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Multi-Objective Demand Side Management to Improve Economic and Environmental Issues of a Smart Microgrid

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Abstract- *In the last years, microgrids have been introduced for better managing the overall power network. The two-way communication between supplier and consumer sides of a smart microgrid causes to better apply the demand side management methods to this type of system. For this reason, the multi-objective demand side management of a smart microgrid is investigated in this study. The economic and environmental indices of the microgrid are considered as the primary objective functions of the proposed demand side management method. The load variations of the microgrid are improved based on the applied demand response program. The operator of the microgrid can provide the demand of the system using a wind turbine, photovoltaic panel, diesel generator, micro turbine, fuel cell, energy storage system and the upstream network. The stochastic behavior of renewable units is also considered to evaluate the proposed method in a more realistic condition. The combination of the multi-objective ant lion optimization algorithm and the analytical hierarchy process method is utilized to solve the demand side management problem. Numerical results, which are obtained from evaluating the proposed method in a sample microgrid, demonstrate the high efficiency of the proposed demand side management method in improving the economic and environmental indices of the microgrid.*

Keyword: Analytical hierarchy process, Demand side management, Distributed generation, Energy storage system, Environmental issues, Multi-objective optimization.

1. INTRODUCTION

The stability and proper management of power networks are essential because of their role in the success of societies and countries. Moreover, the optimal operation of the power network has a high effect on economic issues and the satisfaction of consumers from electrical energy [1]. Smart microgrids are one of the practical methods for increasing the efficiency of the system. Indeed, the microgrid improves the local stability and flexibility of the electric power system [2]. Smart microgrids have the ability for two-way communication between the producers and customers. Therefore, the incentive of consumers to control their demand can be increased by applying various costs of electrical energy. It is called the demand response program, which causes the improvement of the load pattern of consumers [3]. In this study, the price-based demand response program is used to affect consumer's electricity consumption. Although microgrids can buy the electrical energy from the upstream network, they should supply part of their demand using local energy sources. Local distributed units can play a crucial role in the economic issues of the microgrid and environment-friendly electricity generation [4]. Wind turbines, photovoltaic panels, diesel generator, micro turbine and fuel cell are the most useful technologies of distributed generation units in microgrids. Although distributed generation units, especially renewable ones, improve the performance and environmental parameters of the microgrid, the instability behavior of renewable units decreases the stability of the produced power of local sources. For this reason, an electrical storage system is also used in the microgrid. The extra electrical energy of the microgrid can be stored in the electrical storage system and be used later [5]. Thus, local energy sources including distributed generations and electrical storage systems reduce the dependence of the microgrid on the upstream network. Of course, the operational schedule of local energy resources has a high effect on their performance and the efficiency of the microgrid.

In the last years, some researchers have studied the microgrids and demand side management. For instance, the authors in Ref [6] have studied the scheduling of the

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photovoltaic panel and energy storage system in a grid-connected smart grid. Minimizing the electricity cost was considered as the objective function. In this study, the market price of electrical energy is based on the time-of-use program. In another study, optimizing the performance of the microgrid has been studied to minimize operating costs and emissions in the presence of renewable distributed generation units [7]. The stochastic model of renewable DGs has been considered. In this paper, incentive-based payments have been recommended as a price offer package to implement DR programs. The multi-objective particle swarm optimization method has been used to solve the demand side management. In Ref [8], a bi-level programming model has been proposed to optimize the location and size of the battery energy storage system by a numerical optimization algorithm. The power network has been considered in the presence of a wind farm. The result of numerical simulations indicates that the located battery at the load center performs better than the located battery at the wind farm. In Ref [9], Miao and Hossain studied on determining the size and location of optimal electrical energy storage systems. The combined system consists of wind turbines and fuel cells. The gray wolf optimization algorithm has been utilized to optimize the economic objective function and selecting the optimal situation of an energy storage system in a microgrid. A novel approach to optimize the size and cost of hybrid energy storage systems based on a solar photovoltaic panel has been proposed in Ref [10]. A stand-alone DC microgrid is the considered system for locating the hybrid energy storage system. The multi-objective genetic algorithm has been used to optimize the objective functions in order to assure the long life of batteries and well-being during the operation. The authors in Ref [11] presented a control strategy for distributed battery energy storage system in a centrally controlled microgrid to enhance the calendar life of storage system. The proposed strategy manages the charging and discharging schedule of individual batteries based on state of charge, state of health and maximum capacity. The controller selects the energy storage system with better health and higher capacity for operating in the microgrid. In other research, the simultaneous minimization of peak load and electricity cost of residential customers has been presented [12]. The demand response program of the distribution system has been considered based on the time-of-use program. The considered problem has been modeled as a multi-objective mixed integer linear programming. In Ref [13], a frequency and voltage relaying based demand side management scheme has been investigated to reduce the load on distribution system during peak hours without resorting to blanket load shedding. The energy management system controller automatically detects the frequency and voltage changes in the system and responds to respective loading patterns. A multi-level algorithm based on demand side management strategy has been proposed to provide more degrees of freedom for a stand-alone microgrid in Ref [14]. The microgrid is a multi-source system including solar, wind, tidal, wave energies and an energy storage system. The load shifting and load shedding strategies have been also considered for evaluating the most critical situations. Experimental studies of smart microgrid and its devices have been presented in Ref [15]. In this study, multi-objective optimization has been presented for simultaneously minimizing the total cost of the distribution system and maximizing the stability of the network. The particle swarm optimization has been utilized to find the best combination of battery and hydrogen storage system based on the cost, the occupied area, legislation and the local pollution. In another study, a typical Indian institutional energy system has been considered for operating as a smart microgrid under market energy pricing dynamic [16]. The energy system has a photovoltaic panel and battery storage system. An operational energy dispatch strategy for microgrid has been proposed for optimizing the technical and economic objective function and improving the performance of the microgrid.

According to previous studies, it can be said that the multi-objective optimization of both supplier and consumer sides of the smart microgrid is the topic that has been less studied. For this reason, multi-objective demand side management is investigated in a microgrid in this research. The novel points of this study are:

- Multi-objective managing both supplier and consumer sides of the smart microgrid
- Considering the stochastic behavior of renewable distributed generation units
- Utilizing the combination of multi-objective ant lion optimizer and analytical hierarchy process method for finding the best demand side management program

Thus in this study, the demand side management of a smart microgrid is studied as a multi-objective optimization for improving the economic and environmental issues of the system. The load pattern of the microgrid is improved based on the applied demand response program. The real time pricing method is used in this study. The operator of the microgrid can provide the demand of the system using wind turbine, photovoltaic panel, diesel generator, micro turbine, fuel cell, energy storage system and also the upstream network. Moreover, the smart microgrid can sell the energy to the upstream network when the produced power of distributed units is more than the demand. The combination of the multi-objective ant lion optimization algorithm and the analytical hierarchy process method is utilized to solve the demand side management problem.

The rest of the paper is organized as follows: Section 2 provides a general introduction to energy sources of the microgrid. Objective functions and constraints of the proposed demand side management program are explained in Section3. The method for solving the demand side management is described in Section 4. Section 5 discusses the numerical results and Section 6 is the conclusion.

2. ENERGY SOURCES OF THE MICROGRID

In this study, it is considered the microgrid has renewable energy sources including wind turbine and photovoltaic panel and nonrenewable ones including diesel generator, micro turbine and fuel cell. Moreover, the energy storage system is also utilized in the microgrid. In the following, the description of local energy sources is presented [5, 17-18].

Diesel generator: It uses a diesel engine and electric generator to produce electricity. The output power of it can be changed based on the demand of the network. **Micro turbine**: It has the unique ability to produce electricity and heat simultaneously. This type of distributed generation unit can produce electricity based on the required load. **Fuel cell**: It is a technology to convert the chemical energy from a fuel into electrical energy. The fuel cell can inject electricity into the microgrid based on demand. **Energy storage system**: It is a useful device to convert electrical energy into a form that can be stored for converting back to electricity when required. When the energy storage system is used in the microgrid in the presence of renewable energy units, it can reduce the effect of the instability of the produced power of renewable technologies.

2.1. Modeling the stochastic behavior of renewable units

Renewable energy sources such as wind turbine and photovoltaic panel have a high effect on environmental issues besides improving economic and technical parameters. The stochastic behavior of wind turbine and photovoltaic panel is one of their disadvantages. For this reason, the probability distribution functions are considered to model the stochastic behavior of renewable units. In the following, firstly, the modeling of renewable units is explained and then the method for producing the stochastic parameters is described.

Photovoltaic panel: The produced power of a photovoltaic panel is related to the situation of solar irradiance. The Beta probability density function is utilized to model the variation of the solar irradiance. Mathematically, the probability function of solar irradiance is presented by Eq. (1). This equation is acceptable if $0 \le S \le 1, \alpha \ge 0, \beta \ge 0$.

$$f(S) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} \times S^{(\alpha-1)} \times (1-S)^{(\beta-1)} \tag{1}$$

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

$$\alpha = \frac{\mu \times \beta}{1-\mu} \tag{3}$$

Where α and β are parameters of the Beta probability density function. The parameter S shows solar irradiance and $f(S)$ is the probability of solar irradiance based on Beta function. The produced active power of the photovoltaic panel can be calculated by Eq. (4). Here, A and η are the area and the efficiency of the panel, respectively

$$P(S) = A \times \eta \times S \tag{4}$$

Wind turbine: The produced power of a wind turbine has a direct relation to the wind speed in the swept area. The model of wind speed is modeled using Rayleigh probabilistic density function. The Rayleigh function is a particular form of Weibull probability density function. Thus, the probability function of wind speed is mathematically formulated by Eq. (5).

$$f(V) = \frac{2}{C^2} V e^{-\left(\frac{V}{C}\right)^2} \qquad 0 \le V \le \infty \tag{5}$$

Here, V and $f(V)$ demonstrate wind speed and probability of it, respectively. The scale index of the Rayleigh function shows with C. Mathematically, the output power of wind turbine based on wind speed is calculated by Eq. (6). In this equation, V_{ci}, V_r and V_{co} are the cut-in, rated and cut-out speed of wind turbine, respectively, while $P_{w-rated}$ is the power rate of it.

$$P(V) = \begin{cases} 0 & 0 \le V \le V_{ci} \ , V_{co} \le V \\ P_{w-rated} \times \dfrac{V - V_{ci}}{V_r - V_{ci}} & V_{ci} \le V \le V_r \\ P_{w-rated} & V_r \le V \le V_{co} \end{cases} \tag{6}$$

Stochastic data producing: In this study, the Latin hypercube sampling algorithm is used to produce estimates of stochastic parameters and the K-means method is utilized to reduce the number of scenarios in order to increase the speed of the simulation. The Latin sampling method samples layers from the entire distributions of random variables. It can produce more stable and precise estimates in faster run time than traditional sampling methods. In the first step of this method, M samples are produced to show the stochastic nature of the uncertain variable. Then, the cumulative distribution function of the uncertain parameter is divided into M intervals with equal probability of $1/M$. Afterward, a value is randomly selected from each interval and then transformed into the inverse value using the inverse of the distribution function. After producing stochastic variables, the K-means clustering algorithm is used to reduce the number of scenarios. The main method of this scenario reduction algorithm is to arrange original scenarios of stochastic parameters into clusters; this arrangement is applied according to similarities of produced scenarios. The mean value of each cluster is selected as the centroid of that group. It is worth mentioning that the output of the K-mean clustering method is the cluster centroids and the number of scenarios allocated to each cluster. The flowchart of producing stochastic variables is shown in Fig. 1 [19].

3. OBJECTIVE FUNCTION AND CONSTRAINTS

In this study, the demand side management is done in the microgrid as a multi-objective problem. Daily profit of the microgrid and its daily produced pollutant gases are the objective functions. These indices are optimized in the presence of constraints including the production and consumption power balance, maximum produced power of energy sources and constraints of the energy storage system. In the following, considered objective functions and constraints are explained mathematically.

3.1. Objective functions

Daily profit of the microgrid: This objective function, which is the profit of the microgrid distribution company from selling the electricity, is the economic objective function of the demand side management. Mathematically, the daily profit of the microgrid (P_{MG}) is calculated by Eq. (7).

$$P_{MG} = I_{load} + I_{UG} - C_{UG} - C_{LS} \tag{7}$$

I_{load}, which is calculated by Eq. (8), is the income from selling the energy to the microgrid's consumers.

$$I_{load} = \sum_{i=1}^{n_c}\sum_{j=1}^{H} P_{ij}^{D} \times Pr_j^{M} \tag{8}$$

Here, n_c and P_{ij}^{D} are the number of customers and their consumption at each interval, respectively. Pr_j^{M} is the market price at interval j. H is the number of time intervals in each day.

I_{UG} is the income from selling the extra produced power of local sources to the upstream grid (Eq. (9)).

$$I_{UG} = \sum_{j=1}^{H} P_j^{UG} \times Pr_j^{UG} \tag{9}$$

Where, P_j^{UG} and Pr_j^{UG} are the amount of sold power to the upstream grid and the price of power at interval j, respectively.

Eq. (10) is used to calculate the cost of purchased energy from the upstream grid (C_{UG}). It is worth mentioning that the discharging of the storage system doesn't have an extra cost for the microgrid because the distribution company is the owner of it.

$$C_{UG} = \sum_{j=1}^{H} [(P_j^{WM} + P_{ESS_j}^{Ch}) \times Pr_j^{WM}] \tag{10}$$

In Eq. (10), $P_{ESS_j}^{Ch}$ and P_j^{WM} are the charging energy of the electrical storage system and the extra demand of consumers that should be purchased from the upstream grid, respectively. Pr_j^{WM} is the price of purchased electricity at time interval j,

C_{LS}, which is calculated by Eq. (11), is the cost of the produced power of local energy sources.

$$C_{LS} = \sum_{s=1}^{n_t}\sum_{i=1}^{n_{DG}}\sum_{j=1}^{H} P_{s_{i,j}}^{DG} \times Pr_s^{DG} \tag{11}$$

Here, n_t is the number of different types of sources. n_{DG} and $P_{s_{i,j}}^{DG}$ are the number of units from the considered type and their capacity at time interval j. Pr_s^{DG} is the price of the production active power of the different types of DGs.

Daily produced pollutant gases: This objective function is considered as one of the objective functions of the demand side management because the environmental condition of the world gets worse every year. Daily produced pollutant gases of the microgrid (E_{DP}) is calculated by Eq. (12).

$$E_{DP} = \sum_{h=1}^{H}\sum_{i=1}^{n_{unit}}\sum_{j=1}^{n_{PG}} P_{unit\_i}(h) \times PG_{ij} \tag{12}$$

Here, n_{unit} is the number of energy sources including distributed generation, energy storage system and upstream grid and n_{PG} is the number of pollutant gasses including CO, CO_2, SO_2, NO_x and PM_{10}. The parameter $P_{unit\_i}(h)$ demonstrates the power of unit i at hour h while PG_{ij} is the rate of pollutant gas j of unit i.

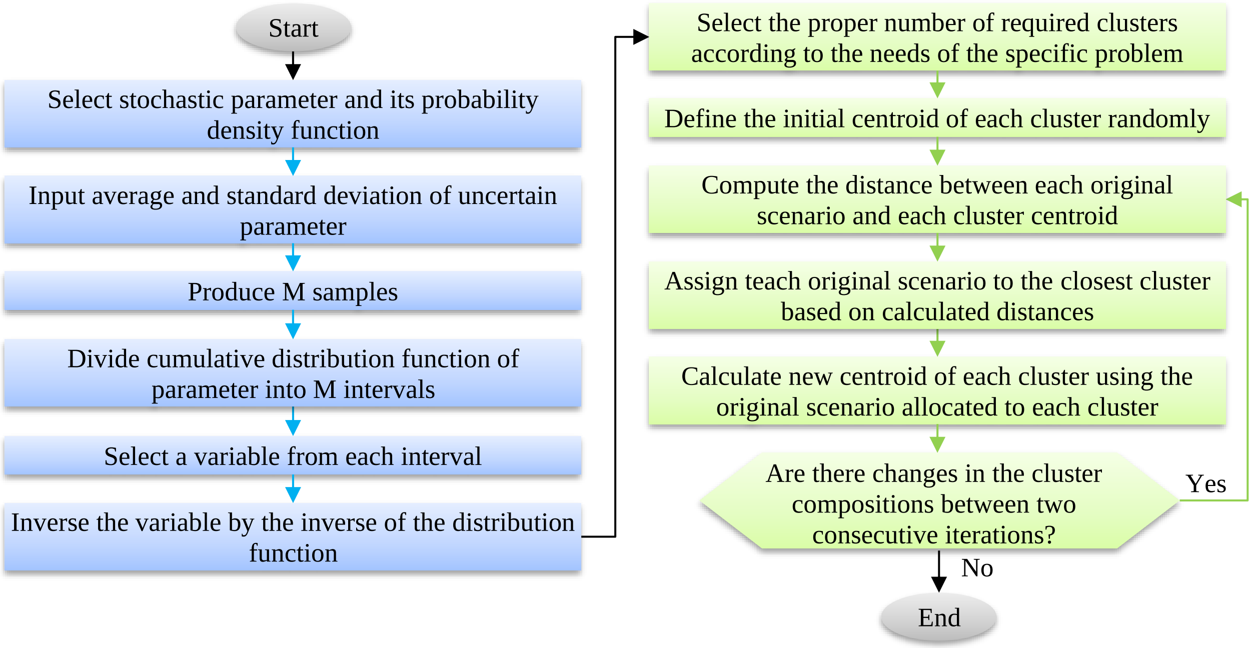

Fig. 1. Flowchart of producing the stochastic variables of renewable units

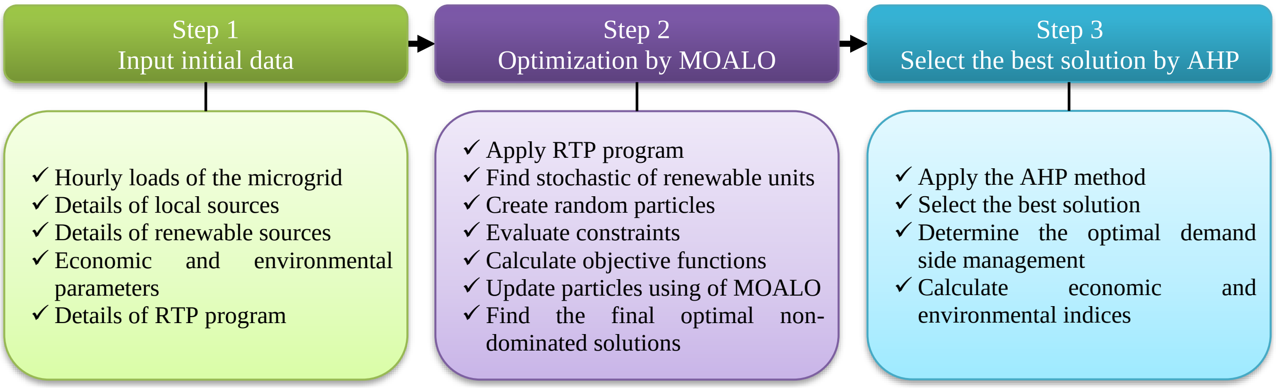

Fig. 2. Flowchart of the proposed demand side management of a microgrid

3.2. Constraints

Production and consumption power balance: This constraint presents the sum of the total power of various types of distributed generation units (P_{LS}), the power energy storage system in discharge mode ($P_{ESS,Dis}$) and the bought power from the upstream grid (P_{G2MG}) should be equal to the sum of the total demand of the microgrid (P_{load}), the power of the energy storage system in charge mode ($P_{ESS,Ch}$) and the sold power to the upstream network (P_{MG2G}). Mathematically, the power balance constraint is calculated by Eq. (13).

$$\sum_{i=1}^{n_{DG}} P_{LS\_i} + P_{G2MG} + P_{ESS,Dis} = \sum_{j=1}^{n} P_{load_j} + P_{MG2G} + P_{ESS,Ch} \qquad (13)$$

Maximum produced power of energy sources: The produced power of each type of local energy sources should be in the presented area by Eq. (14).

$${P_{LS}}^{min} \le P_{LS\_i} \le {P_{LS}}^{max} \qquad (14)$$

Where, ${P_{LS}}^{min}$ and ${P_{LS}}^{max}$ are the minimum and maximum power of each source for producing the electricity, respectively.

Energy storage's charge/discharge constraints: There are limitations of charging and discharging in the energy storage system during each hour. Eq. (15) shows that the charge and discharge of it are not simultaneous.

$$X_t^{ESS,Ch} + X_t^{ESS,Dis} \le 1 \qquad (15)$$

In this equation, $X_t^{ESS,Ch}$ and $X_t^{ESS,Dis}$ indicate a binary variable that shows the charge and discharge state of the storage system, respectively (0 or 1).

The limitation of the total state of charge (SOC) of the storage system is shown in Eq. (16).

$$SOC_{ESS}^{min} \le SOC_t^{ESS} \le SOC_{ESS}^{max} \qquad (16)$$

Where, SOC_t^{ESS} demonstrates SOC of it at time interval t while SOC_{ESS}^{min} and SOC_{ESS}^{max} indicate the minimum and maximum rates.

The maximum amount of charged power of the storage system from the grid and the maximum amount of discharged power of it to the grid are satisfied by Eq. (17) and Eq. (18), respectively.

$$0 \le P_t^{ESS,Ch} \le R_{ESS}^{Ch} \tag{17}$$

$$0 \le P_t^{ESS,Dis} \le R_{ESS}^{Dis} \tag{18}$$

In these equations, R_{ESS}^{Ch} and R_{ESS}^{Dis} show maximum charge and discharge rates, respectively.

Eq. (19) indicates that SOC of the storage system at each time interval (SOC_t^{ESS}) consists of the remaining SOC from the previous interval (SOC_{t-1}^{ESS}), the exchanged power with the microgrid ($P_t^{ESS,Ch}$ and $P_t^{ESS,Dis}$) and the charge and discharge efficiency (η_{ESS}^{Ch} and η_{ESS}^{Dis}).

$$\begin{aligned} SOC_t^{ESS} &= SOC_{t-1}^{ESS} + \left(P_t^{ESS,Ch} \times \eta_{ESS}^{Ch}\right) \\ &- \left(P_t^{ESS,Dis} \times \eta_{ESS}^{Dis}\right) \end{aligned} \tag{19}$$

4. DEMAND SIDE MANAGEMENT METHOD

The demand side management improves the efficiency of the microgrid when all parts of the microgrid are managed optimally based on the situation of the grid and consumers. For this reason, improving the load curve of customers is also investigated in this study. The demand response program is used to increase the incentive of consumers for better managing their load patterns. On the other hand, the combination of multi-objective ant lion optimizer and analytical hierarchy process method is utilized to optimize the economic-environmental objective function and choose the best operational schedule of local energy resources.

Demand response program: The demand response is a way for better matching the consumption curve with the generation curve of electrical power. Thus, it can shave the peak demand, manage risk and reduce carbon emission and energy cost. Demand response programs can be divided into price based programs and incentive based ones. In this study, the real time pricing (RTP) is used as the demand response program in the microgrid. Under this program, electricity price varies continuously in response to the wholesale market prices. The dynamic price is the best motivation for consumers to adjust their electricity consumption to achieve financial benefits. The mathematical model of the RTP program is presented in Eq. (20) [20].

In this equation, $E(i,i)$ and $E(i,j)$ are the self-elasticity and cross-elasticity of demand response, respectively. $d_0(i)$ and $d(i)$ are the demand of the system before and after applying the RTP, respectively. The initial price of each hour is represented using $P_0(i)$, while $P(i)$ demonstrates the price of the hour i after applying the RTP program.

$$d(i) = d_0(i) \times \left[\begin{array}{l} 1 + E(i,i) \dfrac{P(i) - P_0(i)}{P_0(i)} + \\ \sum_{\substack{j=1 \\ j \ne i}}^{24} E(i,j) \dfrac{P(j) - P_0(j)}{P_0(j)} \end{array} \right] \tag{20}$$

Multi-objective ant lion optimization algorithm: This intelligent algorithm is used to multi-objective optimize the objective functions and create the optimal Pareto front. This algorithm mimics the hunting mechanism of ant lions and the interaction of their favorite prey and ants. Similar to other intelligent algorithms, the multi-objective ant lion optimizer (MOALO) approximates the optimal solutions for optimization problems by employing a set of random solutions. This set is improved based on the principles inspired from the interaction between ant lions and ants. This algorithm is proficient, fast converging rate and effectual to handle composite non-linear constraint problems and also having few controlling parameters. Due to these advantages, it has been selected as a preferred method to solve complicated problems like the proposed demand side management of the microgrid [21].

Analytical hierarchy process method: This method is a methodology for selecting the optimal solution between the issues that the user is faced with several conflicting criteria and has to choose the most appropriate one. Therefore, the analytical hierarchy process (AHP) method is used to find the best result between the Pareto optimal solutions, which is obtained by applying the MOALO algorithm, based on the importance of technical and environmental indices of the microgrid. It is considered that both objective functions have the same weight in the AHP method [22]. Ultimately, the flowchart of the proposed method for multi-objective demand side management of a smart microgrid, which is applied in three steps, is demonstrated in Fig. 2.

5. RESULT OF SIMULATION AND DISCUSION

In this section, the proposed demand side management method is tested on a sample microgrid. The maximum demand of the considered microgrid is 3801.69 kW, while the hourly electricity consumption power of the microgrid is shown in Fig. 3.

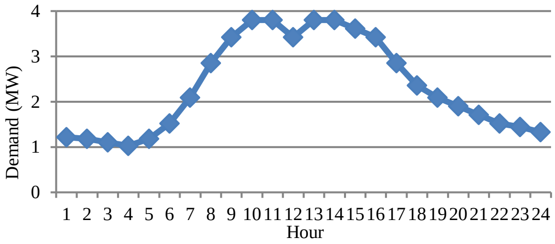

Fig. 3. Hourly consumption power of the microgrid

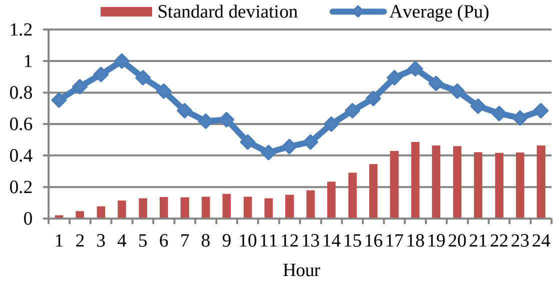

Fig. 4. Hourly average and standard deviation of wind speed

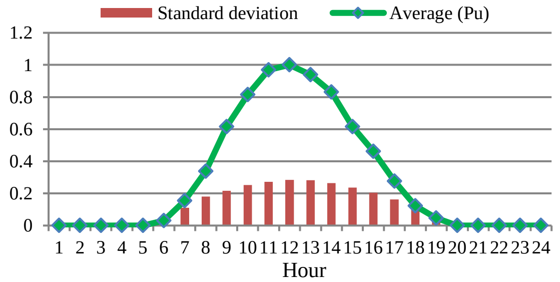

Fig. 5. Hourly average and standard deviation of solar irradiance

Diesel generator, micro turbine and fuel cell are the non-renewable energy units of the microgrid while the renewable sources are photovoltaic panel and wind turbine. An energy storage system is also available in the considered microgrid. Therefore, the operator of the microgrid can utilize the produced power of local energy sources and the bought energy from the upstream network at the required hours for providing the electricity demand of the microgrid. The energy sources of the microgrid are selected regards to the available technologies in the market. The capacities of diesel generator, micro turbine and fuel cell are 1000, 1000 and 85 kW, respectively. The wind turbine and photovoltaic panel can inject 1500 and 335 kW to the microgrid, respectively. Moreover, the cut-in, normal and cut-out speeds of wind turbine are 4, 13 and 25 m/s, respectively. An energy storage system with a capacity of 400 kWh is considered in the microgrid. The hourly charging and discharging limit of ESS is 100 kW. The stochastic produced power of wind turbine and photovoltaic panel is calculated regards to the hourly variation of wind speed and solar irradiance. The statistics amounts of wind speed and solar irradiance including their hourly average and standard deviation are shown in Figs. 4 and 5, respectively [23-24].

Table 1. The pollutant gases of energy sources of the microgrid

Type of energy source	Pollutant gases (kg/kWh)				
	CO_2	SO_2	NO_x	CO	PM_{10}
Diesel generator (DIG)	0.65	0.093	4.483	1.275	0.16
Micro turbine (MT)	0.72	0.002	0.091	0.247	0.018
Fuel cell (FC)	0.46	0.012	0.006	0.002	0
Photovoltaic panel (PV)	0	0	0	0	0
Wind turbine (WT)	0	0	0	0	0
Energy storage system (ESS)	0.02	0	0.00001	0.0003	0.001
Bought energy from upstream grid (Grid)	0.85	2.14	9.723	6.043	0.87

Fig. 6 shows the hourly market price of the microgrid without and with the demand response program. As mentioned above, the considered demand response program is real time pricing program. The costs of producing 1 Kwh using diesel generator, micro turbine, fuel cell, wind turbine and photovoltaic panel are 0.055, 0.043, 0.039, 0.037 and 0.038 $, respectively. The microgrid buys energy from the upstream network with a price of 0.12 $/kWh. Moreover, Microgrid sells energy to the upstream grid with the mean price of the daily market price.

The amounts of emitted pollutant gases of various energy sources of the microgrid and also upstream grid are presented in Table 1. The emitted pollutant gases of a central power plant are considered as the pollutant gases of the upstream network.

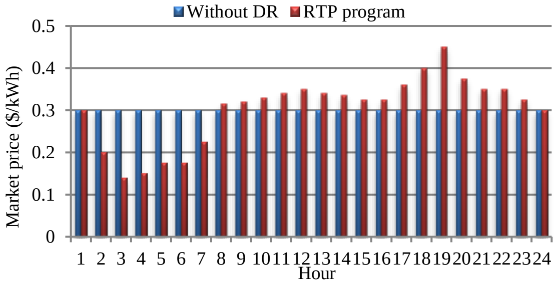

Fig. 6. The market price of the microgrid

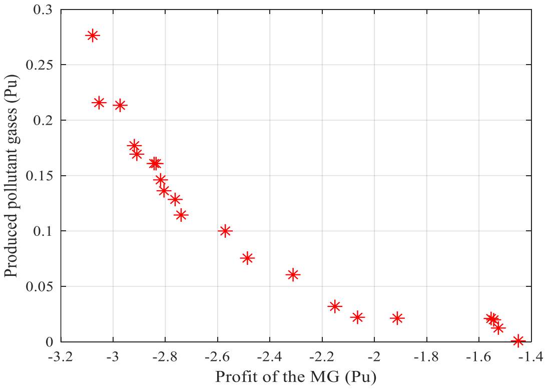

Fig. 7. The obtained Pareto front after applying MOALO

As mentioned in the last sections, the combination of multi-objective ant lion optimizer and analytical hierarchy process method is utilized for optimizing the demand side management in the proposed method. Fig. 7 demonstrates the obtained Pareto front after applying the MOALO algorithm. Then, the analytical hierarchy process method is utilized to select the best particle equal to the best operational schedule of energy sources of the microgrid. For better evaluating the performance of the proposed method, the economic and environmental indices of the microgrid based on the four scenarios including without demand side management and demand response (1), with demand side management (2), with demand response (3), and with demand side management and demand response (4), are evaluated in the following.

Table 2 presents the optimal operational schedule of energy sources (demand side management) without considering demand response program, while the best operational schedule of local energy sources and upstream grid during 24-hour in the presence of real time pricing program is presented in Table 3.

Table 2. The optimal operational schedule of energy sources of the microgrid without demand response

Hour	Power of energy resources (kW)						
	DIG	MY	FC	PV	WT	ESS	Grid
1	0.0000	849.13	79.39	0.000	1136.61	0.000	-848.530
2	0.0000	946.45	38.38	0.000	1296.00	0.000	-1102.25
3	0.0000	509.65	35.26	0.000	1293.00	0.000	-735.360
4	148.42	799.99	21.39	0.000	1278.95	-50.00	-1172.24
5	146.64	924.18	45.61	0.000	1294.70	-17.56	-1214.98
6	466.43	668.06	32.95	5.900	1301.40	-91.21	-862.770
7	755.09	945.69	71.09	48.70	1282.90	53.97	-1066.41
8	1000.0	1000.0	85.00	119.1	1294.50	0.000	-647.180
9	1000.0	1000.0	85.00	212.8	1287.60	0.000	-163.700
10	1000.0	1000.0	85.00	276.8	1283.60	-98.35	254.840
11	990.31	1000.0	85.00	325.4	1304.00	97.18	0.00000
12	1000.0	1000.0	85.00	335.0	1288.50	0.000	-286.800
13	1000.0	1000.0	85.00	318.0	1293.60	-99.16	204.450
14	1000.0	1000.0	85.00	283.3	1294.80	96.88	41.9100
15	1000.0	1000.0	85.00	215.5	1289.30	-99.42	121.420
16	1000.0	1000.0	85.00	161.6	1282.90	0.000	-107.800
17	915.09	799.65	42.32	94.70	1301.30	65.76	-367.400
18	1000.0	1000.0	85.00	36.90	1301.80	0.000	-1066.53
19	107.02	670.69	56.04	14.30	1286.00	94.01	-137.020
20	928.39	957.34	28.61	0.000	1296.70	97.69	-1407.79
21	908.11	923.55	11.24	0.000	1301.30	96.13	-1529.48
22	470.44	743.06	77.84	0.000	1300.60	-83.78	-987.400
23	462.07	791.75	80.34	0.000	1301.20	0.000	-1190.64
24	217.71	1000.0	85.00	0.000	1290.40	-98.42	-1164.03

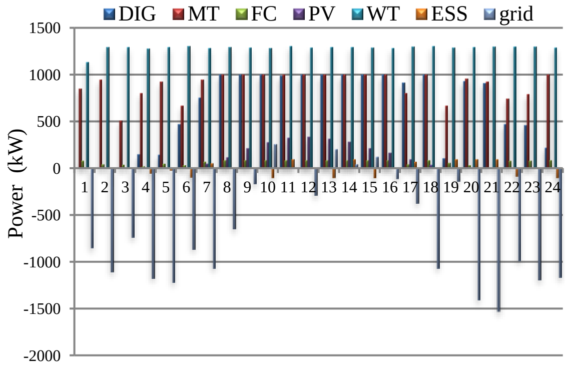

Fig. 8. The hourly produced power of energy units without RTP

Table 3. The optimal operational schedule of energy sources of the microgrid in the presence of RTP program

Hour	Power of energy resources (kW)						
	DIG	MY	FC	PV	WT	ESS	Grid
1	64.530	859.14	82.69	0.000	1089.51	0.000	-886.010
2	23.810	863.81	33.01	0.000	1296.00	0.000	-959.890
3	0.0000	40.300	21.58	0.000	1292.99	-100.0	0.00000
4	0.0000	511.41	25.71	0.000	1303.30	0.000	-635.220
5	0.0000	770.16	38.37	0.000	1294.70	0.000	-740.650
6	688.25	1000.0	85.02	5.900	1279.87	0.000	-1410.13
7	480.02	861.83	77.71	48.70	1282.90	-43.69	-515.340
8	830.03	676.79	34.82	119.1	1294.50	-53.51	-96.8300
9	1000.0	1000.0	85.00	212.8	1287.60	-25.45	-206.370
10	955.00	1000.0	85.00	276.8	1283.60	98.95	0.00000
11	1000.0	1000.0	85.00	325.4	1304.00	0.000	-42.8300
12	1000.0	1000.0	85.00	335.0	1288.50	0.000	-428.670
13	875.19	1000.0	85.00	318.0	1293.60	99.79	0.00000
14	1000.0	1000.0	85.00	283.3	1294.80	-95.12	117.250
15	837.49	1000.0	85.00	215.5	1289.30	99.63	0.00000
16	853.07	937.49	60.02	161.6	1282.90	-77.67	123.880
17	983.79	1000.0	85.00	94.70	1301.30	-29.48	-722.600
18	938.39	1000.0	85.00	36.90	1301.80	-54.33	-1132.99
19	185.23	967.14	28.51	14.30	1286.00	68.85	-695.920
20	906.39	852.67	76.85	0.000	1296.70	36.36	-1380.98
21	886.64	918.55	47.66	0.000	1239.67	55.46	-1508.06
22	358.41	833.05	31.42	0.000	1300.60	0.000	-1065.78
23	286.49	1000.0	54.89	0.000	1301.20	0.000	-1231.81
24	214.14	995.29	52.79	0.000	1290.40	0.000	-1229.33

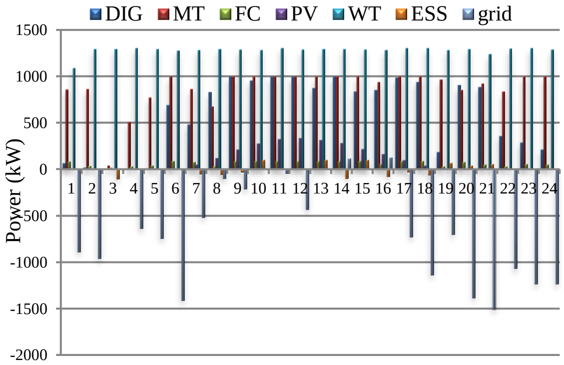

Fig. 9. The hourly produced power of units in the presence of RTP

As can be shown in Tables 2 and 3, the percentage of participation of various energy sources in demand side management is different with and without demand response program. For better showing the participation of each energy source in the energy management, the hourly produced power of each unit without and with the RTP program is demonstrated in Fig. 8 and Fig. 9, respectively.

Although all non-renewable sources produce more than 50 % of the demand in both conditions, the wind turbine provides respectively 42.21 and 43.41 % of all energy of the microgrid with and without the RTP program. Therefore, the wind turbine has the highest effect on the performance of the microgrid. The photovoltaic panel injects about 4 % of the overall energy to the microgrid. The participation percentage of the energy storage system in demand side management is about 1 %. It is worth mentioning that the dependence of the microgrid on the upstream grid is reduced by 62 % after utilizing the demand response program so that the bought power from the upstream grid is only 0.33 %

of total power when the proposed demand side management and real time pricing program are applied to the microgrid. Details of participation of energy sources in demand side management with and without the RTP program are shown in Fig. 10. According to the produced capacity of local energy sources, it can be said that the proposed method is useful to increase the independence of the microgrid. Moreover, the microgrid can also inject power into the upstream grid when the produced power of local sources is more than the demand. In the following, the proposed method is pondered based on the considered objective functions. Table 4 represents the amount of economic and environmental indices of the microgrid in various operational conditions.

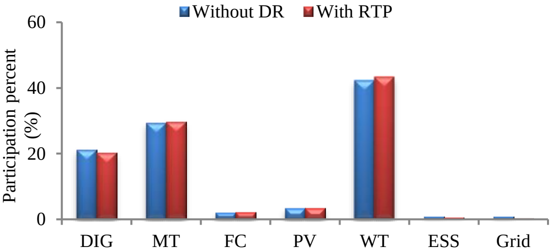

Fig. 10. The participation of various technologies in DSM

Table 4. The hourly amount of the profit and pollutant gases of the microgrid in different conditions

	The profit of microgrid ($)				The produced pollutant gases of microgrid (kg)			
Hour	Without DR		With RTP		Without DR		With RTP	
	Without DSM	With DSM	Without DSM	With DSM	Without DSM	With DSM	Without DSM	With DSM
1	218.9	385.1	217.7	385.25	23877.0	953.47	23744.8	1395.6
2	212.1	395.7	100.5	278.84	23130.9	1038.6	24664.6	1105.6
3	198.4	347.8	125.1	195.04	21638.6	566.33	24628.0	53.800
4	184.7	342.9	136.1	185.79	20146.2	1861.2	23653.3	563.64
5	212.1	396.6	174.9	244.81	23130.9	1994.9	26742.0	848.65
6	273.7	428.3	190.6	326.03	29846.3	3842.8	32361.4	5703.2
7	376.3	620.9	230.1	426.05	41038.7	6084.3	43022.8	4163.7
8	513.2	779.3	546.9	750.45	55961.9	7779.8	55048.9	6275.1
9	615.9	889.1	670.7	933.17	67154.3	7779.8	65817.4	7779.8
10	684.3	921.1	776.7	1063.9	74615.8	12781	72594.4	7482.1
11	684.3	979.1	807.7	1091.5	74615.8	7717.3	72058.3	7779.8
12	615.9	899.2	754.3	1037.6	67154.3	7779.8	64370.0	7779.8
13	684.3	925.0	807.7	1093.9	74615.8	11792	72058.3	6950.5
14	684.3	975.5	792.3	1031.7	74615.8	8604.9	72326.3	10080
15	650.1	881.9	723.0	997.98	70885.1	10162	69219.3	6699.4
16	615.9	884.5	684.9	904.39	67154.3	7779.8	65576.2	9153.0
17	513.2	761.4	651.0	902.21	55961.9	6979.1	53239.6	7671.8
18	424.2	684.2	608.9	841.95	46261.8	7779.8	42681.9	7369.4
19	376.3	558.7	611.8	816.85	41038.7	1464.7	36388.7	2291.5
20	342.1	597.9	455.9	698.72	37307.9	7231.8	35091.0	6994.3
21	307.9	558.5	377.1	618.95	33577.1	7051.9	32185.0	6920.1
22	273.7	440.6	335.2	533.21	29846.3	3971.9	28608.8	3300.4
23	260.0	465.5	289.2	497.27	28354.0	3969.9	27687.7	3012.6
24	239.5	403.3	238.1	440.13	26115.5	2568.9	25970.9	2524.6

Table 5. The statistical data of economic and environmental objective functions

Index	Operational condition of microgrid	The statistic data		
		Minimum	Maximum	Average
The profit of the microgrid ($)	Without DR and DSM	184.77 at hour 04	684.34 at hour 10	423.43
	Without DR and with DSM	342.90 at hour 04	979.17 at hour 11	646.78
	With DR and without DSM	100.54 at hour 02	807.75 at hour 11	471.15
	With DR and DSM	185.79 at hour 04	1093.9 at hour 13	678.99
The produced pollutant gases (kg)	Without DR and DSM	20146 at hour 04	74615 at hour 10	46168.6
	Without DR and with DSM	566.33 at hour 03	12781 at hour 10	5814.06
	With DR and without DSM	23653 at hour 04	72594 at hour 10	45405.8
	With DR and DSM	53.802 at hour 03	10080 at hour 14	5162.51

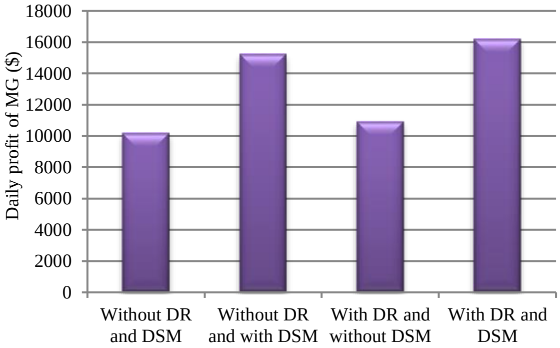

Fig. 11. Daily profit of microgrid in various operational conditions

The daily profit of the microgrid is 10162 $ in the base case (without demand side management and demand response). Applying the demand response program improves this objective function by about 7.33 %, while demand side management increases the amount of daily profit by 49.79 %. Thus, the operator of the microgrid can provide most of the demand using local energy sources. The daily profit increases considerably when both demand side management and real time pricing are utilized in the microgrid so that this objective function is 16196 $ after applying the proposed method. Fig. 11 shows the daily profit of microgrid in various operational conditions.

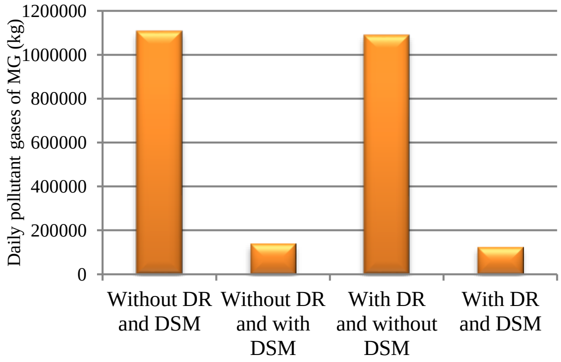

Fig. 12. Daily produced pollutant gases of microgrid in various operational condition

The daily produced amount of pollutant gases of the microgrid is demonstrated in Fig. 12. As can be known, renewable energy sources have a high effect on this objective function. The amount of pollutant gases decreases by about 87 % when the proposed demand side management operates the local energy sources. Of course, this objective function is improved by about 89 % when the RTP program is also used besides of demand side management.

The hourly profit of the microgrid and the produced pollutant gases during a 24-hour are also evaluated by statistical calculations. The statistical detail of the economic and environmental objective functions of the microgrid is presented in Table 5. According to the statistical results of this Table, the minimum and maximum hourly produced profit and pollutant gases of the microgrid are different in various operational conditions. The daily average amounts of economic and environmental objective functions are improved by about 11 and 2 % when the DR program is only utilized in the microgrid, respectively. The daily average profit of the microgrid is increased by about 53 % using the proposed DSM method while the daily average produced pollutant gases are also decreased by about 87 % in this operational condition of the microgrid. The microgrid with the proposed DR program and DSM method has the best performance so that the highest hourly profit (1093.9 $) and the lowest produced pollutant gases (53.80 kg) which are happened at hours 13 and 3, respectively.

According to the numerical results, the proposed method is practical in improving the economic and environmental indices of the microgrid and decreasing the dependence of it on the power of the upstream grid. Thus, the performance of the microgrid is increased considerably by the proposed method.

6. CONCLUSION

In this study, a new intelligent method based on the multi-objective ant lion optimizer and analytical hierarchy process method was proposed for demand side management in the microgrid in order to improve the economic and environmental indices of the system. Diesel generator, micro turbine, fuel cell, wind turbine, photovoltaic panel and electrical storage system were the local energy sources of the microgrid. The real time pricing program was used to increase the incentive of consumers to better control their electricity consumption.

The numerical results show that local energy sources including renewable and nonrenewable distributed units and electrical energy system accurately provide the most of the microgrid's demand during 24-Hour so that after applying the proposed method, the bought energy from the upstream grid is just 0.33 % of total daily load of the microgrid. The wind turbine produces the highest part of the total demand. The proposed method has also a practical performance in improving the economic and environmental indices of the microgrid. According to the results of the simulation, the proposed method, which is the combination of the demand response and optimal operating of local energy sources based on the proposed demand side management, increases the daily profit of the microgrid by about 60 % and decreases the daily produced pollutant gases by about 90 %. Ultimately, it can be said that the proposed method can considerably improve the performance of the microgrid and reduce its dependence on the upstream grid.

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