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MULTI-OBJECTIVE OPTIMIZATION OF DEMAND SIDE MANAGEMENT IN THE PRESENCE OF DG AND DEMAND RESPONSE

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Abstract – In this study, the combination of multi-objective particle swarm optimization and fuzzy decision-making method is utilized to find the best schedule for demand side management. The distribution system is considered in the presence of multi distributed generation (renewable and nonrenewable) and demand response. Economic and environmental indices are evaluated during the optimization. For better evaluation the results, the daily performance of grid and DG is optimized with and without consideration of demand response. Finally, the proposed algorithm is implemented on test distribution system. The obtained numerical results indicate the impact of demand side management on improving the economic and environmental indices of distribution system.

Keywords - Distributed generation, Demand response program, Demand side management, Multi-objective particle swarm optimization.

I. INTRODUCTION

Demand side management (DSM) is the modification of demand for energy through various methods such as financial incentives and behavioral change through education. DSM is the planning, implementation and monitoring of utility activities that are designed to influence the consumption of customers. The total goal of DSM is encouragement of consumers to decrease their energy consumption during peak hours or to move the time of energy use to off-peak times. Distributed generation (DG) units are one of the important devices that are utilized to apply the DSM to distribution system. Renewable and non-renewable DG units are used in the distribution system; these units assist the grid to supply the demanded power of network. Another useful technology of DSM is demand response (DR). Demand response can be defined as a method for improving the energy consumption pattern of an electric utility customer. DR causes to better match the demand for power with the suitable and expected daily load pattern [1-3].

In the last years, DSM has been studied by researchers that some examples of them are mentioned in the following. The authors in Ref [4] proposed a concept of DSM through the spatial and temporal DSM. The minimum daily energy losses and minimum daily operating costs are the objective functions of problem. In Ref [5], a DSM model has been developed to investigate the response capacity and rapid response capability of different resources. The considered resources are including of distributed generation and electrical vehicle. Shakouri and Kazemireported an intelligent energy management framework for DSM [6]. The minimization of electrical peak load and reduction of electricity cost are considered as objective functions in this study. The used model for DSM is a multi-objective mixed integer linear programming. In Ref. [7], DSM has been done to accommodate curtailed wind power with a typical wind power output profile and energy storage systems.

In this article multi-objective optimization of DSM is done in the distribution network with improving the economic and environmental indices. Renewable and nonrenewable distributed generation and demand response program are considered to reach the best schedule for DSM. The multi-objective particle swarm optimization is utilized to optimize the objective functions while the fuzzy decision-making method is used after multi-objective optimization to select the best result from Pareto optimal fronts. Evaluation the proposed method on the IEEE 33-bus distribution system indicates the high efficiency of DSM to improve the performance of distribution system. Moreover, the obtained numerical results indicate the impact of demand side management on improving the economic and environmental indices of distribution system.

II. PROBLEM DEFINITION

In this study, DSM is done in the distribution system in the presence of multi DG and demand response program. Renewable and nonrenewable DGs are considered so that each type of them has unique performance depends on their technology. The details of DGs and DR are explained as follow:

2.1 Distributed generation

In this study, diesel generator (DIG), micro turbine (MT) and fuel cell (FC) are considered as nonrenewable DG while renewable DG units are including of photovoltaic (PV) and wind turbine (WT).

A diesel generator uses a diesel engine and electric generator to generate electrical energy. Liquid fuels or natural gas are usually used as a primary fuel of DIG. The output power of DIG can be changed based on demand of network. Moreover, a DIG can produce active and reactive power, simultaneously. Micro turbine is a technology which has the unique ability to produce electricity and heat simultaneously. MT can run on a variety of fuels, including natural gas, propane and fuel oil. A MT has capable of injection both active and reactive power to the network. A fuel cell is a nonrenewable DG that converts the chemical energy from a fuel into electricity. A FC produces just active power [8, 9].

Photovoltaic panel which produces only active power is one of the popular and useful technologies of renewable DGs. The output power of each PV panel is related to the amount of solar irradiance (μ), the area (A_{pv}) and efficiency of the solar panel (β). Mathematically, the active power of PV can be calculated by (1) [8].

$$P_{PV} = A_{pv}\beta\mu \quad (1)$$

In the most countries which are pioneer in the clean energies, wind turbine is one of the common and useful renewable DG technologies. A WT usually consumes reactive power to produce active power. The output active power of WT has direct relation with wind speed (V_w) and swept area of the turbine (A_{wt}); although, the other parameters such as air density (ρ) and power coefficient (C_p) affect the power of WT. Therefore, the active power of WT can be evaluated by (2) [8].

$$P_{WT} = \frac{1}{2}\rho A_{wt} V_w^3 C_p \quad (2)$$

2.2 Demand response

Demand response programs are one of the methods for modifying the consumption curve of customers. Totally, DR is a change in the power consumption of an electric utility customer to better match the demand of system with the supply. On the other words, DR programs seek to adjust the demand for power instead of adjusting the supply. In this study, time of use (TOU) program is utilized as demand response program because it is a common and useful demand response program and also TOU is easier than other DR programs to apply to the distribution system. Therefore, it can be said that results of this study are so close to the result of the operation of a real distribution system. Totally, the considered model of DR program can be calculated by (3) [10].

$$d(i) = d_0(i) \times [1 + E(i,i)\frac{P(i) - P_0(i)}{P_0(i)} + \sum_{\substack{j=1 \\ j\neq i}}^{24} E(i,j)\frac{P(j) - P_0(j)}{P_0(j)}] \quad (3)$$

III. OBJECTIVE FUNCTIONS

In this study, optimization the best schedule for DSM is done as multi-objective optimization. As mentioned above, objective function is including of economic and environmental indices. Mathematically, the considered objective function is formulated as:

$$objective\ function : \min \{I_{OC}, I_{PE}\} \quad (4)$$

Where I_{OC} and $I_{PE}$are operational cost index (economic index) and pollution emission index (environmental index), respectively.

3.1 Economic index

Economic is the integral part of decision-making in all daily activities. The distributions system is also not exempt from this principle. Here, the operational cost index is considered as economic index of optimization for DSM. The daily operational cost index can be calculated by (5).

$$I_{OC} = OC_{DG} + OC_{grid} + MC \quad (5)$$

where,OC_{DG} and OC_{grid} are the operational cost of multi DG and grid, respectively, while MC is related to the situation of units; on the other words, MC shows running and shutting down costs for the i^{th}unit during the h^{th} hour.

$$OC_{DG} = \sum_{h=1}^{24}\left[\sum_{i=1}^{n_{DG}}\left(P_{DG\_i}(h) \times C_{DG_i}\right)\right] \quad (6)$$

$$OC_{grid} = \sum_{h=1}^{24}\left[P_{grid}(h) \times MP(h)\right] \quad (7)$$

$$MC = \sum_{h=1}^{24}[\sum_{i=1}^{n_{unit}}(C_{ss_i} \times |M_{unit\_i}(h) - M_{unit\_i}(h-1)|)] \quad (8)$$

In these equations, P_{DG_i} and P_{grid} are the power of i^{th} DG and grid at h^{th} hour, respectively. The parameter MP is the market price; moreover, C_{DG_i} and C_{ss_i} are the cost of power generation at i^{th} DG and the cost of start-up/shut-down at i^{th} unit, respectively.

3.2 Environmental index

Nowadays, most countries have special attention to environmental aspects of their decisions because the environmental condition gets worse every year. In this study, the considered environmental index is equal to the amount of pollution emission of all units. The main pollutant gases are Carbon Monoxide (CO), Carbon Dioxide (CO_2), Sulfur Dioxide (SO_2), Nitrogen Oxides (NO_x) and Particulate Matter (PM_{10}) [11]. Therefore, the considered pollution emission index can be calculated by (9).

$$I_{PE} = \sum_{h=1}^{24} \sum_{i=1}^{n_{unit}} \sum_{j=1}^{n_{PG}} P_{unit\_i}(h) \times PG_{ij} \quad (9)$$

Where, P_{unit_i} and PG_{ij} are the power of i^{th} unit at h^{th} hour and the rate of j^{th} pollution gas of i^{th} unit, respectively.

IV. PROBLEM CONSTRAINT

There are following constraints during the implementation of the proposed algorithm.

a. The range of power generation of DG units

The utilized DG unit must have the allowable size as the following range:

$$P_{DG}{}^{min} \leq P_{DG\_i} \leq P_{DG}{}^{max} \quad (10)$$

b. Power balance constraint

The total power generated by multi DG and grid must be equal to the sum of the total demand and active loss of distribution system.

$$\sum_{i=1}^{n_{DG}} P_{DG\_i} + P_{grid} = \sum_{j=1}^{n} P_{demand_j} + \sum_{i=1}^{N_{br}} P_{loss_i} \quad (11)$$

c. Energy storage system constraint

There are limitations of charging and discharging in energy storage system (ESS) during each hour. The following equations can be expressed for limitations of ESS. In these equations, W_{ESS} is the energy stored within the ESS at h^{th} hour [3].

$$W_{ESS}(t) = W_{ESS}(t-1) + \eta_{charge} P_{charge}(t) - \frac{1}{\eta_{discharge}} P_{discharge} \quad (12)$$

$$W_{ESS\_min} \leq W_{ESS}(t) \leq W_{ESS\_max}$$

$$P_{charge}(t) \leq P_{charge\_max} \quad (13)$$

$$P_{discharge}(t) \leq P_{discharge\_max}$$

V. OPTIMIZATION ALGORITHM

As mentioned above, the combination of MOPSO and fuzzy decision-making is utilized to multi-objective optimization of economic and environmental indices.

5.1 Multi-objective particle swarm optimization

PSO is a stochastic global optimization technique which uses swarming behaviors observed in flocks of birds, schools of fish or swarms of bees, in which the intelligence is emerged. Each particle keeps track of its coordinates in the solution space which are associated with the best solution that has achieved so far by that particle and is called as personal best position ($x_{i_{best}}$) and the other best value obtained so far by any particle in the neighborhood of the particle is called global best position (g_{best}). Each particle in the PSO tries to modify its position using the concept of velocity. In PSO, the particles move around according their velocity and position. Equations 14 and 15 are used to update the velocity and position of the particles [12].

$$\acute{V_i} = \omega V_i + c_1 r_1 (x_{i_{best}} - x_i) + c_2 r_2 (g_{best} - x_i) \quad (14)$$

$$\acute{x_i} = x_i + \acute{V_i} \quad (15)$$

Where ω is the inertia weight, r_1 and r_2 represent random number in the range [0, 1]; c_1 and c_2 are the balance factors between the effect of self-knowledge and social-knowledge in moving the particle towards the target. Of course, according to the multi-objective optimization, the multi-objective method of this algorithm (MOPSO) is utilized during this study [12].

5.2 Fuzzy decision-making

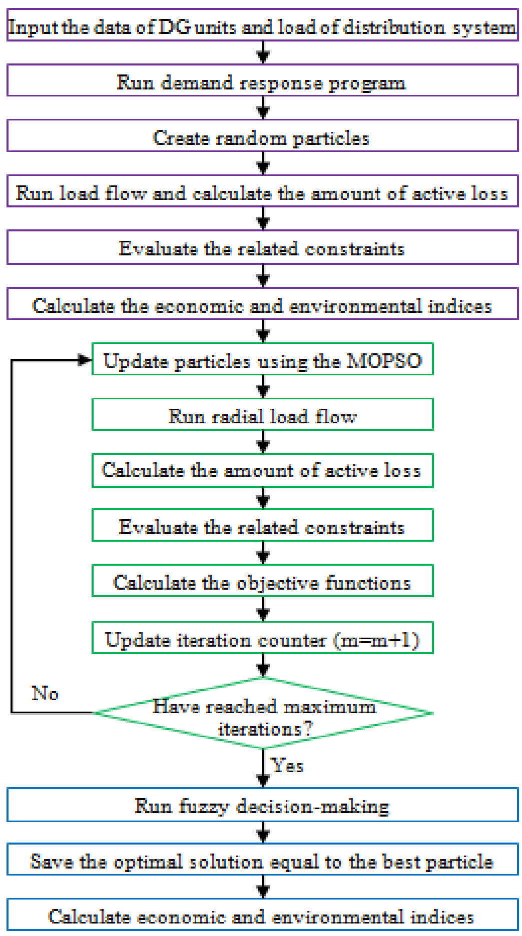

Fig. 1Flowchart of optimization the best schedule for DSM

A fuzzy satisfying method which represents the goals of each objective function is applied to find the best compromise solution from the Pareto optimal front. The membership function is defined as follow:

$$\mu_i^k = \begin{cases} 1 & F_i^k \le F_i^{min} \\ \dfrac{F_i^{max} - F_i^k}{F_i^{max} - F_i^{min}} & F_i^{min} < F_i^k < F_i^{max} \\ 0 & F_i^{max} \le F_i^k \end{cases} \qquad (16)$$

For each member of the non-dominated set, the normalized membership value is calculated using the (17).

$$\mu^k = \frac{\sum_{i=1}^{NO} \mu_i^k}{\sum_{k=1}^{NK} \sum_{i=1}^{NO} \mu_i^k} \qquad (17)$$

The maximum value of the membership μ^k can be chosen as the best compromise solution.

5.3 Proposed method

In previous sections, the details of different technologies of DG, objective functions, constraints and intelligent algorithm were completely explained. In this section, proposed method for optimization the best schedule of DSM is described.

In this study, DSM is done in the distribution system in the presence of demand response. Of course, the distribution system without demand response is also considered for better evaluation the result. Economic and environmental indices are optimized by combination of MOPSO and fuzzy decision-making during finding the best plan for DSM. The power balance and ESS constraints are evaluated in all reiteration of intelligent algorithm. The complete algorithm for finding the optimal schedule for DSM is shown in Fig. 1.

VI. NUMERICAL STUDIES

In this section, the proposed algorithm is test on IEEE 33-bus radial distribution system. The single diagram of this network with the proposed place of DGs based on system's condition is shown in Fig. 2.

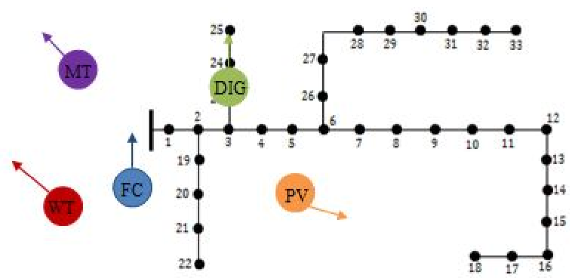

Fig. 2The single diagram of 33-bus network and DG units

The minimum and maximum capacities of DG units are 0.1 and 2 MW, respectively. The hourly variations of produced power of WT and PV and also the daily load curve of system are shown in Fig. 3. Moreover, it is assumed that 40 % of consumers participate in DR.

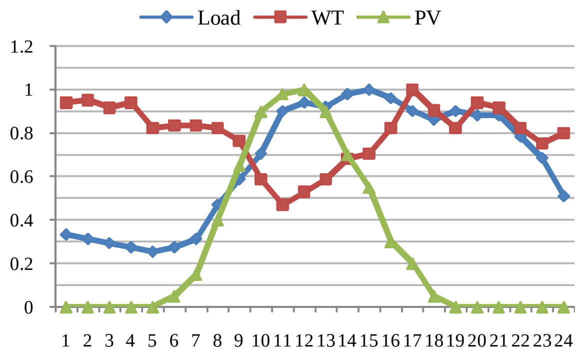

Fig. 3 The hourly variations of RDG and load

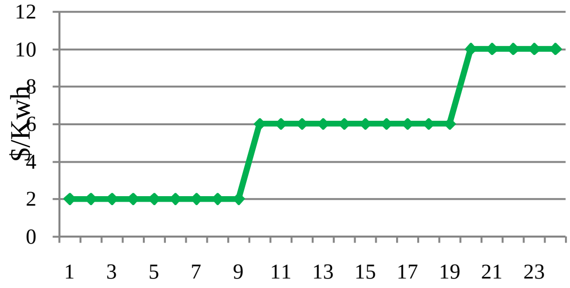

Fig. 4The real-time market price

Table 1: The economic and environmental information of sources

	Economic data						
	DIG	MT	FC	PV	WT	ESS	Grid
C_{DG_i}\$/Kwh	1.172	0.914	0.588	5.168	2.146	0.760	0
C_{ss_i} (\$)	0.35	1.92	3.32	0	0	0	0
	Pollution gases rate (Kg/Kwh)						
	DIG	MT	FC	PV	WT	ESS	Grid
CO_2	0.65	0.72	0.46	0	0	0.02	0.85
SO_2	0.093	0.002	0.012	0	0	0	2.14
NO_x	4.483	0.091	0.006	0	0	0	9.723
CO	1.275	0.247	0.002	0	0	0	6.043
PM_{10}	0.16	0.018	0	0	0	0.001	0.87

The minimum and maximum charges of ESS are considered to be 10 and 100 percent of the ESS capacity, respectively, with a charge and discharge efficiency of 94%. The economic and environmental information of various units are presented In Table 1. Fig. 4 shows the real-time market price of network.

For better evaluation the results, DSM is done with and without consideration of demand response program (TOU). The daily optimal produced power of resources without consideration of TOU is presented in Table 2. According to this Table, the nonrenewable DG units have an important role in power generation; the produced power of these technologies is about 66.79 percent of total provided energy. The 24.36 percent of load is produced by renewable DG units. Of course, WT has more influence that PV, so that the produced power of WT is approximately twice higher than produced power of PV in the DSM. Even though the grid has provided the all demanded power of network before DSM, but after doing DSM in the distribution system, the provided power of grid is about 2 percent of total demand. On the other words, DG units can provide the demanded load of system in the most times; therefore it can be said that the grid is the backup resource after doing DSM.

hour	Power of resources (MW)						
	DIG	MT	FC	PV	WT	ESS	Grid
1	0.0000	0.5493	0.5000	0.0000	0.0000	0.1889	0.0000
2	0.0000	0.4045	0.4978	0.0000	0.0181	0.2450	0.0000
3	0.0000	0.4889	0.5000	0.0000	0.0000	0.1037	0.0000
4	0.0000	0.6000	0.5000	0.0000	0.0000	-0.0802	0.0000
5	0.0000	0.0198	0.5000	0.0000	0.0000	0.4271	0.0000
6	0.0020	0.6000	0.5000	0.0000	0.0000	-0.0822	0.0000
7	0.0000	0.1654	0.5000	0.0000	0.0000	0.5000	0.0000
8	0.0814	0.6000	0.5000	0.0000	0.6588	-0.0919	0.0000
9	0.0000	0.6000	0.5000	0.0000	0.5852	0.5000	0.0000
10	0.5633	0.6000	0.5000	0.5400	0.4706	-0.0515	0.0000
11	0.7956	0.6000	0.5000	0.5789	0.3765	0.5000	0.0000
12	1.3000	0.6000	0.5000	0.5900	0.4670	-0.0824	0.1220
13	0.9307	0.6000	0.5000	0.2100	0.7910	0.3620	0.0300
14	1.3000	0.6000	0.5000	0.3940	0.7570	0.0172	0.0740
15	1.2917	0.6000	0.5000	0.3300	0.5647	0.4285	0.0000
16	1.3000	0.6000	0.5000	0.1800	0.6588	-0.0216	0.3000
17	0.8646	0.6000	0.5000	0.1200	0.7959	0.4704	0.0000
18	1.3000	0.6000	0.5000	0.0300	0.7390	-0.0391	0.0750
19	0.7529	0.6000	0.5000	0.4550	0.7100	0.3230	0.0020
20	1.3000	0.6000	0.5000	0.0000	0.7530	0.1252	0.0000
21	1.1282	0.6000	0.5000	0.0000	0.7341	0.3159	0.0000
22	1.0215	0.6000	0.5000	0.0000	0.6544	0.1282	0.0095
23	0.5614	0.6000	0.5000	0.0000	0.6023	0.2859	0.0000
24	0.0000	0.6000	0.5000	0.0000	0.6386	0.1553	0.0000

Table 2 Energy resources scheduling for DSM without DR

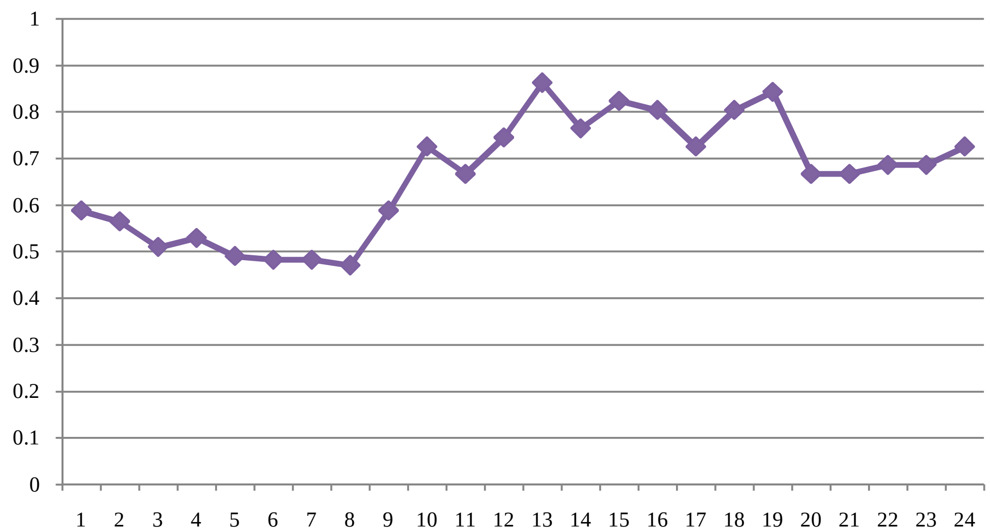

Fig. 5 Load demand after demand repsonse implementation

The considered indices are considerably improved after doing DSM in the distribution system. The reduction of economic and environmental indices is considerable. Operational cost of system is reduced about 499.59 million $ after applying DSM so that the initial amount of economic index is 590.58 million $, while after applying DSM and without DR, this index is 90.98 M$. The amount of environmental index is also improved after DSM in the distribution system so that initial amount of this index is 742.89 M$ while it is 88.07 M$ after DSM without DR. Therefore, the rate of pollution emission is decreased about 88.15 percent than initial amount.

Now the demand response program is also considered in the DSM. The obtained produce power of different types of DG, ESS and grid in the DSM with consideration of TOU program are presented in Table 3. The variation of demanded load of 33-bus system after applying the DR program is also shown in Fig. 5. It can be said that the difference between the minimum and maximum demand of system is considerably reduced by participating the customers in DR. This reduction causes to improve the performance of distribution system.

hour	Power of sources (MW)						
	DIG	MT	FC	PV	WT	ESS	Grid
1	0.0000	0.5944	0.5000	0.0000	0.6785	0.4122	0.0000
2	0.2023	0.6000	0.5000	0.0000	0.7623	0.0333	0.0000
3	0.0000	0.6000	0.5000	0.0000	0.6616	0.1323	0.0000
4	0.0005	0.6000	0.5000	0.0000	0.6086	0.2576	0.0000
5	0.1498	0.6000	0.5000	0.0000	0.6588	-0.1178	0.0303
6	0.0000	0.6000	0.5000	0.0000	0.1921	0.5000	0.0000
7	0.0689	0.6000	0.5000	0.0000	0.6682	-0.0536	0.0086
8	0.0000	0.5857	0.5000	0.0000	0.1626	0.5000	0.0000
9	0.1911	0.6000	0.5000	0.3900	0.6118	-0.1077	0.0000
10	0.0847	0.6000	0.5000	0.5400	0.4706	0.5000	0.0000
11	0.5650	0.5578	0.5000	0.3400	0.6750	-0.178	0.0170
12	0.1400	0.6000	0.5000	0.6000	0.4235	0.5000	0.0045
13	0.9540	0.5599	0.5000	0.5890	0.6200	-0.0690	0.0510
14	0.2679	0.6000	0.5000	0.4200	0.5459	0.5000	0.0071
15	1.1669	0.6000	0.5000	0.2815	0.5647	-0.0538	0.0000
16	0.5477	0.6000	0.5000	0.1800	0.6588	0.5000	0.0000
17	0.7837	0.6000	0.5000	0.1200	0.8000	-0.1117	0.0033
18	0.6318	0.6000	0.5000	0.0300	0.7247	0.5000	0.0000
19	0.7180	0.5690	0.4170	0.5640	0.7550	-0.0830	0.1921
20	0.1238	0.6000	0.5000	0.0000	0.7530	0.5000	0.0000
21	1.1230	0.5288	0.5000	0.0000	0.7060	-0.3890	0.0080
22	0.2908	0.6000	0.5000	0.0000	0.6588	0.5000	0.0000
23	0.8981	0.6000	0.5000	0.0000	0.6023	-0.0519	0.0011
24	0.5302	0.6000	0.5000	0.0000	0.6400	0.4250	0.0000

Table 3Energy resources scheduling for DSM with DR

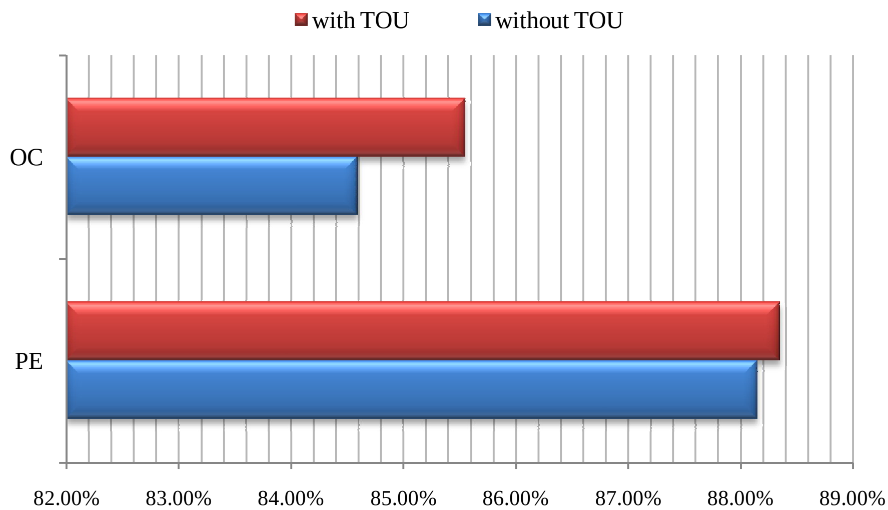

Fig. 6 The reduction amount of indices after DSM with/without DR

After simultaneously applying the DSM and DR, the influence of nonrenewable DGs on total load is 60.18 percent while the effect of renewable DG units increases about 7 percent than the DSM without consideration of DR, so that they provide 31.57 % of total demanded power of network.

After applying the DSM by the proposed method, the considered indices are considerably improved than initial situation. Moreover, the amounts of indices are lower than the DSM without consideration the TOU program. The effect of DR program on the performance of distribution system is clearly shown in Fig. 6. It is evident that the economic and environmental indices are approximately improved about %80 after applying the DSM, DG and DR program by the proposed method.

CONCLUSION

DSM in the distributed network is an effective method to balance the dynamics of power supply and demand at the side of consumption. In this study, DSM was done in the distribution system with multi DG and DR. The combination of MOPSO and fuzzy method was utilized to optimize the economic and environmental indices of distribution network. Finally, the proposed method was tested on IEEE 33-bus distribution system.

The results show that the proposed method can properly optimize the best schedule for DSM so that considered indices of network is improved considerably after applying the DSM. The nonrenewable DG units provide the most part of the demanded power of network because the produced energy of them is stable based on demand of system. Even though the produced power of renewable DGs is about %30 of total demand but effect of them on environmental indices is considerable, because the produced energy of them is clean and eco-friendly. Although, the economic and environmental indices improve after utilizing the DSM, but this improvement is considerable with the participation of customers in DR program. Totally, it can be said that the proposed method has properly performance in improving the efficiency of distribution system by optimization the DSM.

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