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Multi-Criteria Optimal Sizing and Allocation of Renewable and Non-Renewable Distributed Generation Resources at 63 kV/20 kV Substations

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Abstract: The optimal allocation and sizing of distributed generation (DG) resources are important in installing these resources, to improve the technical parameters of the network, including the power losses, voltage profile, and short-circuit level, as well as to increase economic factors. In this paper, a new multi-criteria algorithm and objective function are proposed for the optimal sizing and allocation of renewable and non-renewable DG resources simultaneously. The proposed algorithm is implemented on 63/20 kV substations at 20 kV levels. In the proposed objective function, all important technical and economic factors as well as important constraints, such as penetration level of DGs and budget constraint, are considered in a way that all factors are assigned to monetary values. Moreover, a new mathematical formulation is introduced for the allocation of renewable DG resources to reduce run-time optimization. The genetic algorithm (GA) is employed in the proposed algorithm to minimize the objective function. For renewable DG resources, photovoltaic panels and wind turbines, and for non-renewable DG resources, gas turbines are considered. The 115 buses network of Bakhtar Regional Electric Company (BREC) in Iran is used to evaluate the performance of the proposed algorithm. The results demonstrate that the proposed algorithm improves technical factors efficiently and maximizes the profitability of the investment.

Keywords: allocation; distributed generation; multi-criteria; optimization; sizing

1. Introduction

Innovations in the technology and economic factors of distributed generation (DG) resources have increased the attention paid to DG resources. Installing DG resources on distribution networks has many technical and economic advantages, deferring the necessity of substation developments. Some of the technical advantages include power loss reduction, peak shaving, and improvement in voltage profile, reliability, and power quality [1–3]. Some of the economic advantages include the reduction of transmission and distribution costs [4]. Renewable DG resources are the most imperative part of the modern power system and have many potential economic benefits [5]. Renewable energy sources, which apply to DGs, include wind, solar, and biomass [6]. On the other hand, non-renewable energy sources, which are widely used in DGs, include microturbines, gas turbines, and fuel cells [7]. Changes in utility infrastructure and government policies have increased a tendency to use renewable resources in distribution networks. Studies show that if the sizing and allocation of DGs are not decided properly, the aforementioned benefits will not be achieved and network parameters will be degraded [8,9]. The severity of the impacts depends on the type, capacity, and location of DG resources [10]. The most important thing in installing DG resources is the optimal allocation and sizing of them. Accordingly, DGs have been an appropriate solution to the problem of generating and supplying electrical power from the point of view of designers [11].

Many studies on the sizing and allocation of DG resources have been conducted which have been reviewed in [3,10]. Analyzing different papers, the power loss reduction, and voltage profile improvement have often been considered as an objective in most studies [1,12–14]. Article [15] has suggested another type of objective for sizing and siting which includes the purpose of increasing the penetration level of DGs in distribution networks. In study [16], the penetration limit of solar DG has been determined in the network. In study [17], the authors have aimed for power loss reduction, maintaining short-circuit level, and voltage profile improvement. The algorithms proposed by [2] for siting and sizing DGs have considered loss reduction, voltage profile, and reliability improvements in transmission systems. Paper [18] has reviewed how algorithms for the optimal allocation of distributed generation play an important role in improving the efficiency of results. Reference [19] has presented the best solution for the optimal placement and sizing of DGs in distribution systems with a hybrid genetic algorithm at the cost of a longer processing time. For the first time in [20], the manta ray foraging optimization algorithm (MRFO) has been presented to optimize a multi-objective problem. Using this algorithm, the objective function for the allocation of DG units has been optimized in the radial distribution power system. In [15,21], some indices, such as power loss and voltage profile indices, have been presented in order to evaluate the efficiency of installed DG units. Paper [4] has minimized the benefit-to-cost ratio by considering power loss and voltage profile of the network by assigning them to monetary values. Article [22] has presented the optimal siting and sizing of renewable distributed generators such as wind and photovoltaic units in distribution systems considering the cost of operational risk. Reference [23] has presented a probabilistic generation model for the optimal placement and sizing of wind DG. In paper [24], a two-stage approach for the optimal integration of large-scale wind DG has been presented. An optimal renewable energy management strategy for Iran has been present in [25].

The motivation for this paper is proposing an algorithm for the economic possibility of locating renewable DG resources as well as the optimal sizing and allocation of DG resources at 63 kV/20 kV substations besides decreasing the run-time optimization. The deficiencies in previous studies have been motivated to propose the algorithm. References [3,26] have considered weight factors while the way of selecting weight factors is always questionable. To solve this issue, in this paper, all technical and economic factors are assigned to monetary values. In articles [12,13], some of the technical and economic parameters have not been considered, such as reliability. In paper [4], for DG resources only non-renewable DG resources have been considered and renewable DG resources have not been considered. Also, some of the constraints such as DG penetration in feeders and budget constraints have been ignored in [4,17].

Generally, problems within the previous studies on sizing and siting of DG resources process can be classified into four major deficiencies: (1) ignoring some technical and economic parameters; (2) not presenting any method to identify the optimal number of renewable and non-renewable DGs simultaneously; (3) weighting the siting and sizing parameters arbitrary and without providing sufficient reasons; (4) ignoring some of the most important constraints such as DG penetration in feeders and budget constraints. This paper tries to solve the discussed problems of the previous works on sizing and siting of DGs according to the requirements of Bakhtar Regional Electric Company (BREC).

In this paper, a new multi-criteria objective function (OF) and algorithm are proposed for the optimal sizing and allocation of both renewable and non-renewable DG resources connected to 63/20 kV substations at 20 kV levels. In the proposed algorithm, in order to decline run-time optimization, the economic possibility of locating renewable DG resources is investigated using new criteria before starting the optimization process. The objective function is considered as the ratio of network costs to network benefits to simultaneously pursue decreasing the costs and increasing the benefits. Cost and benefit factors are selected according to the policy of regional electric companies. Costs include initial investment, maintenance, operation, and circuit breaker (CB) replacement. Benefits included purchasing less electrical active and reactive power, loss reduction, voltage profile, deferring the necessity of substation development, and reliability. To omit the arbitrary assignation of weighting

factors, all technical and economic factors are assigned to monetary values. In order to prove the efficiency of the proposed algorithm, it is applied to the 115 bus network of BREC in Iran to optimize the objective function using the GA.

2. The Objective Function

The objective function (OF) is the ratio of the cost to the benefit of installed renewable and non-renewable DG resources as shown in Equation (1).

$$\mathrm{OF} = \frac{\sum_{i=1}^{n} C_i}{\sum_{j=1}^{m} B_j} \quad , \quad n = 4 \ , m = 6 \tag{1}$$

where C_1 is the cost of initial investment, C_2 is a maintenance cost, C_3 is the operational cost, and C_4 is the cost of replacing circuit breakers. B_1 is related to purchasing less active power from the transmission network, B_2 is related to purchasing less reactive power from the transmission network, B_3 is related to power loss reduction, B_4 is related to improvement in voltage profile, B_5 is related to deferring substation capacity development, and B_6 is related to reliability improvement.

2.1. Modeling of DG Installation Costs

2.1.1. Cost of the Initial Investment (C_1)

The annual cost of the initial investment in renewable and non-renewable DG resources is calculated by Equation (2).

$$C_1 = F_{C,gas} \times \sum_{i=1}^{n_{bus}} P_{DG_gas,i} \times A_{gas} + F_{C,PV} \times \sum_{i=1}^{n_{bus}} P_{DG_PV,i} \times A_{PV} + F_{C,wind} \times \sum_{i=1}^{n_{bus}} P_{DG_wind,i} \times A_{wind} \tag{2}$$

where $F_{C,gas}, F_{C,PV}, F_{C,wind}$ are the initial cost of purchasing and installing gas turbine, photovoltaic, and wind DG units ($/MW), respectively, $P_{DG_gas,i}, P_{DG_PV,i}, P_{DG_wind,i}$ are the maximum active power produced by gas turbine, photovoltaic, and wind DG units installed on the ith bus (MW), respectively, and n_{bus} is the number of 20 kV buses in the network. Since the cost of investment is for all years in which DG units are in operation, an annualized factor (A) is considered in Equation (2).

A is used to calculate the share of the investment cost for each year, and it is obtained from Equation (3) [27].

$$A = \frac{r(1+r)^T}{(1+r)^T - 1} \tag{3}$$

where r is the interest ratio, and T is the payback time of investment, which is assumed equal to years in which DG units are in operation.

2.1.2. Maintenance Cost (C_2)

Maintenance cost is the cost of repairing, spare parts, monitoring and maintaining DG units, the cost of workmanship and training, and a benefit that is not acquired when DG units are under repair. Maintenance cost consists of fixed and variable parts in relation to the produced active power of DG units. Therefore, the fixed maintenance cost is divided by produced active power of DG units ($ per MW) and the result is summed by variable part. As a result, the maintenance cost depends on the capacity of DG units and is calculated by Equation (4).

$$C_2 = C_{M,gas} \times \sum_{i=1}^{n_{bus}} P_{DG_gas,i} + C_{M,PV} \times \sum_{i=1}^{n_{bus}} P_{DG_PV,i} + C_{M,wind} \times \sum_{i=1}^{n_{bus}} P_{DG_wind,i} \tag{4}$$

where $C_{M,gas}$, $C_{M,PV}$, $C_{M,wind}$ are the annual cost of maintaining gas turbine, photovoltaic, and wind DG units ($/MW), respectively.

2.1.3. The Operational Cost (C_3)

Although the operating cost of renewable DG resources is negligible, it is considered in this article. The annual operational cost is calculated by Equation (5).

$$C_3 = \sum_{i=1}^{n_{bus}} \left(C_o \times EP_{gas,i} \times 10^3 + C_{o_PV} \times EP_{PV,i} + C_{o_wind} \times EP_{wind,i}\right) \quad (5)$$

where C_o is the cost of fuel ($/kWh) for gas turbine DG resources and is obtained by Equation (6) [28], C_{o_PV} and C_{o_wind} are operational cost for photovoltaic and wind turbine DG resources ($/kWh), respectively. $EP_{gas,i}$, $EP_{PV,i}$, and $EP_{wind,i}$ are yearly produced electricity in MWh by gas turbine, photovoltaic, and wind turbine DG resources on the ith bus, respectively, which are calculated by Equation (7).

$$C_o = \frac{B \times F_o}{HV \times R} \quad (6)$$

where B is a coefficient that converts kcal to kWh and is equal to 860, HV is the thermal value of natural gas (kCal/m^3) which is equal to 8600, R is the efficiency of DG unit (%), and F_o is the cost of natural gas ($/m^3).

$$\begin{cases} EP_{gas,i} = \alpha_i \times P_{DG_gas,i} \times (8760 - h_{main,i}) \\ EP_{PV,i} = \beta_i \times P_{DG_PV,i} \\ EP_{wind,i} = \gamma_i \times P_{DG_wind,i} \end{cases} \quad (7)$$

where $h_{main,i}$ is the total number of hours in a year in which the DG unit is out of service for maintenance, and α_i is the coefficient of participation of gas turbine DG unit which depends on the load curve of the ith bus, and is obtained from Equation (8).

β_i and γ_i are the yearly electricity production of photovoltaic and wind turbine DG resources on the ith bus per MW, respectively. β_i and γ_i are obtained according to the geographical location [29,30].

$$\alpha_i = \frac{\int_0^{P_{DG_gas,i}} \int_{j=1}^{8760} E_i(t,p)dtdp}{P_{DG_gas,i} \times 8760} \quad (8)$$

where $E_i(t,p)$ is the function of the load curve of the ith bus.

2.1.4. Cost of Replacing Circuit Breakers (C_4)

In the presence of DG units, the short-circuit level of the network increases. This increase will cause some protection problems if the short-circuit level of the network exceeds that of CBs. Therefore, some CBs must be replaced after the installation of DG resources. The annual cost of replacing CBs is calculated using Equation (9) [28].

$$C_4 = A \times \sum_{i=1}^{n_{bus}} C_{Switch,i} \quad (9)$$

where $C_{Switch,i}$ is the cost of replacing the ith circuit breaker in $.

2.2. Modeling Benefits Obtained from DG Installation

2.2.1. The Benefit of Purchasing Less Active Power from the Transmission Network (B_1)

The benefit of buying less active power from transmission systems (B_1) is obtained through Equation (10).

$$B_1 = \sum_{i=1}^{n_{bus}} (EP_{gas,i} \times E_{P_gas} + EP_{PV,i} \times E_{P_PV} + EP_{wind,i} \times E_{P_wind}) \quad (10)$$

where E_P is the price of electrical energy for gas turbine, photovoltaic and wind DG resources in ($/MWh).

2.2.2. The Benefit of Purchasing Less Reactive Power from Transmission Systems (B_2)

Although the main purpose of installing DG resources is active power generation because the installation price of these resources is more expensive than other resources used for reactive power compensation, gas turbine DG resources can operate in a way that the power factor of them is not unit. Therefore, gas turbine DG resources can compensate for reactive power. The benefit of buying less reactive power from transmission systems (B_2) is obtained through Equation (11).

$$B_2 = \sum_{i=1}^{n_{bus}} EP_{gas,i} \times \frac{\sqrt{1 - \cos^2 \varphi}}{\cos \varphi} \times E_Q \quad (11)$$

where E_Q is the price of reactive power per hour ($/MVarh) and $\cos \varphi$ is the power factor of gas turbine DG units.

2.2.3. The Benefit of Reducing Power Loss (B_3)

The annual benefit of reducing power loss (B_3) is obtained using Equation (12).

$$B_3 = \sum_{i=1}^{8760} (P_{Loss,i}^{WithoutDG} - P_{Loss,i}^{WithDG}) \times E_P \quad (12)$$

where $P_{Loss,i}^{WithoutDG}$ is power loss in the ith hour without any DG resources, and $P_{Loss,i}^{WithDG}$ is power loss in the ith hour with DG resources which are not out of service for maintenance.

2.2.4. The Benefit of Voltage Profile Improvement (B_4)

One of the advantages of using DG resources is improving voltage profile which reduces the usage of tap changers in transformers. Therefore, by reducing the number of transformer taps, the lifetime of transformers gains [31].

The benefit of improvement in voltage profile (B_4) is obtained using Equation (13).

$$B_4 = 2 \times \sum_{k=1}^{365} \sum_{j=1}^{N_{Tr,i}} \sum_{i=1}^{n_{bus}} \frac{N_{ijk}^{Without\,DG} - N_{ijk}^{With\,DG}}{Tap_{Max,ij}} \times C_{T,ij} \quad (13)$$

where N_{Tr} is the number of transformers at the ith substations, $N_{ijk}^{Without\,DG}$ and $N_{ijk}^{With\,DG}$ are the taps number of the j^{th} transformer at the ith substation, at the kth hour of year before and after installing DG resources, respectively. Tap_{Max} is the maximum number of taps allowed by the manufacturer and $C_{T,ij}$ is the cost of each 63/20 kV transformer at the ith substation ($).

According to the daily load curve for improving the voltage profile, the number of taps required to provide the maximum daily load is the same as the number of taps required to return to the base load. For this reason, Equation (13) is multiplied by two.

2.2.5. The Benefit Obtained from Deferring Substation Capacity Development (B_5)

The annual benefit obtained from deferring substation capacity expansion is given by Equation (14) [28].

$$B_5 = A \times \sum_{i=1}^{n_{bus}} \sum_{j=1}^{N_{Tr,i}} C_{T,ij} \times \left[1 - \left(\frac{1+IF}{1+r}\right)^{\Delta T_i}\right] \quad (14)$$

where IF is the annual inflation rate and ΔT is the length of time in which substation capacity development can be deferred. ΔT is determined by Equation (15).

$$\Delta T = \frac{Log(\frac{1}{1-\gamma})}{Log(1+\alpha_{Load})} \quad (15)$$

where γ is the ratio of the capacity of DG unit to the peak load of substation and α_{Load} is the annual growth rate of loads.

2.2.6. The Benefit of Reliability Improvement (B_6)

By using DG resources, the reliability of the network is improved. Power outage can occur in power systems due to discontinuity and failure in supplying electrical energy. The annual benefit of reliability improvement is obtained by Equation (16).

$$B_6 = E_{demand} \times \sum_{i=1}^{n_{bus}} (S_{DG_gas,i} + S_{DG_PV,i} + S_{DG_wind,i}) \times U_i \quad (16)$$

where E_{demand} is the price of demand in the electrical network in (\$/MVAh), $S_{DG_gas,i}$, $S_{DG_PV,i}$, and $S_{DG_wind,i}$ are the apparent power of gas turbine, photovoltaic, and wind turbine DG units installed on the ith bus (MVA), respectively, and U_i is the annual time of power outage on the ith bus in hours.

3. Mathematical Analysis for the Allocation of Renewable DG Resources

One of the main concerns about the allocation of DG resources is run-time optimization. For this purpose, in this paper new criteria for the allocation of renewable DG resources are presented. The proposed criteria are based on comparing the effect of locating renewable DG resource with the effect of locating non-renewable DG resource on the ith bus.

Hypothesis 1 (H1). *According to the natural factor of geographical point place of the ith bus, the values of* β_i *and* γ_i are constant.

$$\beta_i = \text{const},\ \gamma_i = \text{const for } i = 1, 2, \ldots, n_{\text{bus}}$$

3.1. Location of Photovoltaic DG Resources

To find the optimal location of photovoltaic DG resources, the difference between photovoltaic DG resources and non-renewable DG resources (in this paper, gas turbine DG resources) in each function of the objective function is obtained by Equations (17) and (18).

$$\begin{array}{lll} \Delta C_1^i = C_{1,PV}^i(P) - C_{1,gas}^i(P) & \rightarrow & \Delta C_1^i = (F_{C,PV} \times A_{PV} - F_{C,gas} \times A_{gas}) \times P \\ \Delta C_2^i = C_{2,PV}^i(P) - C_{2,gas}^i(P) & \rightarrow & \Delta C_2^i = (C_{M,PV} - C_{M,gas}) \times P \\ \Delta C_3^i = C_{3,PV}^i(P) - C_{3,gas}^i(P) & \rightarrow & \Delta C_3^i = (C_{o_PV} \times \beta_i - C_o \times \alpha_i \times (8760 - h_{main,i}) \times 10^3) \times P \\ \Delta C_4^i = C_{4,PV}^i(P) - C_{4,gas}^i(P) & \rightarrow & \Delta C_4^i = 0 \end{array} \quad (17)$$

$$\begin{array}{lll}
\Delta B_1^i = B_{1,PV}^i(P) - B_{1,gas}^i(P) & \rightarrow & \Delta B_1^i = (\beta_i \times E_{P_PV} - \alpha_i \times (8760 - h_{main,i}) \times E_{P_gas}) \times P \\
\Delta B_2^i = B_{2,PV}^i(P) - B_{2,gas}^i(P) & \rightarrow & \Delta B_2^i = (-\alpha_i \times (8760 - h_{main,i}) \times \frac{\sqrt{1-\cos^2\varphi}}{\cos\varphi} \times E_Q) \times P \\
\Delta B_3^i = B_{3,PV}^i(P) - B_{3,gas}^i(P) & \rightarrow & \Delta B_3^i = 0 \\
\Delta B_4^i = B_{4,PV}^i(P) - B_{4,gas}^i(P) & \rightarrow & \Delta B_4^i = 0 \\
\Delta B_5^i = B_{5,PV}^i(P) - B_{5,gas}^i(P) & \rightarrow & \Delta B_5^i = 0 \\
\Delta B_6^i = B_{6,PV}^i(P) - B_{6,gas}^i(P) & \rightarrow & \Delta B_6^i = 0
\end{array} \tag{18}$$

Hypothesis 2 (H2). In order to justify economic benefit, the profit must be greater than the value of the interest rate.

According to the Hypothesis 2, Equation (19) can be written.

$$\sum_{j=1}^{6} \Delta B_j^i > (1 + r) \times \sum_{k=1}^{4} \Delta C_k^i \tag{19}$$

By substituting Equations (17) and (18) into Equation (19), the following Equation (20) yields.

$$\beta_i > \frac{(1+r)\times\left[(F_{C,PV}\times A_{PV} - F_{C,gas}\times A_{gas}) + (C_{M,PV} - C_{M,gas}) + (-C_o\times\alpha_i\times(8760-h_{main.i})\times 10^3)\right] + \alpha_i\times(8760-h_{main,i})\times(\frac{\sqrt{1-\cos^2\varphi}}{\cos\varphi}\times E_Q + E_{P_gas})}{E_{P_PV} - (1+r)\times C_{o_PV}} \tag{20}$$

where β_i is the yearly electricity production of photovoltaic DG resources on the ith bus per MW. Photovoltaic DG resources can be located on buses that can establish Equation (20).

3.2. Location of Wind Turbine DG Resources

To find the optimal location of wind turbine DG resources, the difference between wind turbine DG resources and non-renewable DG resources (in this paper, gas turbine DG resources) in each function of the objective function is obtained by Equations (21) and (22).

$$\begin{array}{lll}
\Delta C_1^i = C_{1,wind}^i(P) - C_{1,gas}^i(P) & \rightarrow & \Delta C_1^i = (F_{C,wind} \times A_{wind} - F_{C,gas} \times A_{gas}) \times P \\
\Delta C_2^i = C_{2,wind}^i(P) - C_{2,gas}^i(P) & \rightarrow & \Delta C_2^i = (C_{M,wind} - C_{M,gas}) \times P \\
\Delta C_3^i = C_{3,wind}^i(P) - C_{3,gas}^i(P) & \rightarrow & \Delta C_3^i = (C_{o_wind} \times \gamma_i - C_o \times \alpha_i \times (8760 - h_{main.i}) \times 10^3) \times P \\
\Delta C_4^i = C_{4,wind}^i(P) - C_{4,gas}^i(P) & \rightarrow & \Delta C_4^i = 0
\end{array} \tag{21}$$

$$\begin{array}{lll}
\Delta B_1^i = B_{1,wind}^i(P) - B_{1,gas}^i(P) & \rightarrow & \Delta B_1^i = (\gamma_i \times E_{P_wind} - \alpha_i \times (8760 - h_{main,i}) \times E_{P_gas}) \times P \\
\Delta B_2^i = B_{2,wind}^i(P) - B_{2,gas}^i(P) & \rightarrow & \Delta B_2^i = (-\alpha_i \times (8760 - h_{main,i}) \times \frac{\sqrt{1-\cos^2\varphi}}{\cos\varphi} \times E_Q) \times P \\
\Delta B_3^i = B_{3,wind}^i(P) - B_{3,gas}^i(P) & \rightarrow & \Delta B_3^i = 0 \\
\Delta B_4^i = B_{4,wind}^i(P) - B_{4,gas}^i(P) & \rightarrow & \Delta B_4^i = 0 \\
\Delta B_5^i = B_{5,wind}^i(P) - B_{5,gas}^i(P) & \rightarrow & \Delta B_5^i = 0 \\
\Delta B_6^i = B_{6,wind}^i(P) - B_{6,gas}^i(P) & \rightarrow & \Delta B_6^i = 0
\end{array} \tag{22}$$

By substituting Equations (21) and (22) into Equation (19), the following Equation (23) yields.

$$\gamma_i > \frac{(1+r)\times\left[(F_{C,wind}\times A_{wind} - F_{C,gas}\times A_{gas}) + (C_{M,wind} - C_{M,gas}) + (-C_o\times\alpha_i\times(8760-h_{main,i})\times 10^3)\right]}{E_{P_wind} - (1+r)\times C_{o_wind}} + \frac{\alpha_i\times(8760-h_{main,i})\times(\frac{\sqrt{1-\cos^2\varphi}}{\cos\varphi}\times E_Q + E_{P_gas})}{E_{P_wind} - (1+r)\times C_{o_wind}} \tag{23}$$

where γ_i is the yearly electricity production of wind turbine DG resources on the ith bus per MW. Wind turbine DG resources can be located on buses that can establish Equation (23).

4. Application of Proposed Algorithm

4.1. Case Study

The proposed algorithm in this paper is applied to the Bakhtar Regional Electrical Company (BREC) network in Iran. This network constitutes the electrical network of three provinces including Markazi, Hamedan, and Lorestan. The number of 63/20 kV substation in this network is 115 (Figure 1).

Technical and economic information about this network are presented in Table 1 [32–34]. In Table 2, the peak load of each BREC 63/20 kV substation is tabulated, and in Table 3, CBs level of each bus in the BREC network is presented.

Table 1. Technical and economic information about the BREC network.

Parameter	Gas Turbine DG	Photovoltaic DG	Wind DG
F_C ($/MW)	458,000	1,210,000	1,000,000
C_M ($/MW)	16,000	30,000	34,000
C_o ($/MWh)	13.158	0.062	0.074
T (year)	15	20	20
r (%)	18	18	18
IF (%)	15	15	15
E_p ($/MWh)	30	171	129
E_Q ($/MVarh)	17.70		
h_{main} (hour)	336		

Table 2. The peak load of each BREC 63/20 kV substation.

Bus Location	Max Load (MW)	Bus Location	Max Load (MW)	Bus Location	Max Load (MW)	Bus Location	Max Load (MW)	Bus Location	Max Load (MW)
1	15.7	24	19.5	47	7	70	35.6	93	18
2	24	25	36	48	5	71	13	94	40
3	32.3	26	21.5	49	14.9	72	20	95	14.4
4	42	27	47	50	21	73	23	96	51.5
5	17	28	19	51	13	74	26	97	26
6	27	29	18	52	24	75	10	98	20.6
7	10.8	30	16.8	53	9	76	39	99	13.9
8	5.2	31	4.3	54	29	77	30	100	22
9	19	32	2	55	19.5	78	8.9	101	10
10	17	33	16	56	7	79	13	102	3.9
11	9.4	34	19.3	57	6.3	80	18	103	12.5
12	6.8	35	17.4	58	26.4	81	17	104	0.1
13	10.2	36	6.4	59	16	82	10	105	21
14	16.7	37	4	60	14	83	12.4	106	29.5
15	26.3	38	13.5	61	22	84	23	107	28.1
16	15.5	39	16	62	21	85	16.6	108	13.2
17	35.2	40	12	63	16	86	16.6	109	8.3
18	19	41	13	64	5	87	28	110	7
19	26	42	16	65	21.4	88	22	111	6.5
20	14	43	10.5	66	25	89	28	112	6
21	8.2	44	6.5	67	16	90	8	113	14.1
22	50.5	45	15.5	68	32	91	18	114	9
23	42.5	46	23.5	69	21	92	6.3	115	6.4

Table 3. CBs level of each bus in the BREC network.

Bus Location	CBs Level (kA)	Bus Location	CBs Level (kA)	Bus Location	CBs Level (kA)	Bus Location	CBs Level (kA)	Bus Location	CBs Level (kA)
1	26	24	20	47	25	70	20	93	25
2	14	25	20	48	12	71	20	94	20
3	20	26	20	49	25	72	20	95	25
4	20	27	20	50	20	73	26	96	20
5	20	28	25	51	20	74	20	97	20
6	20	29	20	52	20	75	20	98	20
7	20	30	14	53	20	76	20	99	20
8	20	31	20	54	20	77	20	100	20
9	20	32	20	55	25	78	20	101	20
10	25	33	20	56	14	79	20	102	22
11	12	34	20	57	26	80	25	103	20
12	20	35	20	58	20	81	14	104	25
13	20	36	20	59	20	82	20	105	12
14	20	37	20	60	20	83	20	106	12
15	20	38	20	61	20	84	20	107	20
16	20	39	20	62	20	85	25	108	20
17	20	40	20	63	20	86	20	109	20
18	25	41	20	64	25	87	25	110	20
19	20	42	20	65	20	88	20	111	20
20	20	43	20	66	26	89	16	112	20
21	25	44	20	67	20	90	20	113	20
22	20	45	20	68	25	91	25	114	20
23	20	46	20	69	20	92	20	115	20

4.2. Constraints and Assumptions of the Problem

For the proposed algorithm, technical and economic limitations are considered. Technical constraints contain the maximum penetration of DG in feeder, the capacity of DG units, the power factor of DG resources, the efficiency of gas turbine DG units, the maximum allowable tap of transformers, the amount of voltage changes in each tap, allowable limits of voltage, the annual growth rate of loads, and the time of power outage. Economic constraint is a budget constraint. Assumptions of the proposed algorithm, containing the cost of natural gas, replacing CBs, and transformers, and the price of demand, are determined according to the location of the BREC network. In the following sub sections, limitations are explained in detail.

4.2.1. Maximum Penetration of DG in Feeder

According to the installing DG resources regulation in BREC, the maximum penetration of DG units in feeders is 60%, per Equation (24)

$$P_i^{DG} < 60\% \times P_{load,i}^{\max} \qquad i = 1, 2, \ldots, n_{bus} \tag{24}$$

4.2.2. The Capacity of DG Units

Since BREC aims to install reciprocating DG units with capacities in the range of 10 MW to 25 MW with a step size of 5 MW, these values are used as assumed capacities.

4.2.3. The Power Factor of DG Resources

The power factor of each gas turbine DG units is constant and equal to 0.986 and for PV and wind DG units are 1.

4.2.4. Budget Constraint

One of the essential constraints is the budget constraint, which is not considered in many papers. The BREC annual budget for developing DG resources in the distribution network is 80 million $, Equation (25).

$$Budget \geq C_1 + C_2 + C_4 \quad (25)$$

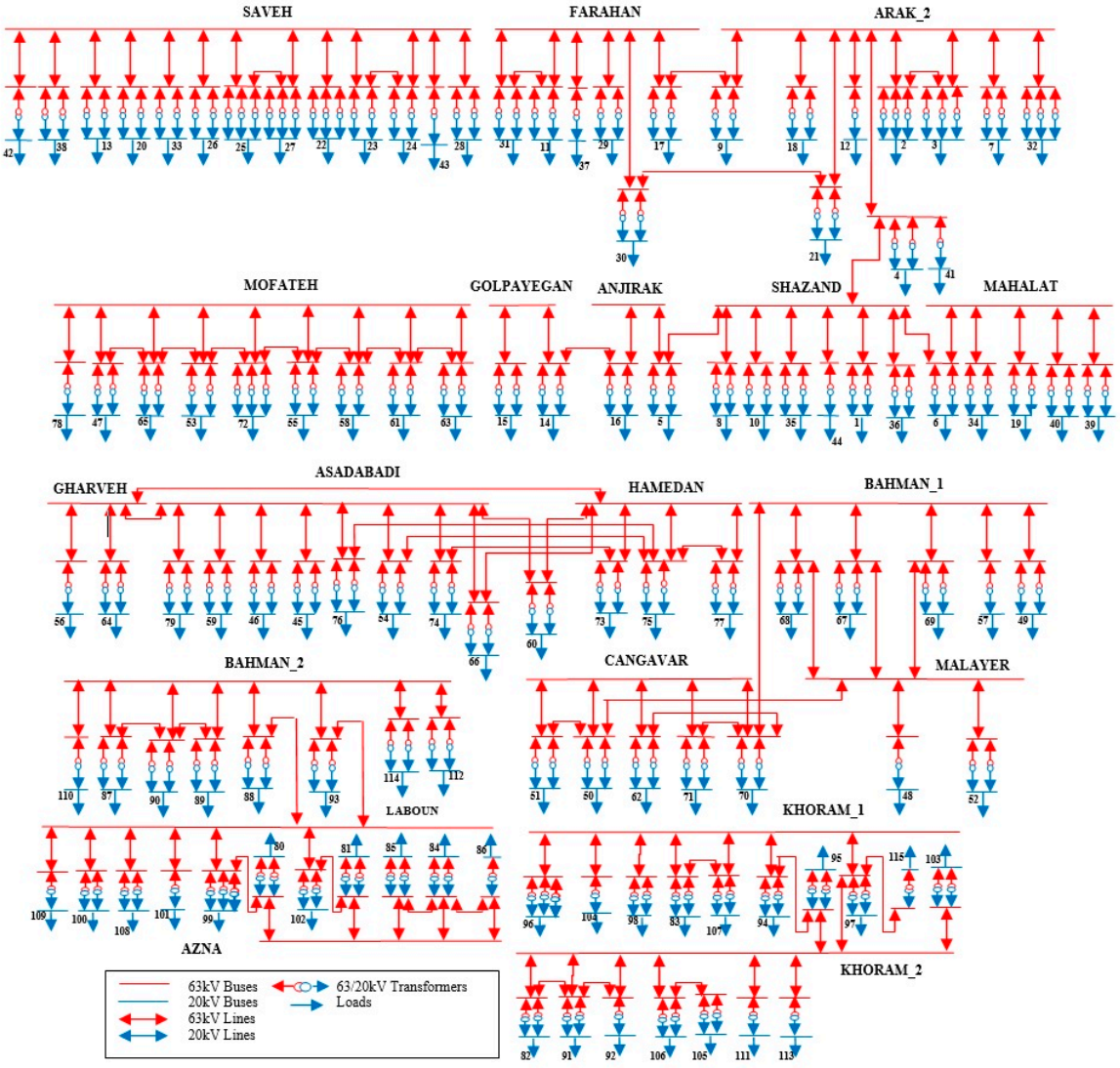


Figure 1. Single line diagram of the BREC network.

4.2.5. The Efficiency of The Gas Turbine Dg Unit (R)

The efficiency of the gas turbine DG units depends on the elevation, weather conditions and humidity. In this case study, since they are stochastic parameters, the efficiency of the gas turbine DG units is constant and equal to 38% throughout the network.

4.2.6. Cost of Natural Gas (F_o)

The cost of natural gas in Iran is 0.05 \$/m^3. The cheap price of natural gas in Iran does not diminish the merit of this research because other countries that have a higher price of natural gas, to the same extent, have a higher price of electricity than Iran.

4.2.7. The Cost of Replacing CBs

In this paper, it is assumed that if CB needs to be replaced, it will be replaced with 25 kA switches. The price of a 25 kA CB is 430,022 $.

4.2.8. Maximum Allowable Tap (Tap_{Max})

This value is obtained from the transformer datasheet. According to the data of BREC transformers, this value assumed 250,000.

4.2.9. The Amount of Voltage Changes in Each Tap

According to the BREC data, each transformer has 16 taps and each tap is capable of changing the voltage by 2.5%.

4.2.10. Allowable Limits of Voltage

The minimum and maximum limits of voltage are selected to be 0.95 (p.u.) and 1.05 (p.u.), respectively [21].

4.2.11. The Cost of Transformers (C_T)

The cost of 63/20 kV transformers in BREC is 13,500 $/MVA.

4.2.12. The Annual Growth Rate of Load (α_{Load})

The annual growth rate of loads in BREC is 4.20%.

4.2.13. The price of demand in the electrical network (E_{demand})

The price of demand in BREC is 56.60 ($/MVAh) [33].

4.2.14. The time Of Power Outage (U)

The time of power outage in each bus of the case study network is equal. The total time of power outage in the BREC network is 15.8 h. 11.5 h of this is the time of power outage in the distribution system. Therefore, the power outage time of the upper distribution system is 4.3 h [33].

4.3. Software and Optimization Technique

The proposed algorithm and the real network are simulated in DIgSILENT Power Factory software. In this paper, the Genetic Algorithm (GA) is used to minimize the Objective Function (OF). More information about used GA, its operation, and optimization technique is presented by the authors in [17,26]. The number of chromosomes and other parameters has been selected according to the present problem of the article. In this case study, the minimum size of DG resources is 10 MW and the maximum penetration of DGs in feeders is 60%. Therefore, on buses where the maximum load is under 16.67 MW, DG resources cannot be installed. On 58 buses, the maximum load is under 16.67 MW. As a result, gas turbine, photovoltaic, and wind DG units can install on 57 buses. A string with 171 chromosomes (57 × 3) is required for each population. In Figure 2, the string of each population is shown. Each string is divided into 57 segments in a way that the each segment is the representative of one of the network buses.

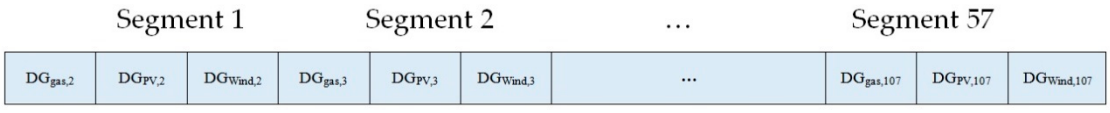


Figure 2. The string of each population.

According to Equations (20) and (23), for allocating photovoltaic and wind turbine renewable DG resources, a constraint is considered to determine the location of these resources. If these equations are not met, a part of the segment (chromosome), which is related to the renewable DG resources, is zero. In other words, when Equation (20) on the *i*th bus is not met, a chromosome related to the active power of the photovoltaic DG resource in the related segment is zero. Similarly, a chromosome related to the active power of the wind turbine DG resource in related segment becomes zero when Equation (23) on the *i*th bus is not met. Thus, the length of string and as a result, the run-time optimization is reduced. Since the BREC network has 115 buses, the run-time optimization is high when a string has 171 chromosomes. However, using the proposed mathematical formulation, the run-time optimization is significantly decreased by declining the number of chromosomes in string.

Reducing run-time optimization is not the sole impact of decreasing the number of chromosomes. It can reduce the probability of that the optimization gets stuck in local minima. Decreasing the number of chromosomes leads to the optimization convergence to global minimum. Besides, Equations (20) and (23) investigate the economic possibility of installing renewable DG resources on a bus.

4.4. Proposed Algorithm for Determining the Optimal Number and Sizing of DG Units

The flowchart of the proposed algorithm for determining the optimal number, sizing, and location of DG units is shown in Figure 3. At the first stage, the number of possible buses (called segment in this paper) for locating DG units is determined according to constraints which are described in Sections 4.2.1 and 4.2.2 Then, the possibility of locating renewable DG resources, which are photovoltaic and wind turbine in this paper, on each segment is investigated by the proposed criteria which are explained in detail in Section 3. In the next step, the proposed objective function, presented in Section 2, is minimized using GA. The cost and benefit functions, presented in Section 2, are linear functions with respect to active power. Therefore, on each segment, only one type of DG resources is sited. If according to optimization results, the capacity of DG units on a segment violates the penetration constraint, the initial capacity of DG units is considered equal to 60% of the maximum load on the segment. Since according to the constraint in Section 4.2.2, the capacity of DG units cannot accept any amount, the greatest allowed capacity of DG units that is smaller than the optimized capacity of the DG units is considered as the final capacity of DG units. Finally, the capacity of DG units on each segments are obtained according to the results of the GA optimization and constraints.

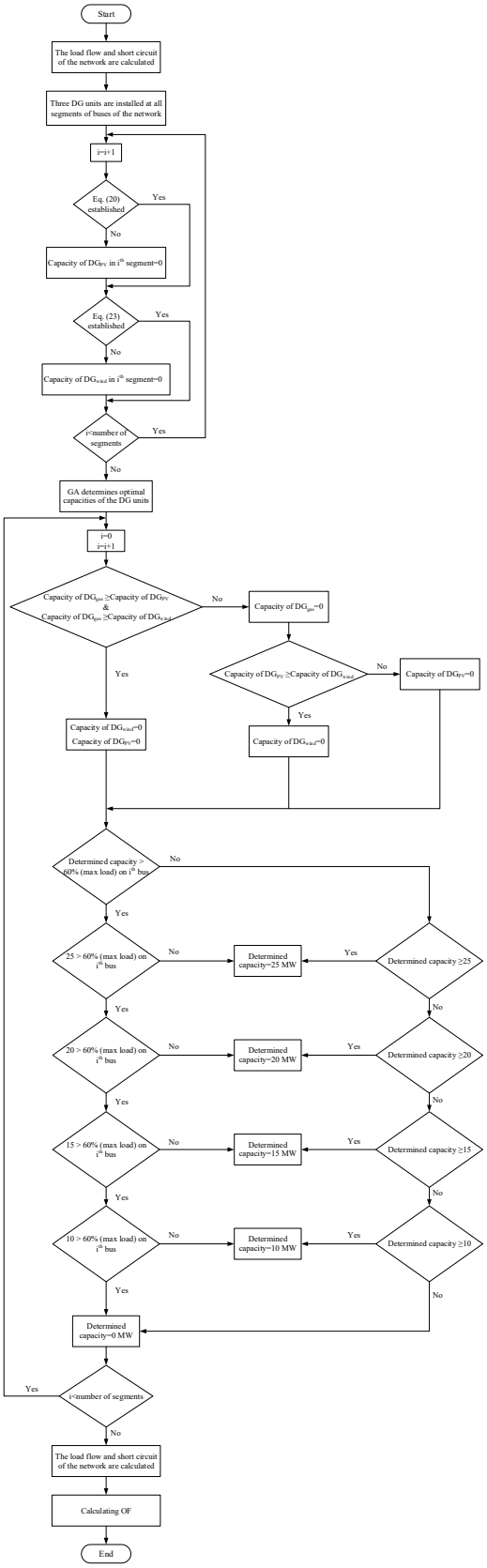


Figure 3. The flowchart of determining the optimal number, sizing and location of DG units.

5. Results and Discussions

Bus locations where Equation (20) established in the BREC network are presented in Table 4. In this table yearly electricity production per MW of the photovoltaic DG resource in each location is presented.

Table 4. Yearly electricity production per MW of the photovoltaic DG resource.

Bus Location	Yearly Electricity Production Per MW (MWh)	Bus Location	Yearly Electricity Production Per MW (MWh)
4	1690	50	1710
12	1690	51	1690
14	1700	82	1700
15	1700	88	1690
16	1710	89	1700
19	1700	90	1700
20	1700	96	1700
25	1710	97	1700
27	1710	98	1690
34	1780	103	1690
39	1700	105	1720
40	1770	106	1720

Bus locations where Equation (23) established in the BREC network are presented in Table 5. In this table yearly electricity production for 660 kW of the wind turbine DG resource in each location is presented.

Table 5. Yearly electricity production for 660 kW of the wind turbine DG resource.

Bus Location	Yearly Electricity Production for 660 kW (MWh)
5	1394
7	1394
10	1403
21	1398
37	1414
75	1480
89	1279
90	1279
107	1274
114	1295

According to the proposed algorithm, results in Tables 4 and 5 are indicated where photovoltaic and wind turbine DG resources can be located.

The new mathematical formulation causes that the GA seeks to obtain the optimal location and sizing of renewable DG resources among candidate buses instead of all buses. Therefore, the advantage of the usage of the new formulation is reducing the amount of calculation. As a result, run-time optimization is decreased. This is an important advantage which distinguishes this article from other previous references.

The run-time optimization without considering Equations (20) and (23) is 26 h and 38 min while by considering these equations, the run-time optimization is decreased to 5 h and 25 min. It means that using the proposed algorithm, the time to reach the optimum results becomes one fifth.

The optimal size and locations of DG resources, which are determined by the proposed algorithm, are presented in Table 6. The optimal number of sitting DG resources is 41 and the total size is 540 MW, that 7 of these DG resources are photovoltaic (on buses number 4, 19, 27, 34, 50, 88, and 96) and the sum of them is 120 MW, 3 of these DG resources are wind turbine (on buses number 10, 89 and 107)

and the total size of them is 40 MW, and other 31 of these DG resources are gas turbine and the total size of them is 380 MW.

According to the simulation results, the penetration of DG resources in this paper for the BREC network is 25.96%, while in reference [4], this value is 61.43% which is not acceptable, because it is higher than the limit of the maximum penetration of DG.

Table 6. Optimal size and locations of DG resources.

Bus Location	DG Size (MW)	Bus Location	DG Size (MW)	Bus Location	DG Size (MW)	Bus Location	DG Size (MW)	Bus Location	DG Size (MW)
1	0	24	0	47	0	70	15	93	10
2	10	25	0	48	0	71	0	94	0
3	15	26	10	49	0	72	0	95	0
4	25	27	25	50	10	73	10	96	25
5	0	28	10	51	0	74	15	97	0
6	15	29	0	52	0	75	0	98	0
7	0	30	10	53	0	76	20	99	0
8	0	31	0	54	15	77	15	100	10
9	10	32	0	55	10	78	0	101	0
10	10	33	0	56	0	79	0	102	0
11	0	34	10	57	0	80	10	103	0
12	0	35	10	58	10	81	10	104	0
13	0	36	0	59	0	82	0	105	0
14	10	37	0	60	0	83	0	106	0
15	0	38	0	61	10	84	10	107	15
16	0	39	0	62	10	85	0	108	0
17	20	40	0	63	0	86	0	109	0
18	0	41	0	64	0	87	0	110	0
19	15	42	0	65	0	88	10	111	0
20	0	43	0	66	10	89	15	112	0
21	0	44	0	67	0	90	0	113	0
22	20	45	0	68	15	91	10	114	0
23	15	46	10	69	0	92	0	115	0

In Table 7, the total size of each type of DG per province and the share of each type of DG in the BREC network is shown. The percentage of installing renewable DG resources using the proposed optimal sizing algorithm is 29.63%, and other DG resources are non-renewable DG resources.

The current capacity of installed renewable DG resources in Iran's power grid is 831 MW [32] while the peak load is 58,254 MW [35]. It means that the present share of renewable DG resources in Iran's grid is approximately 1.43%. However, using the proposed algorithm, the share of renewable

DG resources in the case study is 7.69%. Consequently, the proposed algorithm can efficiently gain the participation of renewable DG resources in generating energy.

Table 7. The total size of each type of DG resources per province.

Province	Photovoltaic DG (MW)	Wind DG (MW)	Gas DG (MW)	Total (MW)
Markazi	75	10	155	240
Hamedan	10	0	165	175
Lorestan	35	30	60	125
Total (MW)	120	40	380	540
Total (%)	22.22%	7.41%	70.37%	100%

In Table 8, the annual value of considered cost and benefit factors is indicated. The value of the OF is 0.8185, and the ratio of the benefit to the cost is 1.2217 which is more than the interest ratio. Thus, the results show the efficiency of the proposed algorithm.

Table 8. The annual value of cost and benefit factors.

Annual Cost Factors ($)		Annual Benefit Factors ($)	
C_1	68,781,042.12	B_1	126,712,251.10
C_2	11,040,000.00	B_2	8,128,230.75
C_3	35,748,802.80	B_3	3,754,794.45
C_4	168,915.22	B_4	328,959.90
		B_5	2,342,278.30
		B_6	132,738.37
Total	115,738,760.14	Total	141,399,252.87

In Table 9 the short circuit level of each buses in the BREC network is presented after optimal allocation and sizing of DG resources. According to these results, the short circuit level at two buses, which are buses number 2 and 27, have exceeded the allowable range of CBs. Thus, these CBs must be replaced.

To save costs we can change the placement of CBs in the BREC network in a way that the short circuit level of all buses is in the allowed range. For this reason, it is not unnecessary to purchase new CBs. According to results of simulations, we changed the CBs place of buses 1 and 2 each other, and 21 and 27 one another. In other words, the replacing cost of circuit breakers (C_4) can be zero. As a result, the value of the OF equals 0.8173 and following this, the ratio of the benefit to the cost is 1.2235. This means that by employing the proposed algorithm for the allocation and sizing of DG units, the benefit is gained by 22.35%.

As mentioned earlier, the value of functions in the objective function are converted to monetary values which is an advantage of the proposed algorithm. This is because of that in references [17,26], weighted coefficients have been considered in their objective function which is always questionable. The results are given in Table 8 for benefit functions. The effect of each benefit function on the objective function is shown in percentage terms in Table 10.

The results of Table 10 indicate that the major part of the benefit is related to purchasing less active and reactive power from the transmission network. If we want to increase or decrease the effect or importance of each of the benefit functions on the objective function in BREC network, we can put a weight coefficients in the OF. Another advantage of the proposed algorithm is that free from any weighted coefficients, the effect of each benefit on the objective function is specified. In Table 10, the comparison of the effect of each benefit function on the OF can be performed because all benefit relations are monetary. It can be seen the benefit of reducing power losses is higher than the benefit

of deferring substation capacity development. Furthermore, the effect of benefit of improvement in voltage profile is higher than the effect of benefit of improvement in reliability.

Table 9. The short circuit level of each bus in BREC after DG allocation.

Bus Location	SC Level (kA)	Bus Location	SC Level (kA)	Bus Location	SC Level (kA)	Bus Location	SC Level (kA)	Bus Location	SC Level (kA)
1	13.3	24	17.6	47	16.8	70	15.2	93	16.1
2	21.7	25	11.4	48	2.4	71	15	94	9
3	18.6	26	16.3	49	10.5	72	7	95	10.2
4	16.1	27	24	50	14	73	14.5	96	17.5
5	12.9	28	23.5	51	12.1	74	13.1	97	18
6	4.8	29	18	52	2.2	75	15.8	98	7.4
7	8.5	30	5.9	53	13.9	76	8	99	8.3
8	4.2	31	13.7	54	14	77	13.8	100	14.2
9	16	32	12	55	13.8	78	7.6	101	9.5
10	18.1	33	10.1	56	1.9	79	2.1	102	7.4
11	4.1	34	11.5	57	14	80	9.9	103	3.9
12	3.9	35	15.4	58	16	81	10.2	104	2.5
13	3	36	4.7	59	8.3	82	14	105	1.8
14	7.9	37	3.8	60	13.7	83	8	106	2.8
15	12.5	38	6.6	61	13.8	84	6.7	107	5
16	9.8	39	4	62	12.1	85	12	108	1.8
17	15.8	40	6.2	63	16	86	6.5	109	3
18	14.2	41	5	64	8.8	87	8	110	2.2
19	12.3	42	9.4	65	8.9	88	14.1	111	4.3
20	8.4	43	7.2	66	13.5	89	14.2	112	1.8
21	7.9	44	3.1	67	14	90	10	113	1.7
22	19.9	45	12	68	16.4	91	15	114	2.2
23	15.1	46	14.7	69	14.9	92	10.9	115	2

Table 10. Effect of benefit functions on the OF.

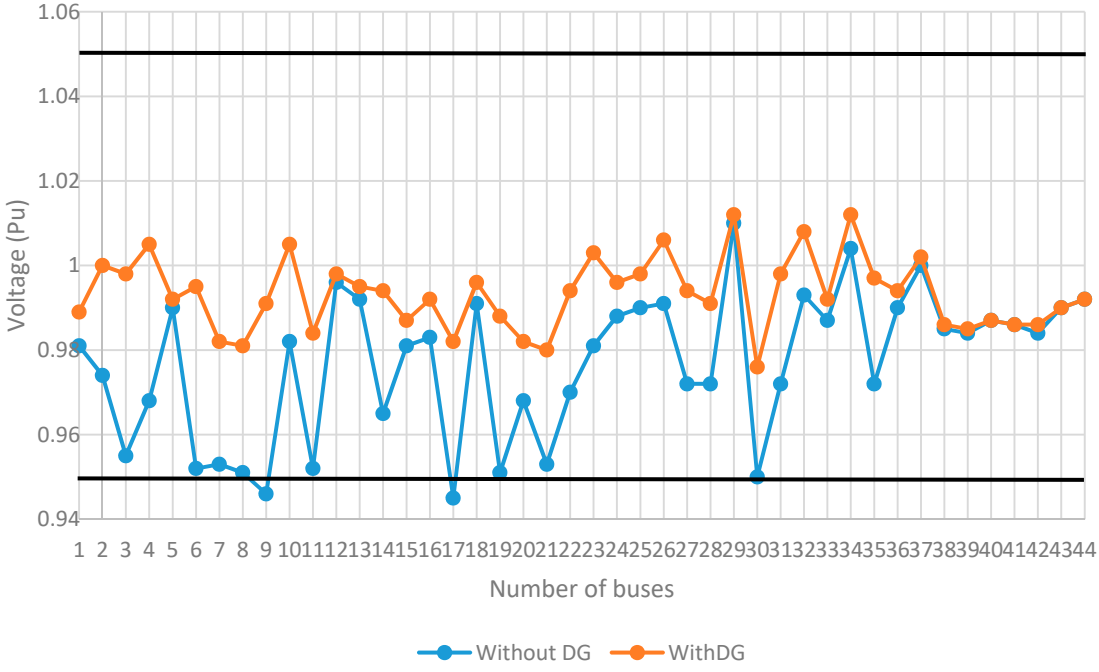
B_1	B_2	B_3	B_4	B_5	B_6
89.61%	5.75%	2.66%	0.23%	1.66%	0.09%

Figure 4 shows the voltage profile of buses for each province. According to Figure 4, after installing DG resources, the voltage profile in each province is placed within the allowable range and around 1 p.u., and it uses less transformer tapping for regulating voltage profile. However, in reference [4], the obtained voltage profile after the allocation of DG units in some buses is not within the allowable range. Thus, the results of this article are superior to the results of reference [4] which shows the significance of the proposed algorithm.

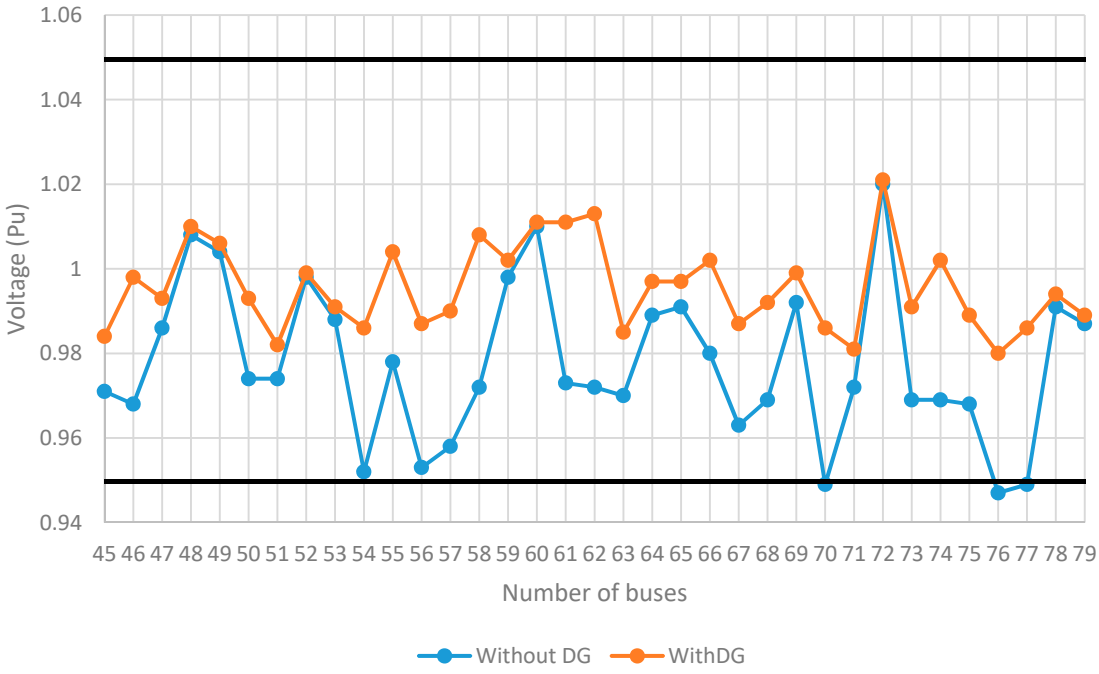
It is obvious that the voltage of buses in which DG resources are located, significantly enhances. In addition, to prevent over voltage, the proposed algorithm does not suggest placing DG resources on buses which the voltage of them is almost 1 p.u. or over them.

The power loss of the BREC network before installing DG resources is 57.34 MW. The power loss after installing DG units with the proposed algorithm without considering Equations (20) and (23) is 43.58 MW.

Figure 5 shows the power loss of the BREC network before and after installing DG resources. The power loss after installing DG units using the proposed algorithm is 43.58 MW. In other words, the power loss is reduced by 24% after installing DG resources in the BREC network.

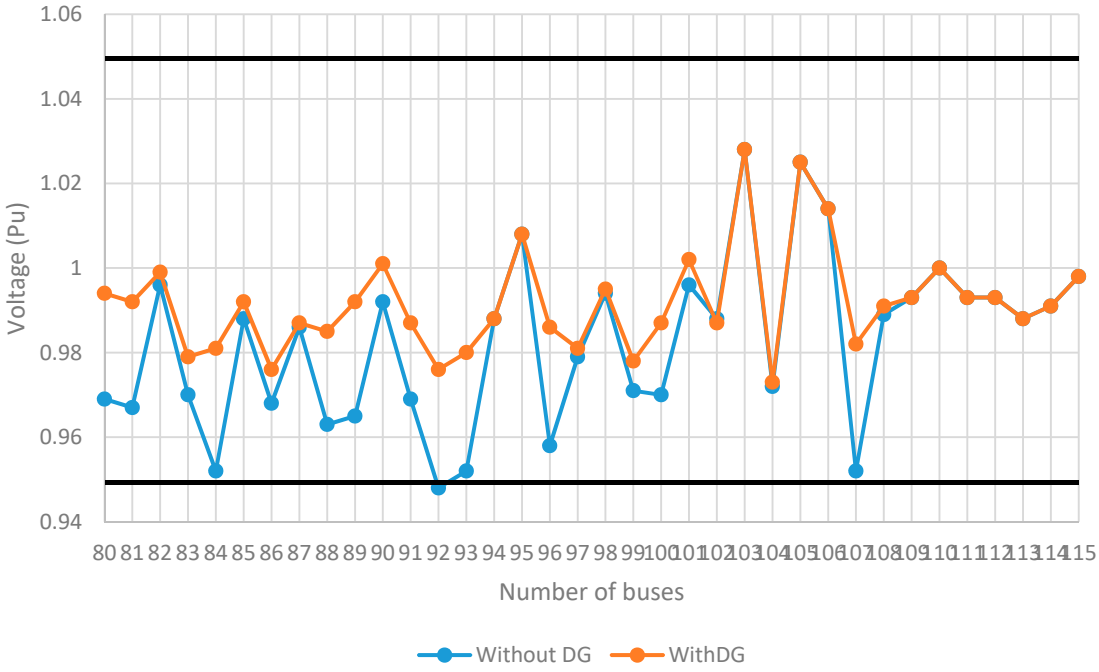


(**a**) Markazi province



(**b**) Hamedan province

Figure 4. *Cont.*



(**c**) Lorestan province

Figure 4. The voltage profile of buses for: (**a**) Markazi province; (**b**) Hamedan province; (**c**) Lorestan province.

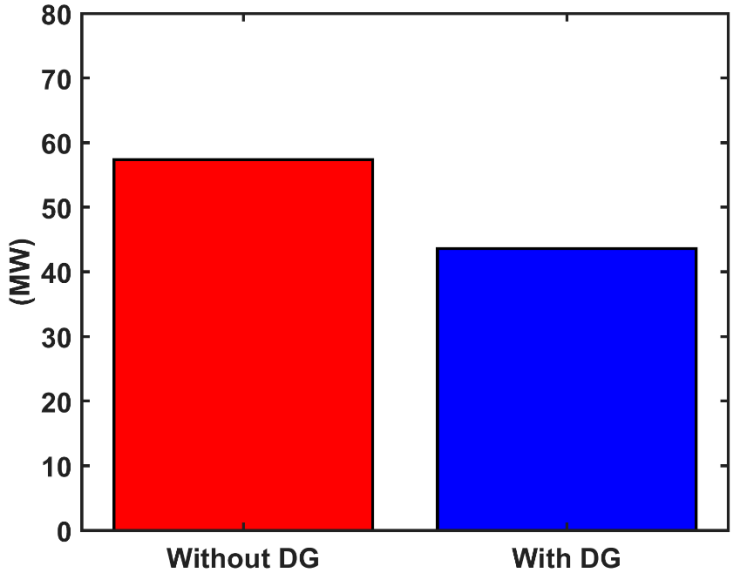


Figure 5. Power loss before and after installing the DG resources.

6. Conclusions

In this paper, a new multi-criteria algorithm was proposed for the optimal sizing and allocation of renewable and non-renewable DG resources simultaneously in 63/20 kV substations at 20 kV levels. Besides, a new mathematical formulation is introduced for the allocation of renewable DG resources. The proposed algorithm uses the genetic algorithm to minimize the proposed objective function. To validate the performance of the proposed algorithm, it was applied to the 115 buses network of Bakhtar Regional Electric Company (BREC) in Iran. The results demonstrate that the proposed algorithm has superior performance compared to the previous research studies. By using

the proposed algorithm, the run-time optimization is decreased by five times which is one of the significant findings of the article. In the proposed objective function all important technical and economic factors as well as important constraints of the network are monetarily considered. This is an important step because the objective function is free from weight coefficients. Using the proposed objective function in the BREC network, the ratio of the benefit to the cost is 1.2235. This means that the proposed algorithm for optimal allocation of DG resources made 22.35% profit, which is worthwhile because it is more than the interest ratio. The optimal number of sitting DG resources is 41 and the total size is 540 MW. In addition, the penetration of DG resources in this paper for the BREC network is 25.96%. The percentage of installing renewable DG resources is 6.26% greater than that of Iran's national grid. Thus, according to a current trend toward expanding the usage of renewable DG resources, the proposed algorithm was successful in covering this trend. In this paper, the effect of each benefit function on the objective function is presented. The major part of the benefit is related to purchasing less active and reactive powers with 89.61% and 5.75%, respectively. The results indicated that, if renewable and non-renewable DG resources are installed according to the proposed algorithm, the power loss will be reduced by 24% and the voltage profile in each province will be around 1 p.u. Suggestions for future work are as follows:

1. The optimal allocation of DG resources by the proposed objective function in the presence of other distributed energy resources (DERs)
2. Comparing the performance of other heuristic, meta-heuristic and non-heuristic optimization algorithms with the performance of the GA for the optimal allocation of DG resources using the proposed objective function

Author Contributions: Methodology, formal analysis, simulation, and investigation, S.S.K.M.; writing—original draft preparation, and writing—review and editing, S.S.K.M. and A.T.S.; All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

BREC	Bakhtar Regional Electric Company
CB	Circuit Breaker
DER	Distributed Energy Resource
DG	Distributed Generation
GA	Genetic Algorithm
OF	Objective Function
PV	Photovoltaic

References

1. Shahzad, M.; Ahmad, I.; Gawlik, W.; Palensky, P. Load Concentration Factor Based Analytical Method for Optimal Placement of Multiple Distribution Generators for Loss Minimization and Voltage Profile Improvement. *Energies* **2016**, *9*, 287. [CrossRef]
2. Nejad, H.C.; Tavakoli, S.; Ghadimi, N.; Korjani, S.; Nojavan, S.; Pashaei-Didani, H. Reliability based optimal allocation of distributed generations in transmission systems under demand response program. *Electr. Power Syst. Res.* **2019**, *176*, 105952. [CrossRef]
3. Prakash, P.; Khatod, D.K. Optimal sizing and siting techniques for distributed generation in distribution systems: A review. *Renew. Sustain. Energy Rev.* **2016**, *57*, 111–130. [CrossRef]
4. Hosseini, S.A.; Eslami, R.; Vahidi, B.; Askarian Abyaneh, H.; Sadeghi, S.H.H.; Mohseni, K. Installing distributed generation units and capacitors simultaneously in a distribution system considering economic issues. *J. Renew. Sustain. Energy* **2014**, *6*, 023122. [CrossRef]

5. Naeem, A.; Hassan, N.U.; Yuen, C.; Muyeen, S.M. Maximizing the Economic Benefits of a Grid-Tied Microgrid Using Solar-Wind Complementarity. *Energies* **2019**, *12*, 395. [CrossRef]
6. Bahrami, M.; Abbaszadeh, P. An overview of renewable energies in Iran. *Renew. Sustain. Energy Rev.* **2013**, *24*, 198–208. [CrossRef]
7. Ghorashi, A.H.; Rahimi, A. Renewable and non-renewable energy status in Iran: Art of know-how and technology-gaps. *Renew. Sustain. Energy Rev.* **2011**, *15*, 729–736. [CrossRef]
8. Sadiq, A.A.; Adamu, S.S.; Buhari, M. Optimal distributed generation planning in distribution networks: A comparison of transmission network models with FACTS. *Eng. Sci. Technol. Int. J.* **2019**, *22*, 33–46. [CrossRef]
9. Kayal, P.; Chanda, S.; Chanda, C.K. An analytical approach for allocation and sizing of distributed generations in radial distribution network. *Int. Trans. Electr. Energy Syst.* **2017**, *27*, e2322. [CrossRef]
10. Sambaiah, K.S. A Review on Optimal Allocation and Sizing Techniques for DG in Distribution Systems. *Int. J. Renew. Energy Res.* **2018**, *8*, 1238.
11. Siahi, M.; Porkar, S.; Abbaspour-Tehrani-Fard, A.; Poure, P.; Saadate, S. Competitive distribution system planning model integration of DG, interruptible load and voltage regulator devices. *IJST Trans. B Eng.* **2010**, *34*, 619–635.
12. Mahesh, K.; Nallagownden, P.; Elamvazuthi, I. Advanced Pareto Front Non-Dominated Sorting Multi-Objective Particle Swarm Optimization for Optimal Placement and Sizing of Distributed Generation. *Energies* **2016**, *9*, 982. [CrossRef]
13. Suresh, M.C.V.; Edward, J.B. A hybrid algorithm based optimal placement of DG units for loss reduction in the distribution system. *Appl. Soft Comput.* **2020**, *91*, 106191. [CrossRef]
14. Kumar, S.; Mandal, K.K.; Chakraborty, N. Optimal DG placement by multi-objective opposition based chaotic differential evolution for techno-economic analysis. *Appl. Soft Comput.* **2019**, *78*, 70–83. [CrossRef]
15. Moravej, Z.; Ardejani, P.E.; Imani, A. Optimum placement and sizing of DG units based on improving voltage stability using multi-objective evolutionary algorithm. *J. Renew. Sustain. Energy* **2018**, *10*, 055304. [CrossRef]
16. Dayapera, R.M.; Aguirre, R.A. Determination of penetration limit of solar distributed generation (DG) considering multiple bus integration. In Proceedings of the IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), Kota Kinabalu, Malaysia, 7–10 October 2018; pp. 508–513.
17. Hosseini, S.A.; Madahi, S.S.K.; Razavi, F.; Karami, M.; Ghadimi, A.A. Optimal sizing and siting distributed generation resources using a multiobjective algorithm. *Turk. J. Electr. Eng. Comput. Sci.* **2013**, *21*, 825–850.
18. Pesaran, H.A.M.; Huy, P.D.; Ramachandaramurthy, V.K. A review of the optimal allocation of distributed generation: Objectives, constraints, methods, and algorithms. *Renew. Sustain. Energy Rev.* **2017**, *75*, 293–312. [CrossRef]
19. Ali, A.; Padmanaban, S.; Twala, B.; Marwala, T. Electric Power Grids Distribution Generation System for Optimal Location and Sizing—A Case Study Investigation by Various Optimization Algorithms. *Energies* **2017**, *10*, 960.
20. Hemeida, M.G.; Alkhalaf, S.; Mohamed, A.A.; Ibrahim, A.A.; Senjyu, T. Distributed Generators Optimization Based on Multi-Objective Functions Using Manta Rays Foraging Optimization Algorithm (MRFO). *Energies* **2020**, *13*, 3847. [CrossRef]
21. Hosseini, S.A.; Karami, M.; Karimi Madahi, S.S.; Razavi, F.; Ghadimi, A.A. Finding the optimal capacity and location of distributed generation resources and analyzing the impact of different coefficient factors. *J. Basic Appl. Sci. Res.* **2011**, *1*, 2578–2589.
22. Gong, Q.; Lei, J.; Ye, J. Optimal Siting and Sizing of Distributed Generators in Distribution Systems Considering Cost of Operation Risk. *Energies* **2016**, *9*, 61. [CrossRef]
23. Ahmed, A.; Nadeem, M.F.; Sajjad, I.A.; Bo, R.; Khan, I.A.; Raza, A. Probabilistic generation model for optimal allocation of wind DG in distribution systems with time varying load models. *Sustain. Energy Grids Netw.* **2020**, *22*, 100358. [CrossRef]
24. Masaud, T.M.; El-Saadany, E.F. Optimal Wind DG Integration for Security Risk-Based Line Overload Enhancement: A Two Stage Approach. *IEEE Access* **2020**, *8*, 11939–11947. [CrossRef]
25. Ifaei, P.; Farid, A.; Yoo, C. An optimal renewable energy management strategy with and without hydropower using a factor weighted multi-criteria decision making analysis and nation-wide big data—Case study in Iran. *Energy* **2018**, *158*, 357–372. [CrossRef]
26. Hosseini, S.A.; Karami, M.; Karimi Madahi, S.S.; Razavi, F.; Ghadimi, A.A. Optimal capacity, location and number of distributed generation at 20 kV substations. *Aust. J. Basic Appl. Sci.* **2011**, *5*, 1051–1068.

27. Geoffrey, R.; Tomas, G. *Electricity Economics: Regulation and Deregulation*; John Wiley and Sons: Hoboken, NJ, USA, 2003.
28. Hosseini, S.A.; Abyaneh, H.A.; Sadeghi, S.H.H.; Razavi, F.; Karami, M. Optimal sizing and siting of DG resources at 63 KV/20 KV substations considering the effect of earthquake on technical and economic parameters. *IJST Trans. Electr. Eng.* **2015**, *39*, 133–153.
29. European Commission. Photovoltaic Geographical Information System (PVGIS). Available online: https://ec.europa.eu/jrc/en/pvgis (accessed on 3 August 2020).
30. Gaisma. Solar Energy and Surface Meteorology. Available online: https://www.gaisma.com/en/dir/ir-country.html (accessed on 3 August 2020).
31. Doohnal, D. *On-Load Tap-Changers for Power Transformers*; Maschinenfabrik Reinhausen GmbH: Regensburg, Germany, 2013.
32. Renewable Energy and Energy Efficiency Organization. Information. Available online: www.satba.gov.ir/fa/satba/information (accessed on 3 August 2020).
33. Bakhtar Regional Electric Company's Portal. Available online: w.brec.ir (accessed on 3 August 2020).
34. Trading Economics. Available online: https://tradingeconomics.com (accessed on 3 August 2020).
35. Iran Grid Management Co. Power Grid Status Report. Available online: www.igmc.ir/Power-grid-status-report (accessed on 3 August 2020).

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