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SIMULTANEOUS ALLOCATING OF PROTECTIVE DEVICES AND RENEWABLE SOURCES IN THE DISTRIBUTION NETWORK WITH VARIABLE CONSUMPTION PATTERNS

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Abstract- Selecting the best site and size of distributed generation units and the best site of protective device is an important issue in optimal operating of these devices in the distribution system. For this reason, the simultaneous allocating of protective devices and renewable distributed generation units is studied in the distribution system with variable load model. The load model is considered as a combination of various customers' daily load patterns and sensitive to voltage-frequency. The objective functions of the problem consist of the power loss, the reliability index and the profit of company of distribution system. The multi-objective whale optimization algorithm is utilized to find the best Pareto front; and then a method based on fuzzy set theory is employed to extract one of the Pareto-optimal solutions as the best site and size of devices. Finally, for evaluating the performance of the proposed method, it is implemented on the 69-bus distribution system. The results indicate the high efficiency of the proposed method in improving the technical and economic indices of the distribution system.

Keywords: Fuzzy Method, MOWOA, Protective Devices, Renewable Generation, Variable Load Pattern.

1. INTRODUCTION

Although distributed generation (DG) units improve the performance of the power grid, renewable technologies of DGs can decrease the environmental pollutions beside the other improvements. One of the important points in using DG sources is finding the proper site and size of them according to distribution system's situation [1, 2]. On the other hand, the assumption of power grid without protective devices is approximately impossible. So, researchers and operators of distribution system utilize protective devices such as a breaker, relay and fuse for increasing the grid reliability and stability. Totally, DG units change the direction of power flow and fault current level of the system; so protection plans of the distribution system become unstable. Therefore, protective devices should be replaced in the system based on the site of DGs and new condition of grid [3].

In the last years, some researchers have studied DG units and protective devices in the distribution system. References [4, 10] are samples of these studies that can be divided into three groups. According to the recent studies, important issue that arises in the simultaneous placement of renewable DG and protective device is creation islanded area to reduce the energy not supplied when the fault occurs. So, in this study, stability of created area during a fault is one of the important constraints. So in the remainder of this paper, firstly, the studied issue including of modeling of load and devices is described and then the considered objective functions are explained. Then the multi-objective optimization method is proposed. Finally, the results of computer simulations are presented and pondered in using the 69-bus distribution system.

2. PROBLEM DESCRIPTION

2.1. Load Model

The magnitude of voltage at the buses and frequency of the system affect the actual active and reactive loads of the system. Load model of the system is considered as a combination of daily load pattern and sensitive load to voltage-frequency. Practical voltage-frequency dependent load model can be mathematically expressed as the Equations (1) and (2) [11].

$$P_{l\_i} = P_{l\_0i}\left(\frac{V_i}{V_b}\right)^{k_{pv}}\left[1+k_{pf}\left(f-f_0\right)\right] \quad (1)$$

$$Q_{l\_i} = Q_{l\_0i}\left(\frac{V_i}{V_b}\right)^{k_{qv}}\left[1+k_{qf}\left(f-f_0\right)\right] \quad (2)$$

The load model of the grid is also changed based on customers' daily load patterns. The values of dependence coefficients and the average hourly demand data for different load models are existed in Ref [11].

2.2. RDG and Protective Devices

Renewable distributed generation (RDG) units including wind turbine (WT) and photovoltaic (PV) are considered in this study. The three protective devices including circuit breaker, relay and fuse are utilized for increasing the reliability of distribution grid. The circuit breaker is placed as a basic protective instrument at the beginning of the feeder. Relay and fuse are located respectively on the branch and sub-branch in the system according to the site of multi-DG so that the maximum stability obtains when a fault has occurred.

The stability of created area after a fault in upstream of the protective device is an important subject in the placement of DG and protective devices. So during the optimization, the constraints of the distribution system such as voltage limits are evaluated in the grid and possible islanded areas.

3. OBJECTIVE FUNCTION

Simultaneous placement of RDG and protective devices is done as a multi-objective optimization. These devices increase the performance of distribution system with improving the technical indices of the grid. One of the most important indices of distribution system is power loss index because the most part of the loss of power grid is done in the distribution system. On the other hand, customers of power grid expect to get the uninterrupted electrical energy during the 24-hour.

Therefore, another important technical index of distribution system is the index of reliability. Consequently, the loss and reliability indices are considered as technical objective functions of the proposed method. Of course, an economic index is also considered to evaluate the profitability of simultaneous optimizing of site and size of RDG and protective devices. Therefore, objective functions have been defined including loss, reliability and benefit indices. Mathematically, the main objective function is formulated as

$$objective\ function : \min \{I_L,\ I_R,\ I_B\} \tag{3}$$

3.1. Loss Index

Loss index as the most important technical index is defined as combination active and reactive power loss as:

$$I_L = C_p L_A + C_q L_R \tag{4}$$

$$L_A = \max_{h=1}^{24} \left\{ \sum_{i=1}^{N_{br}} R_i \, |I_{hi}|^2 \right\} / \max_{h=1}^{24} \left\{ \sum_{i=1}^{N_{br}} R_i \, |I_{hi0}|^2 \right\} \tag{5}$$

$$L_R = \max_{h=1}^{24} \left\{ \sum_{i=1}^{N_{br}} X_i \, |I_{hi}|^2 \right\} / \max_{h=1}^{24} \left\{ \sum_{i=1}^{N_{br}} X_i \, |I_{hi0}|^2 \right\} \tag{6}$$

3.2. Reliability Index

Reliability of the grid is the ability to perform the task in the system under certain operating and environmental conditions for a specific timeframe. In the distribution system, the reliability is related to consumer power outages and disruption in the performance of equipment [12].

In this study, system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI) and average energy not supplied index (AENS) are used as reliability indices of load points. So, the reliability index is defined by (10).

$$I_R = \max_{h=1}^{24} \left\{ \begin{array}{l} C_{r1} \times \dfrac{SAIFI_h}{SAIFI_{h0}} + C_{r2} \times \dfrac{SAIDI_h}{SAIDI_{h0}} \\ + C_{r3} \times \dfrac{AENS_h}{AENS_{h0}} \end{array} \right\} \tag{7}$$

The reliability indices of load points are calculated by Equations (8-10) [13].

$$SAIFI = \sum N_i r_i / \sum N_i \tag{8}$$

$$SAIDI = \sum N_i u_i / \sum N_i \tag{9}$$

$$AENS = \sum L_{a(i)} u_i / \sum N_i \tag{10}$$

3.3. Benefit Index

Economic issues are an integral part of decision making in all daily activities; the power grid is not exempt from this principle. The benefit index is defined by (11).

$$I_B = Profit / Initial\_profit \tag{11}$$

$$Profit = Re - Co \tag{12}$$

$$Initial\_profit = Re_0 - Co_0 \tag{13}$$

The initial revenue of distribution system is equal to obtained income from selling energy to customers whereas the ultimate revenue is equal to the sum of the income from selling the energy to customers and income from reducing the energy not supplied. Mathematically, the initial and ultimate revenue of the distribution system can be calculated by Equations (14) and (15), respectively:

$$Re_0 = \sum_{h=1}^{24} \sum_{i=1}^{n_b} P_{lih} \times C_{MR} \tag{14}$$

$$Re = \sum_{h=1}^{24} \sum_{i=1}^{n_b} P_{lih} \times C_{MR} + \sum_{h=1}^{24} Re_{ENSh} \tag{15}$$

$$Re_{ENSh} = \left[\left(ENS_0 - ENS \right) \times \left(C_{MR} - C_A \right) \right] / 8760 \tag{16}$$

The distribution company purchases its power demand from transmission grid. A portion of this power demand is for distribution system customers and another one is spent in line and equipment loss. So the initial cost of the distribution system is calculated by (17).

$$\begin{aligned} Co_0 = {} & \left[\sum_{h=1}^{24} \sum_{i=1}^{n_b} P_{lih} \times C_A \right] + \left[\sum_{h=1}^{24} P_{l_h} \times C_A \right] + \\ & + \left[\sum_{h=1}^{24} Q_{l_h} \times C_R \right] \end{aligned} \tag{17}$$

The ultimate cost of distribution system after placement of devices is calculated by (18). In this function, the cost of produced power of DG and cost of DG and protective devices are added to the total cost of the system. Of course, the distribution company purchases lower power from transmission grid because the part of demand is provided by RDG units.

$$\begin{aligned} Co = {} & \left[\sum_{h=1}^{24} \left(\sum_{i=1}^{n_b} P_{lih} - \sum_{i=tech} \sum_{j=1}^{n_{DG}} P_{DG_{ij}} \right) \times C_A \right] + \\ & + \left[\sum_{h=1}^{24} P_{l_h} \times C_A \right] + \left[\sum_{h=1}^{24} Q_{l_h} \times C_R \right] + \\ & + \left[\sum_{i=tech} \sum_{j=1}^{n_{DG}} P_{DG_{ij}} C_{DG_i} \right] + \left[\sum_{i=p\_type} \sum_{j=1}^{n_{p\_i}} C_{p_i} \right] \end{aligned} \tag{18}$$

4. OPTIMIZATION ALGORITHM

The combination of multi-objective whale optimization algorithm (MOWOA) and fuzzy decision-making method is used to simultaneously optimize of site and size of devices in distribution system. To achieve the best result; firstly, objective functions including the loss, reliability and profit of distribution company are optimized by MOWOA. After applying the intelligent algorithm and improving the objective functions, the fuzzy set theory is utilized to select the optimal site and size of devices from Pareto front.

Intelligent algorithms are typically inspired their performance from nature; the whale optimization algorithm (WOA) is inspired from the hunting behaviour of whales. Whales are considered as the biggest mammals in the world. Even though there are seven different main species of this giant mammal such killer, Minke, Sei, Humpback, Right, Finback and Blue, but the hunting behaviour of humpback whales is considered in this meta-heuristic optimization algorithm. The hunting behaviour of humpback whale is called bubble-net feeding method. Humpback whales prefer to hunt a school of krill or small fishes close to the surface. Humpback whales swim around the prey within a shrinking circle and along a spiral-shaped path simultaneously. Similarly, in the WOA, particles update based on 'Shrinking encircling mechanism' and 'Spiral updating position' during the optimization [13].

After applying the MOWOA, a fuzzy satisfying method is used to find the best compromise solution which represents the best amount of each objective function. The membership function is defined as follow:

$$\mu_i^k = \begin{cases} 1 & F_i^k \le F_i^{min} \\ \dfrac{F_i^{max} - F_i^k}{F_i^{max} - F_i^{min}} & F_i^{min} < F_i^k < F_i^{max} \\ 0 & F_i^{max} \le F_i^k \end{cases} \quad (19)$$

For each member of the non-dominated set, the normalized membership value is calculated by:

$$\mu^k = \frac{\sum_{i=1}^{NO} \mu_i^k}{\sum_{k=1}^{NK} \sum_{i=1}^{NO} \mu_i^k} \quad (20)$$

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

Using the mentioned method, the complete algorithm for simultaneous placement of RDG and protective device in the distribution system is shown in Figure 1.

As regards that nonlinear load model is considered in this study; firstly, the proposed method is used to select the best site and size of DGs and protective devices in each load model including the constant, industrial, commercial and residential model. Secondly, the optimal site and size of devices in each load model is also evaluated in other load models. Thirdly, the results of technical and economic indices of system in different site and size of devices and load models are compared with each other. Finally, the best site and size of RDGs and protective devices are selected, and indices of system are calculated in the different load models.

5. NUMERICAL RESULTS

In this section, the proposed algorithm is applied on IEEE 69-bus distribution system. The single line diagram of the standard distribution system is shown in Fig. 2.

It is assumed that all buses and branches of distribution system have suitable conditions for placement the devices. Moreover, the WT and PV units are considered as a combination of DG and battery so that they can properly supply the required power during the day. For better evaluating the results, the maximum production level of both types of RDG is considered equal to 2500 KW. The amount of weighting factors and commercial information of grid and devices are presented in Table 1 [14, 15].

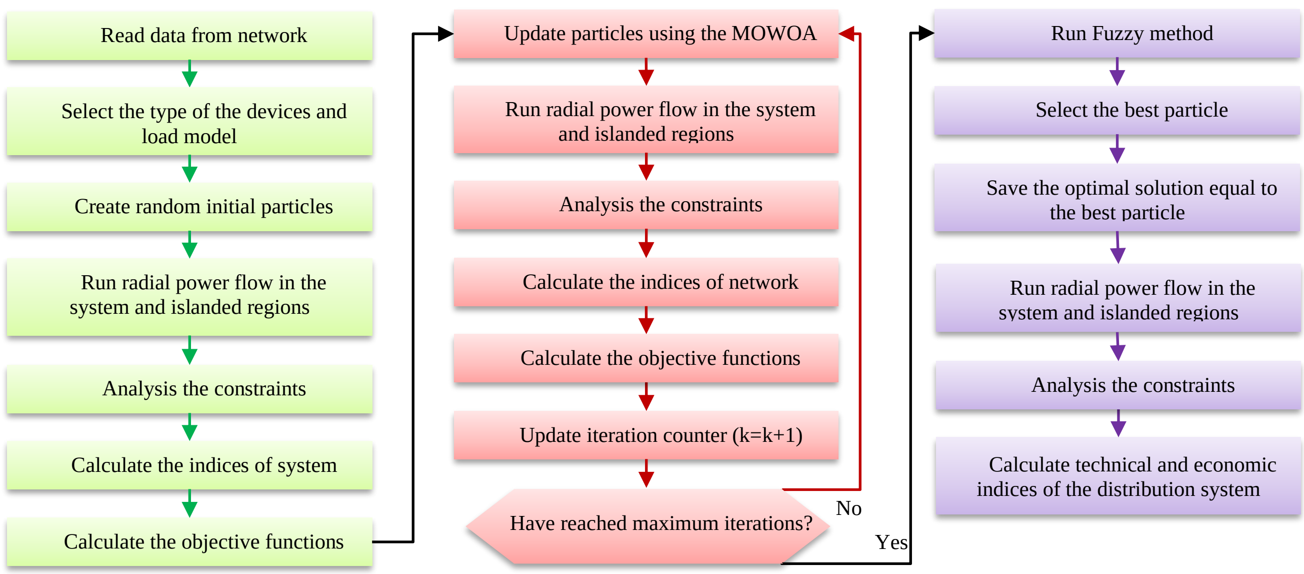

Figure 1. Flowchart of the proposed method for simultaneous placement of RDG and protective devices

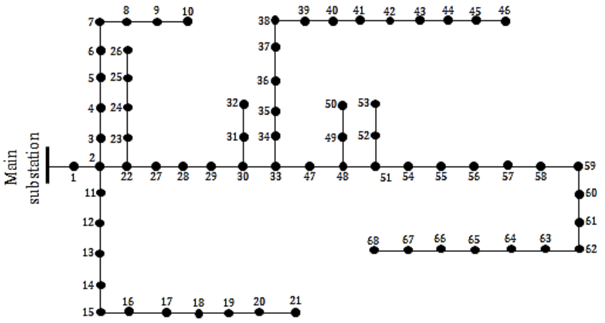

Figure 2. The 69-bus distribution system

Table 1. The required data for simulation

Parameter	Unit		Value
C_A	$\$/\mathrm{MW\,h}$		13.087
C_R	$\$/\mathrm{MVar\,h}$		4.153
C_{WT}	$\$/\mathrm{MW\,h}$		2.146
C_{PV}	$\$/\mathrm{MW\,h}$		5.168
$C_{breaker}$	$\$/\mathrm{year}$		2500
C_{relay}	$\$/\mathrm{year}$		6000
C_{fuse}	$\$/\mathrm{year}$		1500
C_p	-		0.60
C_q	-		0.40
C_{r1} , C_{r2}	-		0.33
C_{r3}	-		0.34
C_{MP}	Unit	Period	Value
	$\$/\mathrm{MWh}$	$23 < h < 7$	35
	$\$/\mathrm{MWh}$	$7 < h < 19$	49
	$\$/\mathrm{MWh}$	$19 < h < 23$	70

Table 2. The best site and size of devices in the system

Number	Type DG	DG		relay		Fuse	
		Position (No. bus)	Size (MW)	Position (No. branch)		Position (No. branch)	
1	PV	48	1.0437	36	48	14	23
		42	1.7874				
2	WT	42	1.0878	36	48	14	23
		57	0.43193				
3	PV	42	1.3193	36	48	14	23
	WT	56	0.5053				

Firstly, the simultaneous placement of DG and protective devices is done in 4 different load models; then the indices of the distribution system are calculated in each load model based on the obtained site and size of devices in different load models. Finally, a fuzzy method is applied again to compare the results (the obtained indices of the system in 16 situations). As a result, the best site and size of DG units and protective devices are calculated for all load models. Table 2 shows the best site and size of devices in the 69-bus grid.

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In this study, the total possible capacities of wind turbine and photovoltaic have been considered equal to 2.5 MW. The capacities of renewable DG units in Table 2 are the optimal size of WT and PV.

As mentioned above, the WT and PV units have been considered as a combination of DG and battery so that they can properly supply the required power during the day. Therefore, the renewable DG units can inject the demand power equal to the optimal size of DGs at the different hours of day.

According to the loads of system, the connected sub-branch to bus 33 is one of the critical and suitable sections for placement the considered devices. On the other hand, the site of protective devices is similar in all tests. It can be seen that the sites of DG units and relays are selected so that island region will be created when a fault occurs. So it can be said that the obtained site of DG units and the protective devices is appropriate based on the structure of system; of course, this conclusion is pondered based on the indices, in the following.

The loss indices of 69-bus system before and after placement of devices are presented in Table 3. The active and reactive power losses are reduced about 46-66 % in the different combinations of devices and load models. The reduction percentage of active and reactive loss is shown in Figure 3.

According to the results of active and reactive loss indices, the PV has better performance than the WT based; the difference of performances depends on the type of DG unit's output.

Table 3. Loss indices of 69-bus distribution system

No. Test	Load model	Loss index	
		Active loss (MW)	Reactive loss (Mvar)
Initial	Constant	0.2249	0.1021
	Industrial	0.1947	0.0887
	Commercial	0.1809	0.0831
	Residential	0.1664	0.0770
1	Constant	0.0740	0.0364
	Industrial	0.0693	0.0340
	Commercial	0.0729	0.0358
	Residential	0.0743	0.0365
2	Constant	0.1035	0.0499
	Industrial	0.0897	0.0435
	Commercial	0.0882	0.0431
	Residential	0.0874	0.0429
3	Constant	0.0825	0.0408
	Industrial	0.0722	0.0359
	Commercial	0.0729	0.0365
	Residential	0.0734	0.0368

As regards that the site of protective devices is similar in all Tests, so the protection areas of standard distribution system after placement of devices are shown in Figure 5. The amount of reliability indices before and after installation of devices in the distribution system has been given in Table 4. According to the results, the reliability of the 69-bus system is improved about 80 % after placement the devices by proposed method.

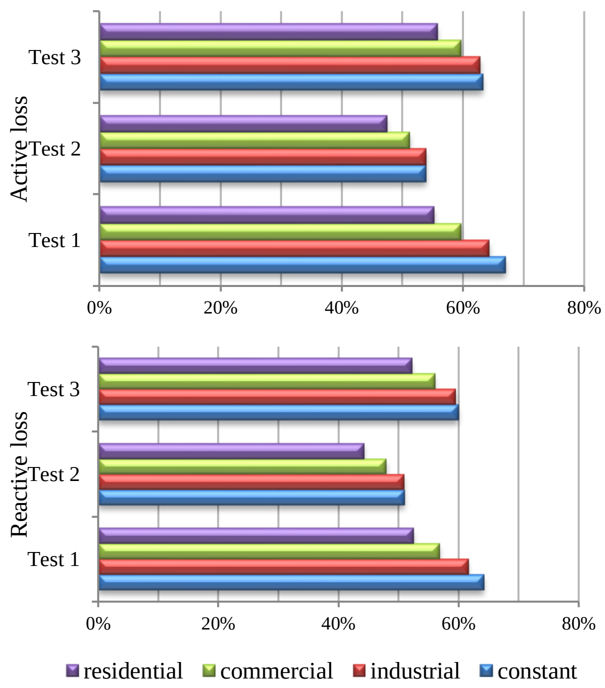

Figure 3. Improved percentage of loss indices after placement of devices

Table 4. Reliability indices of 69-bus distribution system

No. Test	Reliability index		
	SAIFI	SAIDI	AENS
Initial	2.234	1.8163	0.3997
1	0.5571	0.3812	0.0847
2	0.5044	0.3426	0.0774
3	0.4974	0.3392	0.0766

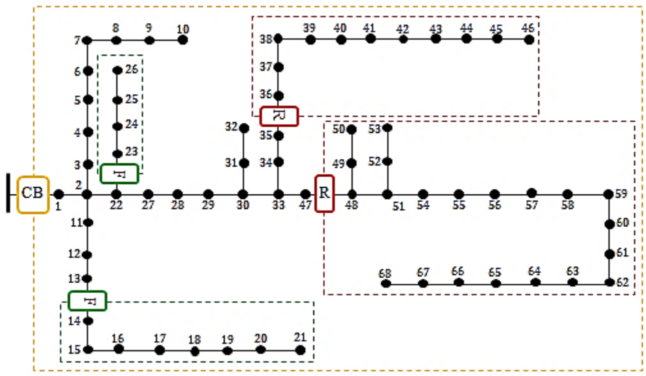

Figure 4. The protection areas after placement the protective devices (CB: Circuit Breaker, R: Relay, F: Fuse)

Based on the reliability index, the WT has better performance than PV. Figure 5 shows the variation of AENS of 69-bus system in the Test 3 during the 24-hour. As can be seen, the amount of reliability indices is variable based on the load of system. Therefore, the protection plans should be proper for different conditions of system.

Although costs of the renewable DGs and protective devices increase the amount of the considered profit function, this index is improved by reduction of losses, improvement of AENS and supply part of the required electricity demand of grid using the DG units. The economic indices of 69-bus distribution system before and after placement of devices have been presented in Table 5. According to the results, the distribution system company can earn about 1000 $ profit more than the initial states of the system in each day. Of course, the costs of RDGs have been considered for the first year so that these costs will decrease in the following years; therefore, the profit of distribution system will be increased subsequently.

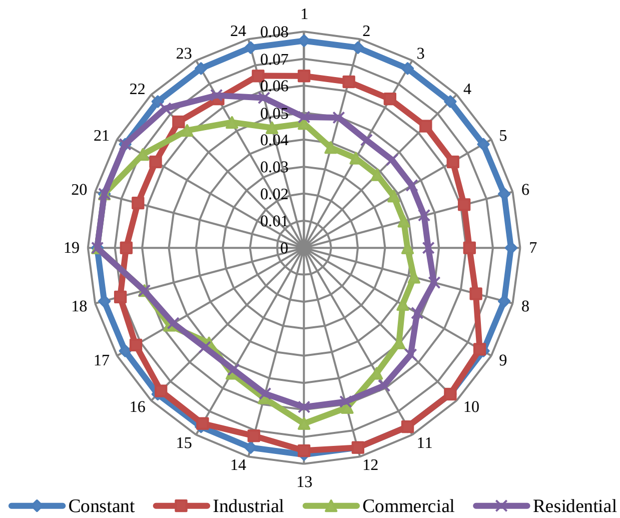

Figure 5. The variation of AENS of 69-bus distribution system in Test 3

Table 5. Economic indices of 69-bus system

No. Test	Load model	Economic index (during the one day)		
		Profit	Revenue	Cost
Initial	Constant	3028.36	4391.18	1362.82
	Industrial	2721.28	3918.79	1197.51
	Commercial	2211.03	3115.08	904.05
	Residential	2395.11	3377.75	982.64
1	Constant	4287.26	4893.60	606.34
	Industrial	3972.85	4435.73	462.88
	Commercial	3461.69	3655.24	193.55
	Residential	3640.76	3909.78	269.02
2	Constant	3905.03	4905.26	1000.23
	Industrial	3597.52	4446.13	848.61
	Commercial	3093.27	3663.65	570.38
	Residential	3270.73	3918.89	648.16
3	Constant	4019.18	4906.63	887.45
	Industrial	3708.37	4447.35	738.95
	Commercial	3200.44	3664.63	464.19
	Residential	3378.72	3919.96	541.24

6. CONCLUSION

The result shows that the proposed algorithm has practical performance in the various load models and affects the amount of loss index so that their changing becomes more linear during a change of load model. This substantial reduction of technical index causes that if load model of some buses changes to another model, grid efficiency will not change much. The site of DG units and protective devices are selected so that the least possible section of the system is removed from the grid when a fault occurs; therefore, the reliability of the grid improves considerably. It can be said that all kinds of renewable units have a useful effect on the amount of technical and economic indices; of course, PV approximately has a better performance than WT. The difference of performances depends on the type of output of DG units. Totally, the results indicate high performance the proposed method in improving the considered indices during the day in different load models and various combinations of devices.

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BIOGRAPHIES

Hossein Shayeghi received the B.S. and M.S.E. degrees in Electrical and Control Engineering in 1996 and 1998, respectively. He re ceived his Ph.D. degree in Electrical Engineering from Iran University of Science and Technology, Tehran, Iran in 2006. Currently, he is a full Professor in Technical Engineering Department of University of Mohaghegh Ardabili, Ardabil, Iran. His research interests are in the application of robust control, artificial intelligence and heuristic optimization methods to power system control design, operation and planning and power system restructuring. He has authored and co-authored of 10 books in Electrical Engineering area all in Farsi, one book and 10 book chapters in international publishers and more than 410 papers in international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of three international journals. He has served on several other committees and panels in governmental, industrial, and technical conferences. He was selected as distinguished researcher of the University of Mohaghegh Ardabili several times. In 2007, 2010, 2012 and 2017 he was also elected as distinguished researcher in engineering field in Ardabil province of Iran. Furthermore, he has been included in the Thomson Reuters' list of the top one percent of most-cited technical Engineering scientists in 2015 - 2019, respectively. Also, he is a member of Iranian Association of Electrical and Electronic Engineers (IAEEE) and Senior member of IEEE.

Masoud Alilou received the B.S. and M.S.E. degree in electrical engineering in 2012 and 2015, respectively. He is studying for a Ph.D. of electrical engineering at Urmia University, Urmia, Iran, from 2016. His research interests are in the application of distributed generation, smart grids, smart homes, demand side management, intelligent algorithms, compensators and reliability improvement in distribution systems. He has authored and co-authored of two books and five book chapters in Electrical Engineering area in Persian and English languages and about 30 papers in international journals and conference proceedings. Also, he collaborates with several international journals as reviewer boards and works as editorial committee of journal of operation and automation in power engineering. He is a member of the Iran energy association (IEA) and the Iranian wind energy association (IRWEA).

Naser Mahdavi Tabatabaei was born in Tehran, Iran, 1967. He received the B.Sc. and the M.Sc. degrees from University of Tabriz (Tabriz, Iran) and the Ph.D. degree from Iran University of Science and Technology (Tehran, Iran), all in Power Electrical Engineering, in 1989, 1992, and 1997, respectively. Currently, he is a Professor in International Organization of IOTPE (www.iotpe.com). He is also an academic member of Power Electrical Engineering at Seraj Higher Education Institute (Tabriz, Iran) and teaches power system analysis, power system operation, and reactive power control. He is the General Chair and Secretary of International Conference of ICTPE, Editor-in-Chief and member of Editorial Board of International Journal of IJTPE and Chairman of International Enterprise of IETPE, all supported by IOTPE. He has authored and co-authored of 10 books and book chapters in Electrical Engineering area in international publishers and more than 170 papers in international journals and conference proceedings. His research interests are in the area of power system analysis and control, power quality, energy management systems, microgrids and smart grids. He is a member of the Iranian Association of Electrical and Electronic Engineers (IAEEE).