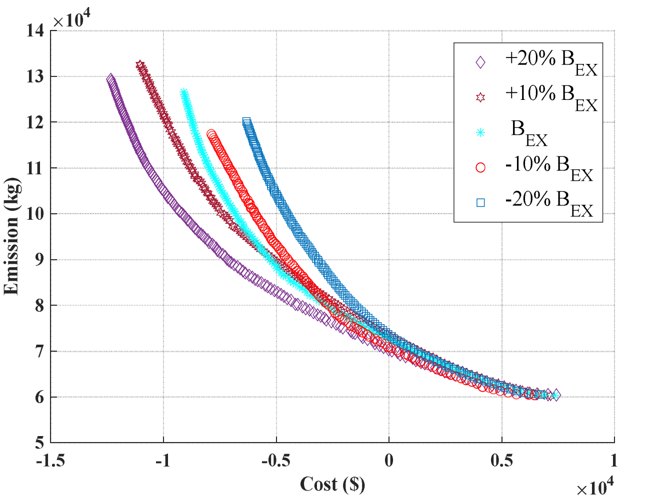

Fig. 6. Impact of the variation of the electricity price on cost and emission indices in the power management of the multi-microgrid system.

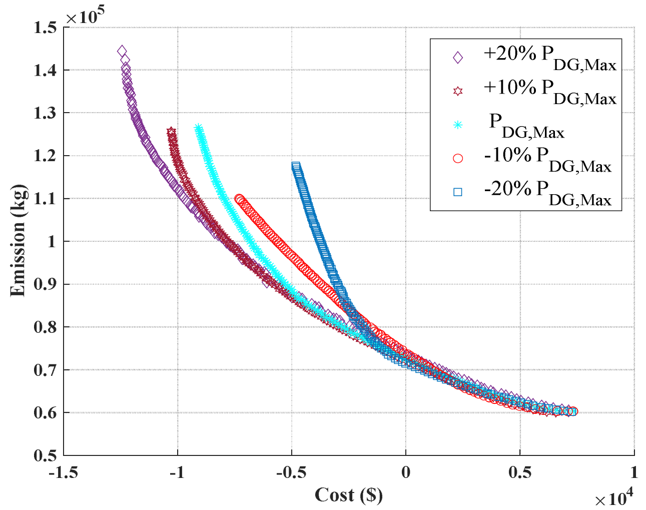

Fig. 7. Impact of the variation of the maximum capacity of diesel generators on cost and emission indices in the power management of the multi-microgrid system.

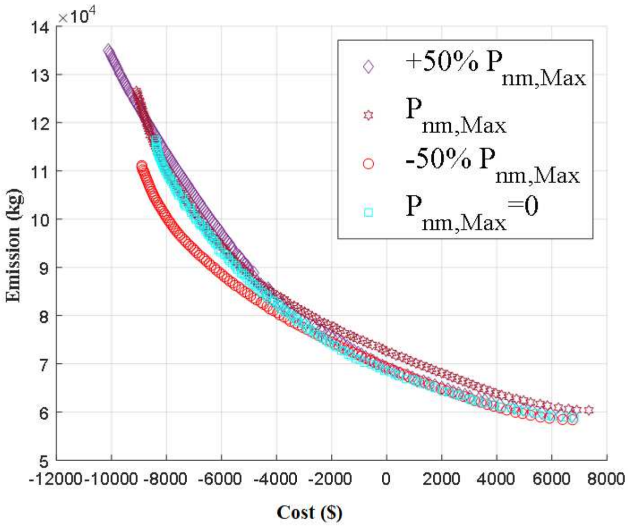

Fig. 8. Impact of the variation of the maximum limit of the exchangeble power among microgrids on cost and emission indices in the power management of the multi-microgrid system.

According to Fig. 9, the variation of the rated power of the PV units has a significant impact on both the maximum achievable profit and the value of the emission. When the rated power of the PV units increases by 10% and 20%, the maximum achievable profit of the MMG system increases by 2% and 12% and the minimum resulted emission decreases by 4% and 17%. By the decrease of 10% and 20% of the rated power of the PV units, the maximum achievable profit of the MMG system reduces by 1% and 2% while the minimum resulted value of the emission increases by 4% and 8%.

Fig. 10. illustrates the impact of the variation of the rated power of the WTs on the power management of the MMG system. According to Fig. 10, the variation of the rated power of the WT units has a significant impact on both the maximum achievable profit and the minimum resulted value of the emission. When the rated power of the WT units increases by 10% and 20%, the maximum achievable profit of the MMG system increases by 1% and 11% and the minimum resulted emission decreases by 4% and 16%. When the rated power of the WT units decreases by 10% and 20%, the maximum

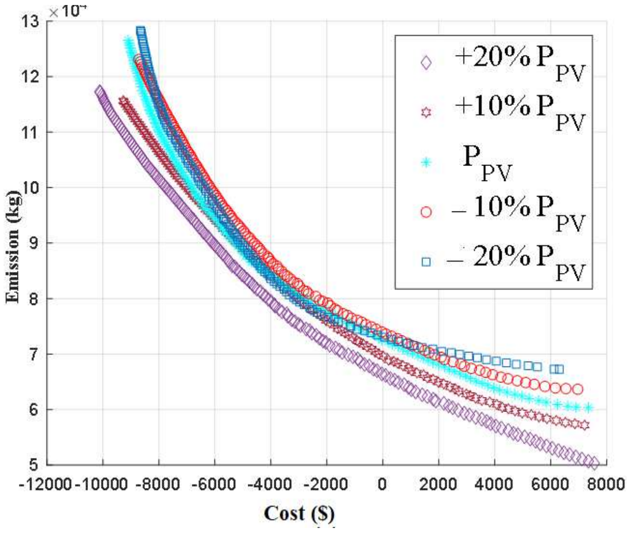

Fig. 9. Impact of the variation of the rated power of photovoltaic units on cost and emission indices in the power management of the multi-microgrid system.

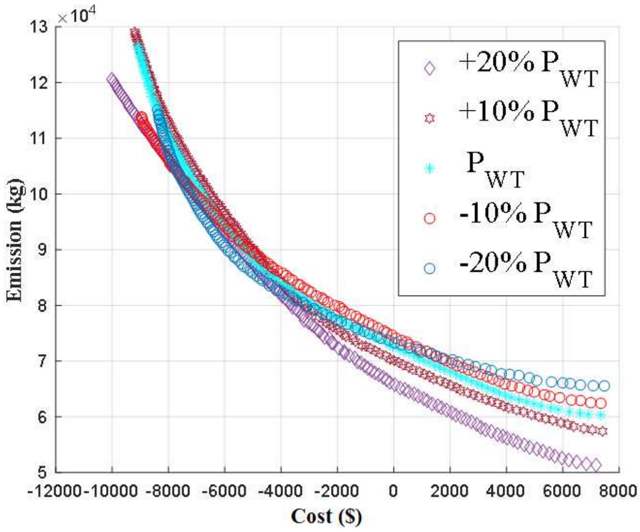

Fig. 10. Impact of the variation of the rated power of the windturbines on cost and emission indices in the power management of the multi-microgrid system.

achievable profit of the MMG system decreases by 1% and 2% and the minimum resulted emission increases by 2% and 8%. From Fig. 9 and Fig. 10, it is obvious that the variations of the rated powers of WTs and PV units have more significant impact on the minimum value of the emission comparing to their impact on the maximum achievable profit.

V. Conclusions

The multi-objective economic-environmental day-ahead scheduling of units in a renewable-based MMG system is studied in this paper. The impact of different parameters on the optimal operation of the studied MMG system is investigated through sensitivity analysis. According to the considered optimization model and the simulation results, it can be concluded that the economic index is more effected by the variation of battery efficiency, the electricity price, the capacity of fossil fuel-based units, the maximum exchangeable power between the MMG system and the electricity grid, and the power exchange among adjacent MGs in the MMG system. It is observed that, the operation cost is considerably affected by the variation of maximum power of DEs, maximum exchangeable power with the main electricity grid and the electricity price. The battery efficiency and the exchangeable power among MGs have more impact on the environmental index compared to the maximum power of DEs, maximum exchangeable power with the main electricity grid and the electricity price. However, the impact of the variation of the battery efficiency and the exchangeable power among MGs is more on the operation cost than the environmental index. It can be concluded that if more efficient batteries and more appropriate DG resources are used the operation of the MMG system will be more profitable. It is also noticed that changing the amount of load demand has a considerable impact on both economic and environmental indices. Moreover, it is observed that changing the capacity of renewable-based units (WT and PV) has a significant impact on the environmental index. However, the impact of changing the capacity of PV units on the minimum amount of emission is more noticeable than the impact of changing the rated power of WTs.

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