Optimal Allocation of Renewable DG and Capacitor for Improving Technical and Economic Indices in Real Distribution System with Nonlinear Load Model

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In this article, simultaneous placement and sizing of renewable distributed generation (DG) and capacitor bank is done in the distribution system with load model sensitive to voltage and frequency. Moreover, the various Customers' daily load patterns are considered for evaluating the proposed algorithm in more realistic conditions. It is shown that the load model and time of day can significantly affect the performance of Renewable DG and capacitor bank in the distribution system. Wind turbine and photovoltaic are considered as renewable DG units. For better evaluating the proposed method, two situations are assumed for renewable DG units; firstly it is considered that their initial conditions are available at all times but in the next step, the DG units are evaluated in the variable weather condition during the 24-hour. The proposed objective functions are the active/reactive power loss, the voltage stability and the profit of company of distribution system. The combination of multi-objective whale optimization algorithm and analytical hierarchy process is used for optimizing the objective functions and selecting the optimal location and size of DG units and capacitor banks. The proposed algorithm is evaluated using the IEEE 69-bus distribution system and the actual 101-bus distribution network in Khoy-Iran. The results indicate the high performance of the proposed method in improving the technical and economic indices of the standard and actual distribution systems.

keywords: *Analytical hierarchy process, Capacitor bank, Multi-objective whale optimization algorithm, Renewable DG, Nonlinear load model.*

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NOMENCLATURE

The main notation needed in this paper is provided in this section for quick reference. Other symbols are defined as required throughout the text.

ρ Air density (kg/m^3)

V_w Wind speed (m/s)

A_{pv} The area of solar panel (m^2)

μ Solar irradiance (w/m^2)

P_{l_i} Active power at actual voltage

Q_{l_i} Reactive power at actual voltage

V_i Voltage of bus i (pu)

f Actual frequency

k_{pv}, k_{qv} Voltage slop for active and reactive power

I_V Voltage Index (voltage stability index)

P_l Active power loss after installation (MW)

Q_l Reactive power loss after installation (Mvar)

R_i Resistance of branch i

I_{hi} Current of branch i at h^{th} hour

C_p, Q_l Penalty coefficient at loss index equation

Vs_0 Voltage stability before installation

Re Ultimate revenue of distribution system ($)

Co Ultimate cost of distribution system ($)

n_b Number of buses

Q_{l_h} Reactive power loss during the $h^t h$ hour

C_R Reactive power purchased price ($/Kw)

C_{C_i} Cost of capacitor ($)

$A_w t$ Swept area of wind turbine (m^2)

C_p Power coefficient (Albert Betz limit)

β The efficiency of solar panel (%)

$P_{l_0 i}$ Active power at nominal voltage

$Q_{l_0 i}$ Reactive power at nominal voltage

V_b Nominal voltage ($V_b = 1pu$)

f_0 Nominal frequency

$k_{\rho f}$,$k_{\rho f}$ Frequency slop for active and reactive power

I_L Loss Index

I_B Benefit Index (profit of distribution company)

P_{l0} Active power loss before installation (MW)

Q_{l0} Reactive power loss before installation (Mvar)

X_i Reactance of branch i

N_{br} Branch number

Vs Voltage stability after installation

Re_0 Initial revenue from distribution system ($)

Co_0 Initial cost of distribution system ($)

$C_M R$ Energy market price ($/(Kw h))

P_{l_h} Active power loss during the h^{th} hour

C_A Active power purchased price ($/Kw)

C_{DG_i} Cost of DG ($/Kw)

$tech$ Type of renewable DG technology

1. INTRODUCTION

Distributed generation (DG) and capacitor bank have a significant impact on the performance of the distribution system when they are operated in the best location with optimal capacity. In the last decades, DG units have been introduced and utilized as the useful devices for producing the electrical energy in the distribution system. One of the important subjects in using DG units is the optimization of location and capacity of them according to distribution system's situation. Optimal allocation of DG improves technical, economic and environmental parameters of the network. Nowadays, various types of technologies are utilized to produce electrical energy in DG units; totally, these technologies can be divided into renewable and nonrenewable groups [1,2].

The suitable level of reactive power is one of the most important criteria of stability of distribution system. The operator of System always controls the amount of reactive power and compensates reactive power in a necessary condition. The capacitor bank is a common and cheap way to compensate the reactive power [3].

Optimization of location and size of DG and capacitor bank is useful for increasing the distribution system's efficiency. So power system researchers and planners have to find the proper way for selecting the best location and size of considered devices in the distribution system. A total review of accomplished researches has been done. The articles about DG and capacitor bank can be divided into three categories; they are explained in the following.

A) Optimal DG locating and sizing: In this group, articles are located that the location and capacity of DG technologies are optimized based on various indices of distribution system [4–6]. The authors in Ref [4], a new way based on Imperialistic Competitive Algorithm proposed to find the best location and size of DG units. PSO based technique has been suggested in Ref [5] to solve the optimal placement of different types of DGs for minimizing the power loss. In another study, an algorithm has been developed for the connection of multiple DGs in distribution networks according to the type of consumers [6].

B) Optimal capacitor locating and sizing: Articles that the location and capacity of capacitor banks are studied in the distribution system, are located in this category [7–9]. In the Ref [7], a new Shark Smell Optimization algorithm has been used to find optimal location and size of capacitor banks. The authors in Ref [8] utilized NSGA-II algorithm to find the optimal location and size of a capacitor in distribution system with nonlinear load model. Karimi and Dashti presented a comprehensive objective function for capacitor placement in distribution networks [9].

C) Simultaneous locating and sizing of DG and capacitor: The last category is related to articles that simultaneous allocation of DG and capacitor is done in the distribution system [10–12]. Rahmani applied GA for simultaneous placement of DG and capacitor bank with considering minimum total cost over the planning period in the distribution network [10]. The authors in Ref [11] utilized intersect mutation differential evolution algorithm to simultaneously find the best location and size of DG and capacitor bank in the distribution system. In the Ref [12], a hybrid method based on an imperialist competitive algorithm and the genetic algorithm has been proposed for optimal placement and sizing of DG and capacitor.

Therefore, some studies have been done in the field of DG and capacitor bank. In this article, for completing the previous studies, the hourly variation of different loads of system and produced power of renewable DG units is considered during the simultaneous optimization of location and size of DG and capacitor bank. The results show the considerable effect of load model and weather conditions on the efficiency of distribution system in the presence of DG and capacitor bank. Consequently, in this paper, a new method based on multi-objective whale optimization algorithm is proposed to find the best location and size of renewable DG units (wind turbine and photovoltaic) and capacitor banks in the distribution network. The load model of the network is considered sensitive to voltage and frequency. Of course, the various customers' daily load patterns are also utilized for evaluating the proposed algorithm in the more realistic condition. The considered objective functions are the power loss index (the combination of active and reactive loss), the voltage stability index and the economic index (the profit of company of distribution system). After multi-objective optimization of the objective functions, the analytical hierarchy process is used for selecting the optimal location and size of DGs and capacitor banks from the Pareto fronts. The proposed algorithm is evaluated using the IEEE 69-bus distribution system and the actual 101-bus distribution system in Khoy-Iran.

The remainder of this paper is as follows; in the Section 2, the studied issue and its formulation are described. In Section 3, the objective functions of optimization are explained. In Section 4, the multi-objective optimization algorithm is proposed. In the Section 5, the results of computer simulations are presented in using the 69-bus distribution system and actual 101-bus distribution system in Khoy-Iran. Section 6 is conclusion.

2. PROBLEM FORMULATION

In this study, simultaneous placement of renewable distributed generation (RDG) and capacitor is done in the distribution system by considering nonlinear load model. The model of two considered type of RDG technologies and also the combination model of network load are explained as follow:

A. Formulation of RDG units

Renewable DG units are the energy resources which produce power with minimum greenhouse gas emissions. A brief description of considered RDG technologies (wind turbine and photovoltaic) and their model in power flow equations are explained as follow [1,2]:

Wind turbine: the output power of wind turbine has direct communication with wind speed and swept area of the turbine; moreover, the other parameters such as air density and power coefficient affect the power of wind turbine. Therefore, the active power of wind turbine can be evaluated by (1) [1].

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

In the Eq. (1), the parameters of ρ, A_{wt} and C_p are the constant data that are related to the technology of wind turbine while the wind speed (v_w) is variable based on the weather condition and time of day. The wind turbine can produce electrical energy when the wind speed is more than the cut-in speed of the wind turbine [1].

The asynchronous (induction) generator is typically used in the wind turbines. The wind turbine consumes reactive power to produce active power. So, wind turbine is modeled as a PQ bus model with variable reactive power in the load flow equations. The consumed reactive power of wind turbine in simple form is given in (2) [2].

$$Q_{WT} = -\left(0.5 + 0.04{P_{WT}}^2\right) \tag{2}$$

Photovoltaic: the suitable level of solar irradiance is the first requirement of photovoltaic. Totally, the output power of each photovoltaic panel depends on the amount of solar irradiance, the area and efficiency of the solar panel. Mathematically, the active power of photovoltaic can be calculated by (3) [1].

$$P_{PV} = A_{pv}\beta\mu \tag{3}$$

In the Eq. (3), the parameters of A_{pv} and β are the fixed information of solar panel that are related its technology while the solar irradiance (β) is variable based on the weather condition and time of day. According to this equation and the variation of solar irradiance, the technology of photovoltaic can be used between the sunrise and the sunset; therefore, the limitation of using the photovoltaic should be considered in planning the network exploitation [2].

This type of DG produces only active power. So, in the load flow analysis, photovoltaic is modeled as a P bus model [1].

B. Formulation of load model

The amounts of active and reactive loads at buses are usually assumed as constant in conventional load flow analysis in the studies of distribution system. The magnitude of voltage at the buses and frequency of the system affect the actual active and reactive loads of the system. Moreover, the amount of consumption is also variable based on the type of the customer during the 24-hour. consequently, with assumed constant load model can't reach the optimum results. Hence, in this study, the non-linear load model is considered for testing the proposed method in the more realistic condition of operating in the distribution system. The load model of the system is considered as a combination of daily load pattern and sensitive to voltage-frequency.

The practical voltage-frequency dependent load model can be mathematically expressed as the (4) and (5) [13].

$$P_{l\_i} = P_{l\_0i}\left(\frac{V_i}{V_b}\right)^{k_{pv}}\left[1 + k_{pf}\left(f - f_0\right)\right] \tag{4}$$

$$Q_{l\_i} = Q_{l\_0i}\left(\frac{V_i}{V_b}\right)^{k_{qv}}\left[1 + k_{qf}\left(f - f_0\right)\right] \tag{5}$$

In this paper, the load model of the network is also changed based on customers' daily load patterns. Therefore, the different patterns of consumption are considered for constant, residential, industrial and commercial customers of distribution system [14].

3. OBJECTIVE FUNCTION

DG units and capacitor bank increase the performance of distribution system with improving the technical indices of network. One of the most important indices of distribution system is power loss index because the most part of the loss of power network is done in the distribution system. Another important technical index of distribution system is the index of voltage stability; in the other words, the voltage of buses should be in the suitable and allowable level for optimal operating the distribution system. Consequently, the loss and voltage 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 location and size of RDG and capacitor bank.

Mathematically, the main objective function including of loss, voltage stability and benefit indices is formulated as:

$$objective function : \min\{I_L, I_V\}, \max\{I_B\} \tag{6}$$

A. Loss index

Loss index as the most important technical index is defined with combination of active and reactive power losses as:

$$I_L = C_p L_A + C_q L_R \tag{7}$$

$$L_A = P_l / P_{l0} \tag{8}$$

$$L_R = Q_l / Q_{l0} \tag{9}$$

Where

$$ActiveLoss = \max_{h=1}^{24}\left\{\sum_{i=1}^{N_{br}} R_i |I_{hi}|^2\right\} \tag{10}$$

$$ReactiveLoss = \max_{h=1}^{24}\left\{\sum_{i=1}^{N_{br}} X_i |I_{hi}|^2\right\} \tag{11}$$

B. Voltage index

In this study, the voltage stability is considered as the voltage index. Mathematically, this index can be calculated by (12).

$$I_V = Vs/Vs_0 \quad (12)$$

$$Vs = \max_{h=1}^{24}\{1 - Voltage\_Stability_h\} \quad (13)$$

$$Vs_0 = \max_{h=1}^{24}\{1 - Initial\_Voltage\_Stability_h\} \quad (14)$$

Voltage stability is the ability of the system to maintain the voltage in an acceptable level. In the other words, when a load of the system is increased from nominal load, the delivered active power to the load by the system will be increased too; therefore both power and voltage remain in the controllable condition. Equation (15) represents the voltage stability index [15].

$$VS_{m_2} = |V_{m_1}|^4 - \left\{4[P_{m_2}X_i - Q_{m_2}R_i]^2\right\} - \left\{4|V_{m_1}|^2\,[P_{m_2}R_i + Q_{m_2}X_i]\right\} \quad (15)$$

C. Benefit index

Economic issues are an integral part of decision making in all daily activities; the power grid also is not exempt from this. So beside technical objectives, economic issues should be considered in developing the distribution network. For this reason, the benefit index is defined according to (16).

$$I_B = (Profit - Initial\_profit)\,/\,Initial\_profit \quad (16)$$

$$Profit = Re - Co \quad (17)$$

$$Initial\_profit = Re_0 - Co_0 \quad (18)$$

The initial and ultimate revenues of Distribution Company are equal to obtained income from selling energy to customers (Eq. 19).

$$Re = Re_0 = \sum_{(i=1)}^{(n_b)} P_{(l-i)} \times C_{MR} \times 24 \quad (19)$$

The costs of the distribution system are variable before and after placement of devices. The Distribution Company purchases its power demand from transmission grid. A portion of this power is consumed by customers of the distribution system and another part of that is spent in line and equipment loss. So the initial cost of the distribution system is formed base on the cost of power demand and the cost of losses. The initial cost of the distribution system is calculated by (20).

$$Co_0 = [\sum_{(i=1)}^{(n_b)} P_{(l-i)} \times C_A \times 24] + [\sum_{(h=1)}^{24} P_{(l_h)} \times C_A] + [\sum_{(h=1)}^{24} Q_{(l_h)} \times C_R] \quad (20)$$

The ultimate cost of distribution system is calculated by (21). In this function, the costs of RDG and capacitor bank are added to the total cost of the system. Of course, the Distribution Company purchases lower power from transmission network than initial state because the part of demand is provided by DG units.

$$Co = \left[\left(\sum_{i=1}^{n_b} P_{l\_i} - \sum_{i=tech}\sum_{j=1}^{n_{DG}} P_{DG_{ij}}\right) \times C_A \times 24\right] + \left[\sum_{h=1}^{24} P_{l_h} \times C_A\right] + \left[\sum_{h=1}^{24} Q_{l_h} \times C_R\right] + \left[\sum_{i=tech}\sum_{j=1}^{n_{DG\_i}} P_{DG_{ij}} C_{DG_i}\right] + \left[\sum_{i=1}^{n_c} Q_{C_i} \times C_{C_i}\right] \quad (21)$$

4. MULTI-OBJECTIVE OPTIMIZATION ALGORITHM

The combination of multi-objective whale optimization algorithm (MOWOA) and analytical hierarchy process (AHP) is used to simultaneously optimize the location and size of devices in distribution system. To achieve the best result; in the first step, objective functions including the loss, voltage and profit of distribution company are optimized by MOWOA. After applying the intelligent algorithm and improving the objective functions, the AHP method is utilized to select the optimal location and size of devices from Pareto front. In the following, the MOWOA and AHP method are explained.

A. Multi-objective WOA

Intelligent algorithms are typically inspired their performance from nature; the whale optimization algorithm (WOA) which is inspired from the hunting behavior of whales. The hunting behavior of humpback whale is called bubble-net feeding method. Humpback whales prefer to hunt a school of krill or fishes close to the surface. In the WOA, particles update based on 'Shrinking encircling mechanism' and 'Spiral updating position' during the optimization [16].

Shrinking encircling mechanism: Humpback whales can recognize the location of prey and encircle them. In the WOA, the current best candidate solution is assumed as the target prey. Then, the other search agents will try to update their positions towards the best search agent. This behavior is represented by (22) [16].

$$\vec{X}(t+1) = \vec{X}^*(t) - \vec{A}.\vec{D} \quad (22)$$

Spiral updating position: in the WOA, after calculating the distance between the whale located at (X, Y) and prey located at (X^*, Y^*), a spiral equation is created between the position of whale and prey to mimic the helix-shaped movement of humpback whales (Equations (23) and (24)) [16].

$$\vec{X}(t+1) = \vec{D}.e^{bl}.cos(2\pi l) + \vec{X}^*(t) \quad (23)$$

$$\vec{D} = |\vec{X}^*(t) - \vec{X}(t)| \quad (24)$$

In the WOA, it is assumed that there is a probability of 50 percent to choose between either the shrinking encircling mechanism or the spiral model to update the position of whales during optimization [16]. It is worth mentioning here that the used method in reference [17] is used to utilize the WOA as multi-objective.

B. Analytical hierarchy process

After obtaining the Pareto optimal set solution by multi-objective optimization, the Analytical Hierarchy Process method is utilized based on the importance of various indices of the distribution system to find the best result of the optimization [18].

Due to the importance of distribution system stability, voltage index has the highest weight whereas loss index as another technical index has the lower weight than voltage index; and finally, the profit of Distribution Company has the least weight. Therefore, the judgmental matrix is created and the final weight of indices is calculated. Finally, Eq. (25) is used to choose the best result from Pareto front.

$$final_F = W_L \times loss + W_V \times Voltage\_stability + W_P \times Profit \quad (25)$$

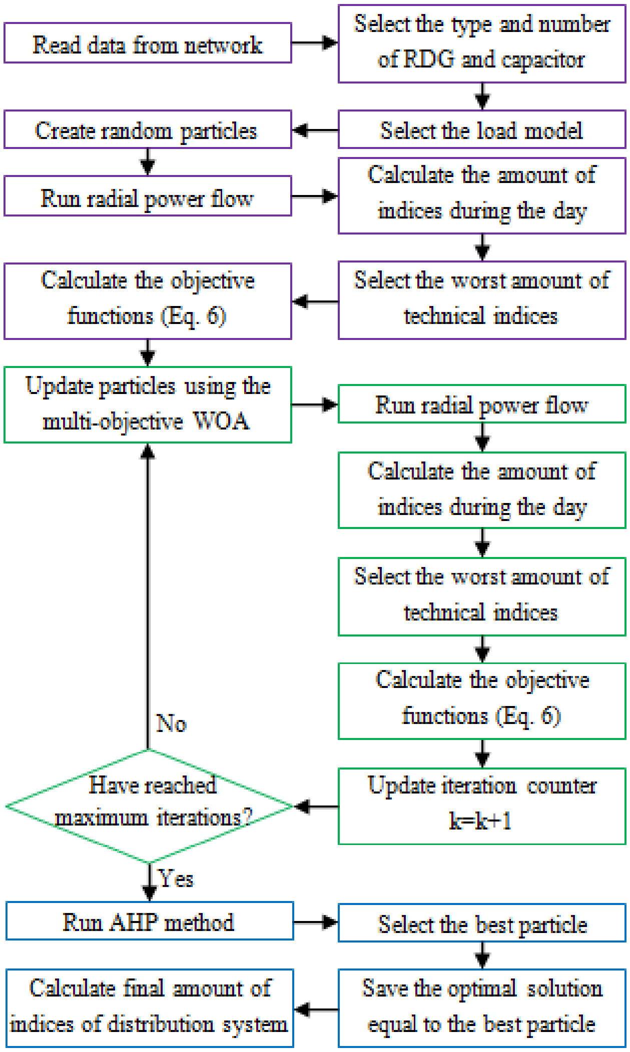

Fig. 1. Flowchart of the proposed method

According to the mentioned method, the complete algorithm for simultaneous placement of renewable DG and capacitor bank in the distribution system is shown in Fig. 1.

As regards that nonlinear load model is considered in this study; firstly, the proposed method is used to select the best location and size of RDGs and capacitor banks in each load model including constant, industrial, commercial and residential model with considering customers' daily load patterns and load model sensitive to voltage-frequency. Secondly, the optimal location and size of devices in each load model is also evaluated in other load models; for example, the obtained location and size of devices in constant load model is evaluated in residential, commercial and industrial load models, too. Thirdly, the results of systems' technical and economic indices in the different location and size of devices and load models are compared with each other. Finally, the best location and size of RDGs and capacitor banks are selected and systems' indices are calculated in the different load models.

5. NUMERICAL RESULTS

In this section, the proposed algorithm for simultaneous allocation of renewable DG and capacitor bank is applied on the IEEE

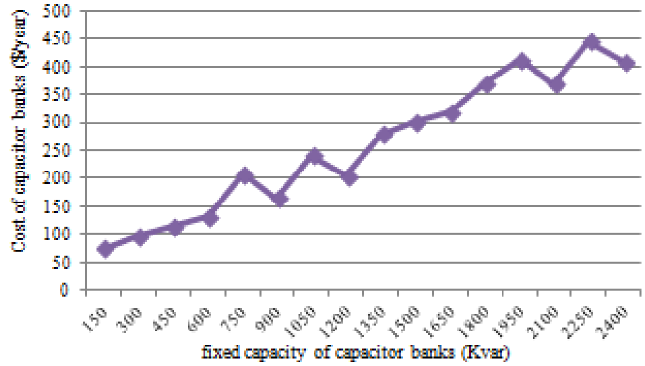

Fig. 2. Capacity and yearly cost of fixed capacity bank [18]

Table 1. Commercial information of network and devices

Parameter	Unit	Value
C_A	$/MW h	14
C_R	$/MVar h	4
$C_{windturbine}$	$/MW h	4
$C_{photovoltaic}$	$/MW h	3
Market Price		
Load level	Period	C_{MP} ($/MWh)
Light	$(23 < h < 7)$	35
Medium	$(7 < h < 19)$	49
Peak	$(19 < h < 23)$	70

Table 2. Load types and values of dependence coefficients [13]

Type of Load	k_{pv}	k_{qv}	k_{pf}	k_{qf}
Constant	0	0	0	0
Residential	1.7	2.6	1.0	-1.7
Industrial	0.1	0.6	2.6	1.6
Commercial	0.6	2.5	1.5	-1.1

69-bus radial distribution system and the actual 101-bus distribution system in Khoy-Iran. For better evaluating the results, the maximum produced level of both types of RDG units is considered equal to 2500 KW. The capacity and yearly fixed cost of capacitor bank are shown in Fig 2. The Commercial information is tabulated in Table 1.

In this paper, the non-linear load model is considered. The values of coefficients of different types of load model are shown in Table 2 [13]. The nominal and network frequencies are considered 1 and 0.98 Pu, respectively. Moreover, Table 4 shows the average hourly demand data in Pu for various types of customers in central Iran from 2011/2/20 to 2011/3/20 [14]. The judgmental matrix and final weights of AHP method are also presented in Table ??.

The simulations are done in two steps. Firstly, it is assumed that all buses of distribution system have suitable weather conditions for allocating of wind turbine and photovoltaic. Then

Table 3. Daily load demand of each type of load (Pu) [14]

Type of load	Hours							
	1	2	3	4	5	6	7	8
Constant	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Residential	0.63	0.65	0.60	0.60	0.60	0.60	0.60	0.65
Industrial	0.83	0.83	0.83	0.83	0.83	0.80	0.80	0.86
Commercial	0.60	0.50	0.50	0.50	0.50	0.50	0.50	0.55
	9	10	11	12	13	14	15	16
Constant	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Residential	0.63	0.73	0.77	0.77	0.77	0.73	0.68	0.68
Industrial	0.98	1.00	1.00	1.00	0.98	0.94	0.98	0.98
Commercial	0.55	0.65	0.70	0.80	0.85	0.75	0.70	0.65
	17	18	19	20	21	22	23	24
Constant	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Residential	0.73	0.80	1.00	1.00	1.00	0.95	0.85	0.75
Industrial	0.94	0.92	0.86	0.83	0.83	0.86	0.83	0.86
Commercial	0.75	0.80	1.00	1.00	0.90	0.80	0.70	0.60

Table 4. Judgment matrix and final weight of indices in the AHP

Judgment Matrix			
Index	Voltage	Loss	Profit
Voltage	1	2	3
Loss	0.5	1	1.5
Profit	0.33	0.66	1
Final Weight	0.5461	0.2731	0.1808

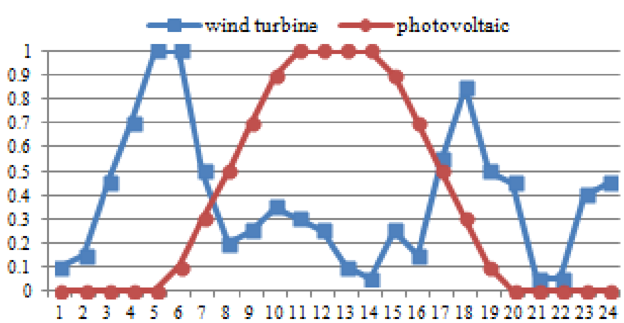

Fig. 3. The variation of production of wind turbine and photovoltaic (Pu)

according to the obtained location and size of RDG units and capacitor banks in the first step, the indices of network are evaluated based on the changes of the weather and the amount of produced energy of RDG units during the 24-hour. The variations of produced energy of RDGs in Pu are shown in Fig. 3.

A. 69-Bus distribution system

The proposed algorithm is applied to the 69-bus test system (Fig. 4) to determine the optimal location and size of devices. According to the above descriptions, in the first step, simultaneous

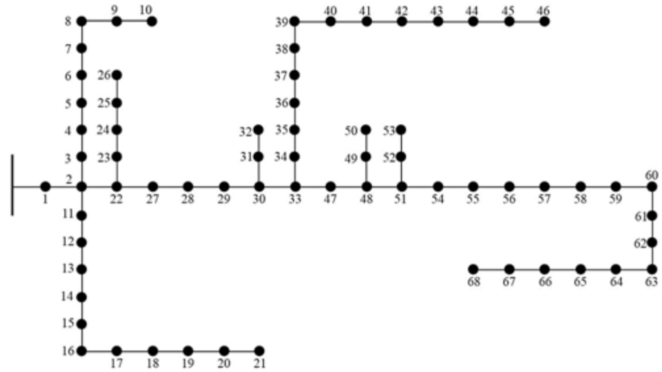

Fig. 4. The variation of production of wind turbine and photovoltaic (Pu)

Table 5. The Optimal location and size of devices in the 69-bus system

No. Test	Type of DG	DG		Capacitor	
		Position (No. bus)	Capacity (MW)	Position (No. bus)	Capacity (Mvar)
1	Photovoltaic	43	2.3272	42	0.9
2	Wind turbine	42	2.478	42	1.2
3	Photovoltaic	43	1.8128	33	0.45
	Wind turbine	33	1.4406	46	0.75

placement of devices is done in the distribution system with a suitable level of weather conditions. As a result, the best location and size of different combination of devices are calculated for all load models.

Table 5 shows the best location and size of devices in the 69-bus distribution system. The considered indices of system before and after placement of devices are presented in Table 6. According to this Table, system's performance improves after operating of devices in the best location with optimal size. The active and reactive power losses are reduced about 57-84 percent in the different combination of devices and load models. The voltage stability is also improved about 70 percent in the different tests. Based on the economic index, the company of distribution system can earn about 550 $ profit more than the initial states of the system in each day. Of course, the costs of renewable DG units are considered for the first year of operating so that these costs will decrease in the following years; therefore, the profit of distribution system will be increased.

The performance of the proposed method is also different in the various types of load model. Based on technical indices, the proposed method has the best and the weakest performance in the industrial and commercial load models, respectively, while based on the economic index, the proposed method has the best and the weakest performance in the constant and residential load models, respectively. Although these differences are not high and the values of indices are close, the insignificant difference is related to the coordination between the consumption pattern of various load models and the hourly produced power of renewable DG units.

At the moment, the weather conditions are applied to the proposed method for calculating the produced energy of RDG units during the 24-hour. Although the considered technical indices of the system are improved by connecting the devices

Table 6. The indices of 69-Bus distribution system during the optimization (Con: Constant, Ind: Industrial, Com: Commercial, Res: Residential)

No. Test	Load model	Technical indices			Economic indices (during the one day)		
		Active loss (MW)	Reactive loss (Mvar)	Voltage stability (Pu)	Profit ($)	Revenue ($)	Cost ($)
Initial	Con	0.2249	0.1021	0.6833	3028.36	4391.18	1362.82
	Ind	0.1947	0.0887	0.7024	2694.37	3918.80	1224.43
	Com	0.1809	0.0831	0.7114	2159.44	3115.08	955.640
	Res	0.1664	0.0770	0.7244	2346.53	3377.75	1031.22
1	Con	0.0391	0.0208	0.9003	3547.97	4391.18	843.210
	Ind	0.0442	0.0203	0.9080	3213.98	3918.80	704.820
	Com	0.0706	0.0295	0.9045	2679.05	3115.08	436.030
	Res	0.0547	0.0235	0.9044	2866.14	3377.75	511.610
2	Con	0.0423	0.0217	0.9035	3488.17	4391.18	903.010
	Ind	0.0512	0.0228	0.9111	3154.17	3918.80	764.620
	Com	0.0813	0.0336	0.9074	2619.08	3115.08	495.830
	Res	0.0633	0.0267	0.9071	2806.34	3377.75	571.410
3	Con	0.0330	0.0188	0.9178	3604.15	4391.18	787.030
	Ind	0.0335	0.0181	0.9239	3270.16	3918.80	648.640
	Com	0.0564	0.0266	0.9199	2735.23	3115.08	379.840
	Res	0.0431	0.0211	0.9187	2922.32	3377.75	455.430

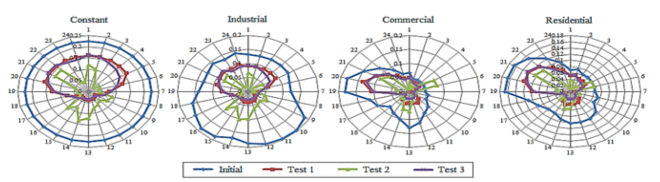

Fig. 5. The variation of active loss on 69-bus distribution system with consideration the weather conditions

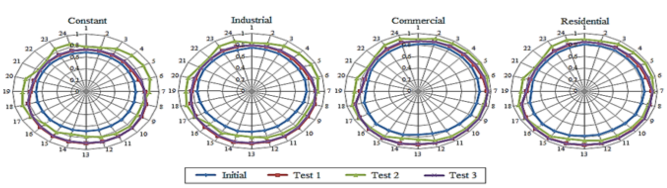

Fig. 6. The variation of voltage stability on 69-bus distribution system with consideration the weather conditions

to the network, the amount of improvement is variable during the day. The variation of active loss is shown in Fig 5 while the variation of reactive loss is as similar as this figure in different load models. The daily variation of voltage stability is also shown in Fig 6.

It can be seen that losses and voltage stability of network are changed by changing the hour and input power of renewable DG units. Photovoltaic power is at the maximum level in the middle of the day while the range of wind turbine power is variable during the day based on the speed of the wind. So in test 1, the distribution system has better performance in the middle hours of the day (hours 8-16). Of course, the technical indices are also improved considerably during the other times of the day. In test 2, the network has better performance during the three periods; the first period is in the morning and between the

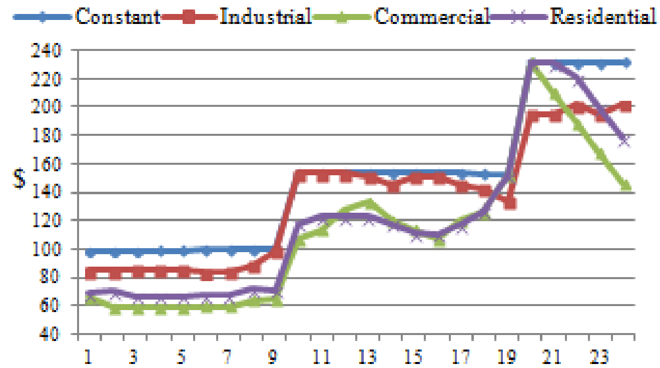

Fig. 7. The variation of hourly profit during the day in Test 3 with consideration the weather conditions in the 69-bus system

hours of 3 and 6. The second and third periods are in the evening (hours 17-20) and at night (hours 23-24), respectively. As regards that in test 3, photovoltaic and wind turbine are simultaneously allocated beside the capacitor banks in the distribution system, the technical indices of the system are affected by the variation of both renewable DG units so that the best performance of the network is between the hours of 7 and 18.

The changes of profit with consideration the weather condition is not considerable than to the previous assumption. Of course, the amount of profit is variable during the 24-hour based on the injected power of RDG, amount of active and reactive losses and load model of the system; For instance, the variation of hourly profit of system in Test 3 is shown in Fig 7.

B. 101-Bus actual distribution system

After testing the proposed algorithm on the standard test system, it is applied to the actual 101-bus distribution system in Khoy-Iran to evaluate its ability for selecting the optimal location and size of devices in the more reality conditions of operating. The single diagram of 101-bus actual system is shown in Fig 8. The system's data including of load and branch data are given in the appendix Table 11. This network is the 20-KV industrial system that 205 customers consume about 21037-KW active and 12806-Kvar reactive power in two feeders. According to the system's data, a large amount of power is consumed by a few numbers of customers; this is one of the main features of the industrial networks. It causes that improvement of the voltage stability and the loss of network are more important than other types of load models because this improvement causes to improve the economy of countries.

According to the costumers of this network in real condition, the industrial load model is considered for simulating of the proposed method. Table 7 shows the best location and size of devices in 101-bus system. The indices of 101-bus network during the optimization are given in Table 8.

According to the Table 8, the performance of actual system improves after allocating of devices. The improved percentage of network's loss during the optimization of different combination of devices is shown in Fig 9. Proposed method reduces the loss of actual network about 40-50 percent.

Moreover, the index of voltage stability is improved about 30 %. The changes of voltage are also evaluated by statistical calculations. The statistical detail of voltage variation at the actual distribution network, before and after installation of devices is

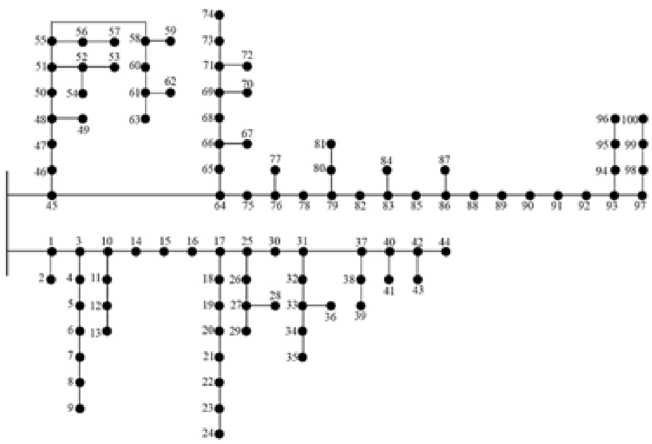

Fig. 8. The actual 101-bus distribution system in Khoy-Iran

Table 7. The optimal location and size of devices in the 101-Bus distribution system

No. Test	Type of DG	DG		Capacitor	
		Position (No. bus)	Capacity (MW)	Position (No. bus)	Capacity (Mvar)
1	Photovoltaic	41	2.4264	35	0.90
		90	2.0332	99	1.05
2	Wind turbine	43	2.2903	43	0.45
		80	2.3992	85	1.50
3	Photovoltaic	90	2.5000	44	1.20
		40	2.5000	100	1.20

Table 8. Indices of actual system before and after placement the devices

No. Test	Technical indices			Economic indices (during the one day)		
	Active loss (MW)	Reactive loss (Mvar)	Voltage stability (Pu)	Profit ($)	Revenue ($)	Cost ($)
Initial	0.4087	0.2394	0.8812	15202.4	21683.9	6481.5
1	0.2214	0.1297	0.9157	16053.9	21683.9	5629.0
2	0.2325	0.1362	0.9164	15987.1	21683.9	5696.8
3	0.2029	0.1189	0.9166	16141.6	21683.9	5542.3

presented in Table 9. Simultaneous placement of different combination of devices improves about 40-45% and 67-76% in the range of voltage changing at the buses and variance of voltage, respectively. These reductions improve the voltage and total stability of the actual network.

The proposed method also has the proper performance based on the economic index. The variation of profit of system during the optimization is shown in Fig 10. According to this figure, the profit of Distribution Company is increased between 780 and 940 $ in the different combination of devices in each day of the first year of operation; this profit will be increased in the following years.

Now, the weather conditions are applied to the proposed method. The changes of technical indices during the day are

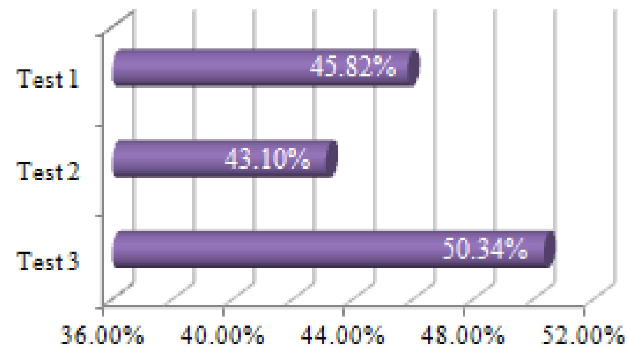

Fig. 9. Improved percentage of actual network loss after placement of devices

Table 9. Detail of voltage at the 101-Bus actual system during the optimization

	Minimum voltage (min_V),pu	Maximum voltage (max_v),pu	voltage variation $(max_v - min_v)$	Average	Variance $\times 10^{-5}$
Initial	0.9733 at bus 99	0.9967 at bus 1	0.0234	0.98397	5.1835
1	0.9837 at bus 72	0.9975 at bus 1	0.0138	0.98907	1.7068
2	0.9832 at bus 99	0.9974 at bus 1	0.0142	0.98899	1.6277
3	0.9850 at bus 72	0.9976 at bus 1	0.0126	0.98979	1.2552

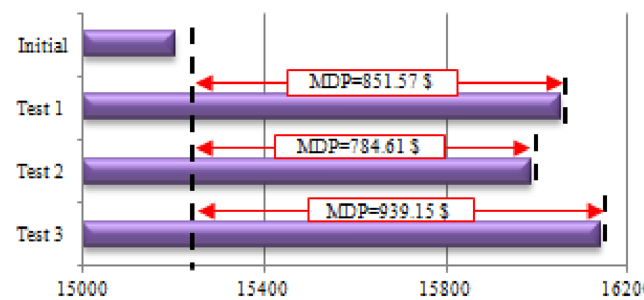

Fig. 10. The amount of daily profit of 101-bus actual system (MDP: the amount of more daily profit than initial state)

shown in Fig 11. In this Figure can be seen that technical indices of distribution system are changing during the 24-hour based on the technology of DG so that in test 1, the industrial distribution system has better performance in the morning (hours 6-8) and at noon (hours 13-18); while in test 2, the actual distribution system has better performance in the morning (hours 3-7). Of course in test 3, the actual network has better performance in the more time than previous tests; in this test, the industrial system has better performance in the hours of 3-17.

The amount of economic index with consideration the weather conditions during the one day is given in Table **??**. According to the information of this table, the profitability of actual network is also improved by applying the proposed method.

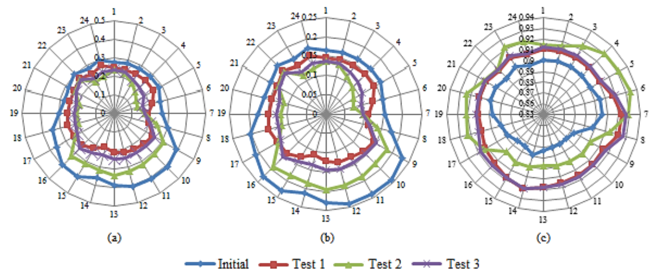

Fig. 11. The variation of technical indices of 101-bus system with consideration the weather conditions (a) Active loss (b) Reactive loss (c) Voltage stability

Table 10. The profit of 101-Bus actual system in the proposed method with consideration the weather conditions

No. Test	Profit ($)	
	During the one day	Yearly profit more than the initial state
1	16016.35	7,130,026.8
2	15954.19	6,585,505.2
3	16102.30	7,882,948.8

6. CONCLUSION

In this paper, simultaneous placement of renewable DG units and capacitor bank was studied in the IEEE 69-bus distribution system and actual 101-bus actual distribution system in Khoy-Iran. The combination of MOWOA and AHP was used for optimizing the proposed technical and economic functions. The load model sensitive to voltage-frequency and also various customers' daily load patterns were considered during the optimization for evaluating the proposed method in the more realistic condition. The two assumptions including the suitable level of input criteria of RDG units and various weather conditions were considered for calculating the daily output power of wind turbine and photovoltaic.

The result shows that the proposed algorithm has the practical performance in the various load models and it affects the amount of loss and voltage indices so that their changing becomes more linear during the change of load model. This substantial reduction causes that if load model of some buses changes to another model, the network efficiency will not change much. Based on the DG types, it can be said that all kinds of renewable technologies have the useful effect on the amount of technical and economic indices while photovoltaic has better performance than wind turbine; the difference of performances depends on the type of output of DG units. The MOWOA algorithm has an accurate performance in complex problems. By using AHP mechanism and the relative priority of indicators, the best location and capacity of the equipment can be selected. Totally, the results indicate the high performance of the proposed method in improving the considered indices during the 24-hour in different load models and various combinations of devices.

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APPENDIX

The details of 101 bus distribution system in Khoy-Iran are presented in Table 11

Table 11. The load and branch data of 101-bus distribution system

Branch number	Bus from	Bus to	R (Ω)	X (Ω)	At the end bus	
					$P_L(KW)$	$Q_L(Kvar)$
1	0	1	0.1092	0.0639	0	0
2	1	2	0.0750	0.0441	170	105.4
3	1	3	0.0792	0.0465	0	0
4	3	4	0.0615	0.0360	85	52.7
5	4	5	0.0396	0.0231	85	52.7
6	5	6	0.0246	0.0144	85	52.7
7	6	7	0.0135	0.0081	136	84.32
8	7	8	0.0423	0.0249	85	52.7
9	8	9	0.1635	0.0960	170	105.4
10	3	10	0.0846	0.0495	0	0
11	10	11	0.0585	0.0345	267.7	166
12	11	12	0.0546	0.0321	85	52.7
13	12	13	0.1362	0.0798	212.5	131.75
14	10	14	0.0273	0.0159	340	210.8
15	14	15	0.0546	0.0321	340	210.8
16	15	16	0.0546	0.0321	267.7	166
17	16	17	0.0681	0.0399	0	0
18	17	18	0.0954	0.0558	170	105.4
19	18	19	0.0531	0.0312	85	52.7
20	19	20	0.0369	0.0216	267.7	166
21	20	21	0.0831	0.0489	42.5	26.35
22	21	22	0.0408	0.024	85	52.7
23	22	23	0.0804	0.0471	267.7	166
24	23	24	0.0423	0.0249	42.5	26.35
25	17	25	0.1092	0.0639	0	0
26	25	26	0.2727	0.1599	212.5	131.75
27	26	27	0.0150	0.0087	0	0
28	27	28	0.1158	0.0678	136	84.32
29	27	29	0.0792	0.0465	85	52.7
30	25	30	0.0396	0.0231	340	210.8
31	30	31	0.1692	0.0990	0	0
32	31	32	0.1869	0.1095	212.5	131.75
33	32	33	0.1092	0.0639	0	0
34	33	34	0.0846	0.0495	170	105.4
35	33	35	0.0477	0.0279	42.5	26.35
36	35	36	0.0969	0.0567	267.7	166
37	31	37	0.0681	0.0399	0	0
38	37	38	0.1227	0.0720	552.5	342.55
39	38	39	0.0735	0.0432	510	316.2
40	37	40	0.2046	0.1200	0	0
41	40	41	0.1431	0.0840	1020	632.4
42	40	42	0.1008	0.0591	0	0
43	42	43	0.1392	0.0816	170	105.4
44	42	44	0.0615	0.0360	170	105.4
45	0	45	0.1704	0.0999	0	0
46	45	46	0.0423	0.0249	85	52.7
47	45	47	0.0327	0.0192	85	52.7
48	47	48	0.1350	0.0792	0	0
49	48	49	0.0765	0.0447	21.3	13.175
50	48	50	0.0654	0.0384	85	52.7
51	50	51	0.1065	0.0624	0	0
52	51	52	0.0669	0.0393	170	105.4
53	52	53	0.2454	0.1440	0	0
54	52	54	0.0696	0.0408	267.7	166
55	51	55	0.3069	0.1797	0	0
56	55	56	0.0723	0.0423	212.5	131.75
57	56	57	0.0531	0.0312	170	105.4
58	55	58	0.1458	0.0855	0	0
59	58	59	0.1146	0.0672	170	105.4
60	58	60	0.0573	0.0336	170	105.4
61	60	61	0.0831	0.0489	0	0
62	61	62	0.1077	0.063	267.7	166
63	61	63	0.0519	0.0303	340	210.8
64	45	64	0.6900	0.4044	0	0
65	64	65	0.1323	0.0774	340	210.8
66	65	66	0.2100	0.1230	267.7	166
67	66	67	0.2781	0.1629	212.5	131.75
68	66	68	0.0465	0.0273	267.7	166
69	68	69	0.2346	0.1374	0	0
70	69	70	0.2127	0.1248	0	0
71	69	71	0.4827	0.2829	0	0
72	71	72	0.2400	0.1407	212.5	131.75
73	71	73	0.0342	0.0201	85	52.7
74	73	74	0.0627	0.0369	42.5	26.35
75	64	75	0.0600	0.0351	382.5	237.15
76	75	76	0.1473	0.0864	0	0
77	76	77	0.3462	0.2031	85	52.7
78	76	78	0.0819	0.0480	85	52.7
79	78	79	0.0435	0.0255	0	0
80	79	80	0.0477	0.0279	42.5	26.35
81	80	81	0.0642	0.0375	170	105.4
82	79	82	0.0477	0.0279	21.3	13.175

Branch number	Bus from	Bus to	R (Ω)	X (Ω)	At the end bus	
					$P_L(KW)$	$Q_L(Kvar)$
83	82	83	0.0273	0.0159	0	0
84	83	84	0.2454	0.1440	340	210.8
85	83	85	0.0615	0.0360	85	52.7
86	85	86	0.0285	0.0168	42.5	26.35
87	86	87	0.2535	0.1488	0	0
88	86	88	0.0627	0.0369	382.5	237.15
89	88	89	0.0504	0.0297	267.7	166
90	89	90	0.0204	0.0120	340	210.8
91	90	91	0.0423	0.0249	85	52.7
92	91	92	0.0423	0.0249	42.5	26.35
93	92	93	0.0423	0.0249	0	0
94	93	94	0.0615	0.0360	212.5	131.75
95	94	95	0.0342	0.0201	42.5	26.35
96	95	96	0.0954	0.0558	170	105.4
97	93	97	0.1023	0.0600	0	0
98	97	98	0.0927	0.0543	340	210.8
99	98	99	0.0231	0.0135	170	105.4
100	99	100	0.0804	0.0471	85	52.7