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MULTI-OBJECTIVE ALLOCATING THE PROTECTIVE DEVICES BESIDE WIND TURBINE AND PHOTOVOLTAIC PANEL IN THE DISTRIBUTION SYSTEM

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Abstract- Although all parts of the power network have the important role in the efficiency of it, the distribution system has the highest effect on its performance and the satisfaction of consumers. Thus, the proper management of the distribution system has a high effect on the satisfaction of customers and the efficiency of electric power. For this reason, the multi-objective allocating of protective devices and renewable energy sources including wind turbine unit and the photovoltaic panel is studied in the distribution network with variable load pattern in this study. The considered load is dependent on a combination of different consumers' hourly load model and sensitive to voltage-frequency. The techno-economic objective functions of the problem consist of the power loss, the reliability index and the profit of company of distribution system. The multi-objective particle swarm optimization (MOPSO) algorithm is used to find the best Pareto front; then the analytical hierarchy process (AHP) method is utilized to extract one of the Pareto-optimal solutions as the best location and capacity of devices. Finally, for evaluating the performance of the proposed method, it is implemented on the IEEE standard 69-bus distribution system. The numerical results demonstrate the high performance of the proposed method in improving the technical and economic parameters of the distribution system.

Keywords: Protective Devices, Reliability, Wind Turbine, Photovoltaic Panel, Variable Load Pattern.

1. INTRODUCTION

Nowadays, distributed generation (DG) units are utilized as a practical technology for increasing the performance of the distribution system. Moreover, renewable technologies of DGs can decrease the environmental pollutions beside the other improvements. Selecting the best place and capacity for distributed generations according to indices of the distribution system is so important in the efficiency of these devices [1, 2]. On the other hand, the power network without protective devices such as relay, breaker and fuse is approximately impossible. So researchers and operators of power network use protective devices including breaker, relay and fuse for improving the system's reliability and stability. Indeed, renewable energy sources change the direction of power flow and fault current level of the network; so protection plans of the distribution system become unstable. Therefore, protective devices should be replaced in the system based on the location of DGs and new condition of the network [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. For example, in [4], a new method was proposed to select the optimal place and capacity of DGs. The modified Imperialistic Competitive Algorithm was utilized to optimize the active power losses and voltage stability margin that are considered as objective functions of the optimization.

An algorithm has been developed for the connection of multiple DGs in distribution networks according to the type of consumers [6]. The authors have considered a different type of DGs with various sizes and also considered different types of voltage-dependent load over several years. In another study, a methodology based on economic analysis was proposed for allocating a recloser and auto-sectionaliser in the best location in the distribution system with nonlinear load pattern [7]. Authors in Ref [10] proposed a method for optimizing the location of protective switches. The protective devices consist of a circuit breaker and recloser. Moreover, the distribution system was considered in the presence of DG units. The single-objective and multi-objective optimization were done in this paper. The objective functions are including the profit of the distribution system operator, SAIDI, SAIFI and system costs.

According to the recent papers, an important issue that arises in the simultaneous optimization of location and size of renewable energy sources and protective device is creation islanded area to reduce the ENS when the fault occurs. Hence, in this paper, stability and reliability of created sections 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. Devices of the Distribution System

In this paper, renewable distributed generation (RDG), which are in two type including wind turbine (WT) and photovoltaic (PV), are studied. On the other hand, three protective instruments including circuit breaker, relay and fuse are used for improving the reliability of distribution system. 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 location of multi-DG so that the maximum stability obtains when a fault has occurred.

The stability of a created section after a fault in upstream of the protective device is an important issue in the placement of the considered devices. So, in each step of the proposed method, the constraints of the system such as voltage limits are pondered in the overall network and islanded parts.

2.2. Non-Linear Load Model

The magnitude of the voltage at the buses and frequency of the system have an effect on the actual active and reactive loads of the grid. As mentioned above, the load pattern of the system is considered as a combination of hourly load model and sensitive load to voltage-frequency. The sensitive load to voltage and frequency of the system can be mathematically calculated by the Equations (1) and (2) [11].

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

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

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

3. OBJECTIVE FUNCTIONS

Simultaneous placement of RDG and protective devices is studied as a multi-objective optimization. These devices improve the efficiency of the system with better managing the technical and economic parameters of the network. So, in this section, the considered technical-economic index is presented completely. The loss, reliability and profit indices of the distribution system are merged in the considered index. Mathematically, the main objective function is formulated as:

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

3.1. Power Loss

The loss index is the sum of the active and reactive power loss of the network in Pu format. This index can be calculated by Equations (4)-(6)

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

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

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

3.2. Reliability of the System

Reliability of the power network 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 customer power outages and disruption in the performance of equipment [12].

Reliability indices of load points are considered for calculating the reliability index. Although various indices of load points have been proposed in previous articles, in this paper, three reliability indices including system average interruption frequency index (*SAIFI*), system average interruption duration index (*SAIDI*) and average energy not supplied index (*AENS*) are considered. Therefore, the reliability index is defined by (7).

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

The reliability indices of load points are calculated by Eqns. 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. Economic Profit of the System

In power grids similar to other industries, economic parameters are not an integral part of decision making in all operation and maintenance activities. For this reason, in this paper, a profit index is considered as an objective function by Eq. (11).

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

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

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

The initial revenue of Distribution Company is equal to obtained income from selling energy to consumers while the ultimate revenue is equal to the sum of the income from selling the energy to consumers and income from decreasing the energy not supplied of the grid. Mathematically, the initial and ultimate revenue of the system can be calculated by Equations (14) and (15), respectively.

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

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

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

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

$$Co_0 = \left[\sum_{h=1}^{24}\sum_{i=1}^{n_b} P_{lih} \times C_A \right] + \left[\sum_{h=1}^{24} P_{l_h} \times C_A \right] + \left[\sum_{h=1}^{24} Q_{l_h} \times C_R \right] \quad (17)$$

The ultimate cost of the distribution system after placement of devices is calculated by (18). In this function, the cost of produced power of DG units and cost of WT and PV and also the protective devices are added to the total cost of the system. Moreover, the distribution company has to buy lower power than initial case from transmission network because the part of demand is provided by WT and PV units.

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

4. OPTIMIZATION ALGORITHM

The combination of multi-objective particle swarm optimization (MOPSO) and analytical hierarchy process (AHP) method is used to simultaneously optimize the location and size of devices in the distribution system. For getting the optimal result; in the first step, objective functions including the loss, reliability and profit of Distribution Company are optimized by MOPSO. After applying the intelligent algorithm and improving the objective functions, the AHP method is utilized to select optimal location and size of devices from Pareto front.

Intelligent algorithms are typically inspired their performance from nature. MOPSO algorithm 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.

Table 1. Judgment matrix and Final weight of indices in the AHP

Index	I_R	I_L	I_P
I_R	1	2	3
I_L	0.5	1	1.5
I_P	0.33	0.66	1
Final Weight	0.5461	0.2731	0.1808

Each particle keeps track of its coordinates in the solution space which is 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. Totally, In MOPSO algorithm, the particles move around according their velocity and position. [13].

After applying the MOPSO, the AHP method is used to find the best compromise solution which represents the best amount of each objective function. The AHP is a methodology for finding the optimal solution in the issues in which user is faced with several conflicting criteria and should select the most appropriate issue between the various schemes proposed.

Due to the importance of consumers and to improve the number of subscribers who are satisfied with received service from the network, reliability index has the highest weight. Loss index has a lower weight than the reliability index. The considered economic index has less weight than technical indicators. To obtain the final weight of criteria, the arithmetic mean method is used. Consequently, the defined criteria of judgmental matrix and final weight are presented in Table 1 [14].

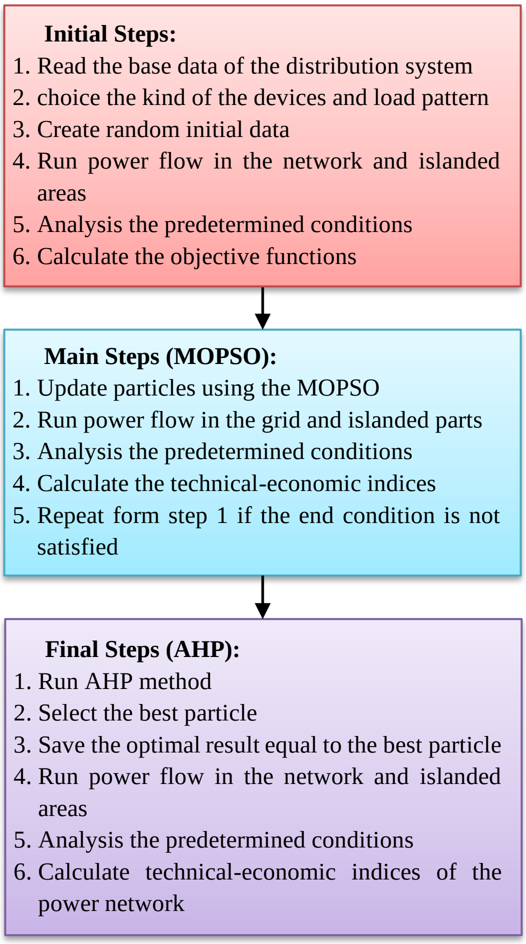

Figure 1. Flowchart of the proposed method for simultaneous allocating of WT, PV, circuit breaker, relay and fuse

Using the mentioned method, the complete algorithm for simultaneous optimizing of location and size of WT, PV and protective device in the distribution network is demonstrated in Figure 1.

As regards that non-linear load pattern is studied in this paper; in the first step, the optimization method is utilized to find the best place and capacity of the considered devices in each load type including the constant, industrial, commercial and residential model. In the second step, the optimal place and capacity of devices in each load pattern is also pondered in other load ones. In the third step, the numerical results of technical-economic indices of the distribution system in various places and capacities of devices and load patterns are compared with each other. Ultimately, the best place and capacity of RDGs and protective devices are selected, and indices of the system are calculated in the different load models.

5. NUMERICAL RESULTS

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

It is assumed that all buses and branches of distribution network have a suitable situation for allocating the devices. Moreover, renewable energy sources are considered as a combination of DG and battery so that they can properly supply the required power at all hours of the day. For better evaluating the numerical results, the maximum production capacity of both types of RDG is equal to 2500 KW. The amount of weighting factors and economic information of system and instruments are presented in Table 2 [15, 16].

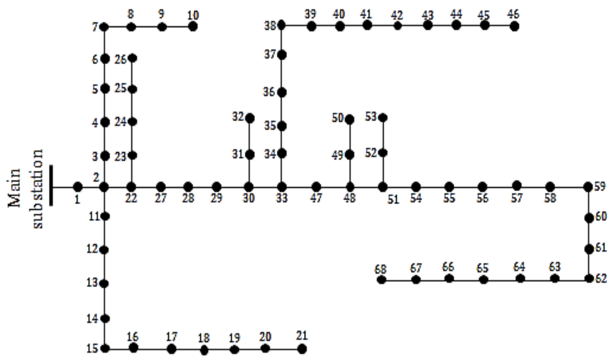

Figure 2. The 69-bus distribution system

Table 2. The required parameters for the proposed algorithm

<table>
<tr><td>Parameter</td><td>Unit</td><td>Value</td><td colspan="2">Parameter</td><td>Unit</td><td>Value</td></tr>
<tr><td>C_A</td><td>$/MWh</td><td>13.087</td><td colspan="2">C_q</td><td>-</td><td>0.40</td></tr>
<tr><td>C_R</td><td>$/Mvarh</td><td>4.153</td><td colspan="2">C_{r1} , C_{r2}</td><td>-</td><td>0.33</td></tr>
<tr><td>C_{WT}</td><td>$/MWh</td><td>2.146</td><td colspan="2">C_{r3}</td><td>-</td><td>0.34</td></tr>
<tr><td>C_{PV}</td><td>$/MWh</td><td>5.168</td><td></td><td>Unit</td><td>Period</td><td>Value</td></tr>
<tr><td>$C_{breaker}$</td><td>$/year</td><td>2500</td><td rowspan="3">C_{MP}</td><td>$/MWh</td><td>$23<h<7$</td><td>35</td></tr>
<tr><td>C_{relay}</td><td>$/year</td><td>6000</td><td>$/MWh</td><td>$7<h<19$</td><td>49</td></tr>
<tr><td>C_{fuse}</td><td>$/year</td><td>1500</td><td>$/MWh</td><td>$19<h<23$</td><td>70</td></tr>
</table>

In the first step, simultaneous allocating of WT, PV, circuit breaker, relay and fuse is done in 4 various load patterns. Finally, the AHP is applied again to ponder the technical and economic indices (the obtained indices of the system in 16 situations). As a result, the best place and capacity of RDGs and protective devices are calculated for all load types. Table 3 demonstrates the best places and capacity of devices in the 69-bus network.

Table 3. The optimal place and capacity of devices

Number	Type DG	DG Position (No. bus)	DG Capacity (MW)	Relay Position (No. branch)		Fuse 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				

As mentioned above, renewable energy sources are considered as a combination of DG and energy storage so that they can properly supply the required power when the power network needs their energy. Hence, WT and PV units can properly inject the demanded power equal to the optimal size of DGs at various hours of the day.

As regards to loads of the system, the connected sub-branch to bus 33 is one of the critical and suitable sections for allocating the considered devices. On the other hand, the place of protective devices is the same in all tests. It can be seen that the place of renewable sources and relays are fined in order to improve the stability of islanded region when a fault occurs. Therefore, it can be said that the obtained place of WT, PV and the protective devices is appropriate based on the structure of system; of course, this claim is pondered based on the indices, in the following.

Table 4. The loss indices of the 69-bus distribution system

No. Test	Load model	Loss index: Active loss (MW)	Loss index: 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

The loss indices of the standard system before and after allocating of devices are shown in Table 4. The active and reactive power losses are decreased by 46-66 % in the different combinations of devices and load patterns. The reduction percentage of active and reactive loss is demonstrated in Figure 3. As regards the results of active and reactive loss indices, the PV panel has better performance than the WT unit; the difference of performances depends on the output power of renewable sources.

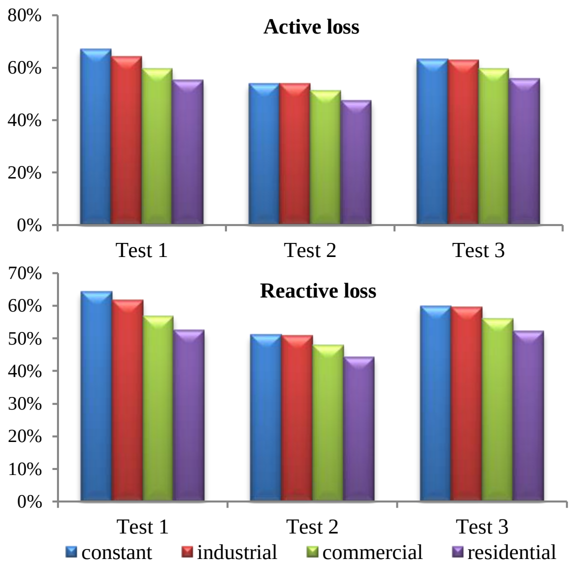

Figure 3. Improved percentage of loss indices after placement of devices

Figure 5 shows the created protections regions after allocating the circuit breaker, relays and fuses in the distribution system. it is worth mentioning that the place of protective devices is the same in all tests. The amount of reliability indices before and after the installation of devices in the distribution system is presented in Table 5. As can be seen in this table, the reliability index of the 69-bus system is increased more than 80% after utilizing the proposed method.

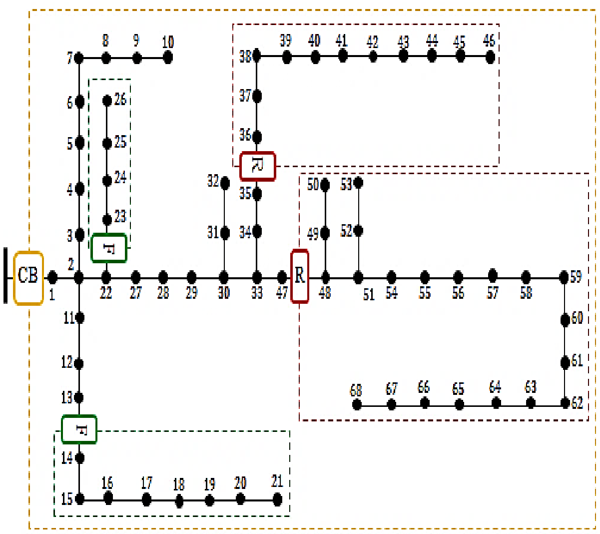

Figure 4. The protection areas after placement the protective devices (CB: Circuit Breaker, R: Relay, F: Fuse)

Table 5. The 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

Table 6. The economic indices of 69-bus system

No. Test	Load type	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

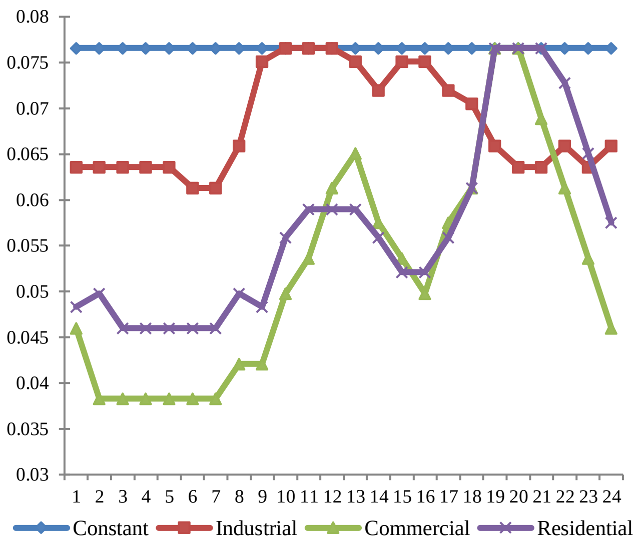

Figure 5. The variation of AENS of 69-bus distribution system in Test 3

Based on the reliability index, the WT has better performance than PV. Figure 5 shows the variation of AENS of 69-bus system in Test 3 in 24-hour. As can be seen, the amount of these indices is variable based on a load of system. So, 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 network using the DG units. The economic indices of the IEEE distribution system before and after the placement of devices are given in Table 6. According to the numerical data, the distribution company of power network earns about 1000$ profit more than the base case of the system at each day. Of course, the costs of RDGs are considered for the first year. In other words, these costs will decrease in the following years; therefore, the profit of Distribution Company will be increased subsequently.

6. CONCLUSION

In this paper, simultaneous optimizing of place and capacity of renewable DG units and protective devices was studied in the distribution system in the presence of variable load pattern. The multi-objective particle swarm optimization algorithm was used to find the best Pareto front; then the analytical hierarchy process method was utilized to extract one of the Pareto-optimal solutions as the best location and capacity of devices. The combination of technical and economic indices of the distribution system was considered as the objective functions of the proposed method.

The results of numerical optimization show that the proposed algorithm had practical performance in the various load patterns. Moreover, the proposed method affects the amount of loss index so that their variation becomes more linear during a change of load pattern. The location of renewable energy sources and protective devices were optimized so that the least possible section of the system is removed when faults occur in the grid. Based on stability, the results demonstrate that the reliability of the network improves considerably. In total, it can be said that all kinds of renewable units have a practical effect on the amount of technical and economic indices. PV panel approximately has a better performance than the WT unit. The difference in performances depends on the type of output of DGs. Therefore, results indicate high efficiency of proposed algorithm in improving the considered indices during the day in various load patterns and combinations of devices.

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BIOGRAPHIES

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