Efficient Placement of Distributed Generation Units in Distribution Networks Using Data Envelopment Analysis Ranking of Proper Busses

Saeed Abapour[1], Mehdi Jalali[2], Kazem Zare[3*]
Department of Electrical Engineering, University of Tabriz, Tabriz, Iran
1- Email: s.abapour90@ms.tabrizu.ac.ir
2- Email: m.jalali90@ms.tabrizu.ac.ir
3- Email: kazem.zare@tabrizu.ac.ir*

Received: March 2014 Revised: June 2014 Accepted: August 2014

ABSTRACT
In this paper, we applied the Data Envelopment Analysis (DEA) ranking method to have efficient placement of Distributed Generation (DG) in distribution network. In this regard first an analytical method to find the optimal size of DG in the network is used to reach the lowest possible losses. In this paper, benchmarks such as improvement of voltage profile, reducing energy not supplied value (as an index of reliability), reducing environmental pollution, and values related to the purchase and installation costs of DG equipment in each busses for selecting the appropriate DG location are considered, in addition to the network loss reduction. This method has been used because the loss reduction of whole the network will not be a complete criteria for selecting the best location to install DG, The necessarily node which has the highest reduction in power losses cannot be considered suitable node for the installation of DG. Therefore we used DEA to determine the most effective location for DG placement. The proposed method is implementation over the network of 33 buses and the results are presented. GAMS software is used for the simulation results extraction.

KEYWORDS: Efficient Placement, Distributed Generation, Data Envelopment Analysis and Ranking.

1. INTRODUCTION

With the development of economic and raising the standard of living of people, customers require more reliable electricity and the quality. By considering the parameters such as low investment cost and compatibility with the environment, Industrial countries have preceded to simultaneous operation of DGs and the main power network to increase the flexibility, reliability and security of power system. In this regard, the loss reduction of distribution systems is a great challenge [1]. Restructuring and the use of active network management are two main ways to loss reduction in distribution systems. Main challenge in using DG for loss reduction is to find the best location, suitable size and its deployment strategy. Inappropriate DG sizes can increases the loss compared with its previous state.

It is obvious that planning, design and the improvement of distribution network, DG placement is a complicated process. There are several criteria for selecting the optimal DG location. For example, the environmental problems caused by the high consumption of energy have increased dramatically so that the environmental protection is more important. The policies of environmental protection and evaluate its cost in many countries is not complete. Thus, the impact of DG in reducing the environmental pollution can be one of these criteria. To evaluate the environmental impacts of DG, a simple model has been used in [2].

On the other hand, if DG can supply the electricity of customers in a reasonable price without the security and reliability reduction, thus it can be on interest case. Therefore, the reliability of distribution networks is one of the most important challenges faced by designers of power systems [3]. So if the size and the location of DG are calculated properly, it can be an effective method to reduce loss, improve the voltage profile and increasing the reliability of networks. The processes of DG placement based on objective functions and solution techniques are several. In most cases the DG placement was performed based on minimizing of networks losses. The several optimization techniques and solving ways such as a nonlinear programming method in combination with GA [4], Tabu Search [5], an innovative methods of repetitive [6], multi objective planning [7] and analytically methodology [8] has been used. In [9-11] the DG placement has been done based on maximizing the capacity of DG. Indices such as reliability, reduce the cost of power outages of customers, reduce the investment costs and improve the voltage profiles are based on DG Placement in [12-14]. In this paper for the best appropriate bus selection to install of DG, its best capacity for loss reduction is found based on the analytical method which is expressed in [15]. Then objectives and various criteria are calculated in each bus for the same specified capacity of DG. Then using the DEA method and based on all indices, the most efficient of busses for DG installations are ranked. DEA is a quantitative method for evaluating the efficiency and recently is used in power system widely [16]. In the power systems area, DEA has been used to measure and evaluate the performance of Electricity Company [17]. In [18] DEA method is used for benchmarking and evaluates the distribution networks and reorganization of the electrical company. In [18, 19] DEA has been used to assess the efficiency of distribution lines and the distribution network restructuring.

The structure of paper is as follows: In section 2, the analytical method to find the optimal location of DG along with the other various technical and economic indices associated with DG is presented. In Section 3, the DEA approach is described in details. In Section 4 provides the numerical results and the related discussion obtained from the application of the proposed approach on the sample network and is discussed onto results and the concluding remarks are made in Section 5.

2. ASSESSMENT SYSTEM

The proposed method for DG allocation is shown in Fig. 1. To select the best buses for DG installation, the required criteria should be evaluated. Since DG placement in distribution networks is done in order to achieve the predefined objective, other objectives and their related should be calculated and then, the busses will be ranked. These objectives are introduced as following:

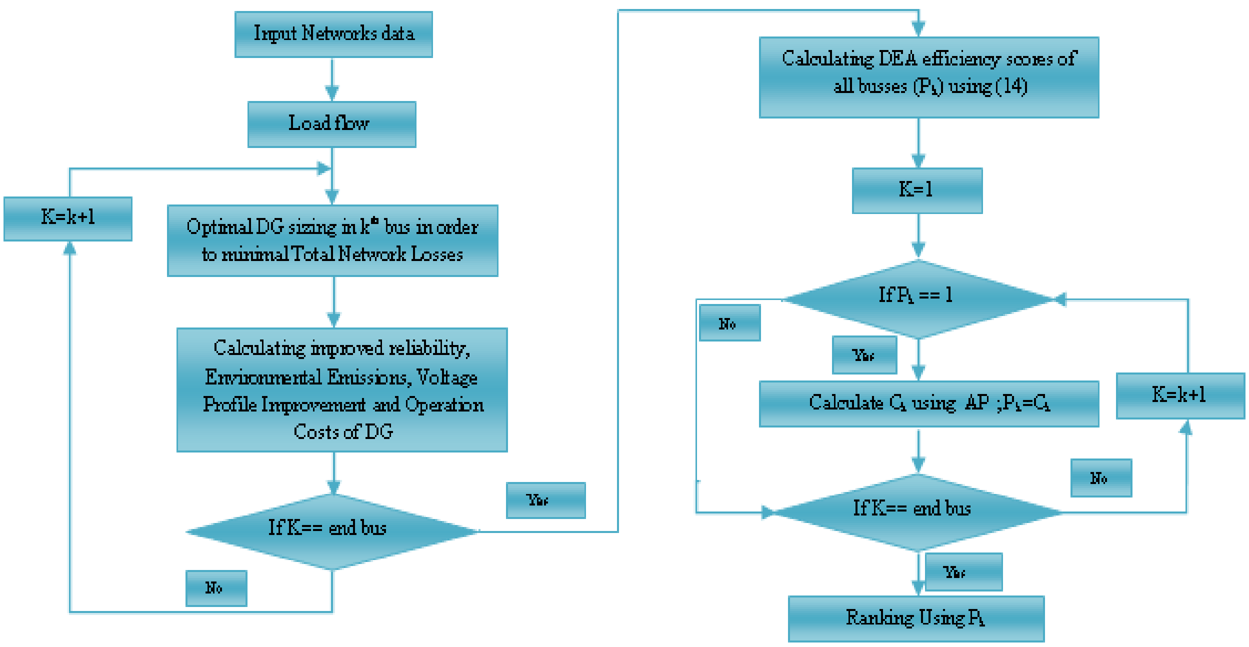

Fig. 1. Flowchart of the proposed algorithm

2.1. Line loss reduction

One of the main objectives of DG installation is the network loss reduction generally through the power generating by DG units, the power transmission of upstream networks towards consumers will be decreased and thus the line loss in distribution network will be decreased. To determine the optimal DG capacity in each bus to minimize the network losses and analytical methodology is proposed in [20]. The total network losses are calculated as follows:

$$P_l = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)] \qquad (1)$$

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos(\delta_i - \delta_j)\ ;\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right) \qquad (2)$$

Where P_i and P_j are active powers and Q_i and Q_j are reactive powers injection at buses i and j respectively. V_i and δ_i represents the amplitude and phase angle of voltage bus i and r_{ij} represents the resistance of the line

between buses i and j. Also N shows the number of network buses.
According to Eq.1, the optimal size of DG at bus i, to have a minimum loss, is calculated as follows:

$$P_{DG_i} = \frac{\alpha_{ii}\left(P_{D_i} + \alpha Q_{D_i}\right) + \beta_{ii}\left(\alpha P_{D_i} - Q_{D_i}\right) - X_i - \alpha Y_i}{\alpha^2 \alpha_{ii} + \alpha_{ii}} \quad (3)$$

Where X_i, Y_i , a and PF_{dg} are as follows:

$$X_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} (\alpha_{ij} P_j - \beta_{ij} Q_j) \quad (4)$$

$$Y_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} \left(\alpha_{ij} Q_j - \beta_{ij} P_j\right) \quad (5)$$

$$\alpha = \left(sign\right)\left(tg\left(\cos^{-1}\left(PF_{DG}\right)\right)\right) \quad (6)$$

The sign function depends on the status of the DG. It will be positive, if the DG generates reactive power and it is negative, if it absorbs reactive power. The DG power factor (PF_{dg}) will depend on its type and operating conditions.

2.2. Voltage Profiles Improvement (VPI)

The voltage profiles improvement of distribution networks is one of the main targets which can be achieved by installing the sufficient DG capacity. One of the methods to VPI measurement is minimizing the voltage deviation from the reference voltage in each node. This index can be expressed as follows:

$$VPI = \sum_{k=1}^{p} \sum_{i=1}^{N_b} \frac{|V_i - V_{ref}|}{V_{ref}} \Delta t_k \quad (7)$$

Where V_i is voltage at node i, V_{ref} is the reference voltage of network. Δt_k is the interval time of operation and P shows the number of operation time intervals.

2.3. Reduce the Energy Not Supplied (ENS)

Another objective for DG installation is to increase the system reliability. Reduction the ENS value can be criteria of increasing the reliability of distribution network. DNOs want to minimize the ENS value in order to enhance the utilization coefficient of the existing network equipment. According to [21] the following equation is used to express the amount of energy not supplied value:

$$P_{ENSj} = \sum_{i=1}^{nb} \left\{ P_{ij} - \left(V_i - V_j\right)^2 / Z_{ij} \right\} - \sum_{i=1}^{nlb} P_{ji} + P_{DG,j} - P_{D,i} \quad (8)$$

Where P_{ENSj} is the active power which is not supplied at j^{th} node. P_{ij} is power transfer from node i to j Z_{ij} is the impedance between two nodes i and j. $P_{D,i}$ is load at node i, P_{DGj} is the installed DG capacity at node j, and Vi is the voltage at node i. n_b is the total number of buses and n_{lb} is load buses in distribution network.

2.4. Environmental Emissions Function

The environmental problems caused by the high consumption of energy are increasing. Therefore the environmental policy and the assessment of its costs is one of the fundamental issues in many countries. The effect of DG in reducing the environmental pollution could be one of the important criteria in DG placement, as following:

$$\varphi = \left(E_c + E_L - E_{DG}\right)\gamma_T - \sum_{j=1}^{N_{DG}} \left[\left(8760 \times N \times P_{DG_i}\right)\gamma_{DG_i}\right] \quad (9)$$

Where γ_T , is the pollution coefficient for a variety of the production technology for energy absorption from the upstream network and γ_{DGi} is the pollution coefficient dependent on j^{th} generator. E_C, E_L, and E_{DG} show the absorbed energy by the consumer, energy loss and generated energy by DG, respectively.

2.5. Installation and Operation Cost of DG

The cost function which encompasses the typical cost of distribution companies [22].

$$Cost\ Function = C_{inv,DG} + C_E + C_{O\&M} \quad (10)$$

In the Eq.8, $C_{O\&M}$ is the operation and maintain cost and $C_{inv,DG}$ is the investment and installation costs of DG which is defined as following:

$$C = \frac{\sum_{i=1}^{B} C_{inv_i} . P_{DG_i}^{\max}}{A \times 8760} \quad (11)$$

Where $C_{inv,i}$ is the capital investment cost for the establishment of DG units. A will be prorate coefficient of capital in the period T years. C_E is the cost of power purchasing from TRANSCO.

$$C_E = \sum_{i=1}^{B} P_{net} C_p + Q_{net} C_Q \qquad (12)$$

Where C_P and C_Q are the cost of purchased active and reactive power from TRANSCO. P_{net} and Q_{net} are the amount of purchased active and reactive power from TRANSCO, respectively. $C_{O\&M}$ is the cost of generation and maintenance of DG units which is defined as the ratio of generated DG power.

In this paper it is considered that the loss reduction is the base objective for DG placement. Accordingly, after its results, other objectives will be evaluated and then by using the DEA methodology, the related buses will be ranked.

3. DATA ENVELOPMENT ANALYSIS (DEA)

In order to evaluate the performance and compare several decisions making units (DMUs), the maximum output of DMUs should be available as a function of their inputs. This function is called the production function which can be written as following:

$$Y = f(W, V) \qquad (13)$$

where inputs of the production function of each DMU includes a vector of known variables (W) and a vector of unknown variables (V).

Using the above function, the information of performance of DMUs can be acquired, however, it is almost impossible to obtain the mathematical form of the above function. Therefore, inevitably, an approximation of production function should be considered. This approximation is regarded in two forms of parametric or non-parametric.

In parametric methods, at first, the shape of production function is considered as a mathematical formula. Then, the parameters of function are determined using special methods such as interpolation which are not capable of determining the shape of the function and hence are unsuitable in multi-output functions.

To deal with these difficulties, in [14], an approximation of the production function as a non-parametric method was proposed in which, using observations and undeniable principles of the economic science, the production possibility set (PPS) is created and its boundary is considered as an approximation for production function. In non-parametric methods, any decision making unit which is on the boundary of this set is called efficient and otherwise is regarded inefficient.

DEA is a non-parametric method based on linear programming to determine the relative efficiency scores of a set of homogeneous organizational units which are called decision-making units (DMUs).

3.1. Relative Efficiency Scores

Assume that there are n decision making units that produce outputs $Y_1, Y_2, \ldots, Y_n$ by employing inputs $X_1, X_2, \ldots, X_n$,respectively. Relative efficiency of j^{th} unit shown with RE_j, can be expressed as:

$$RE_j = \frac{\frac{Y_j}{X_j}}{\underset{1 \le k \le n}{Max}\left(\frac{Y_k}{X_k}\right)} \qquad (14)$$

It is obvious that the, j^{th} decision making unit is relatively efficient if its corresponding RE equals to 1.

3.2. CCR model

Consider that there are n DMUs. Each unit produces s outputs employing m inputs. Taking into account the principles governing in production possibility set, T_c is defined as follows [14]:

$$T_C = \left\{ \begin{array}{l} (X, Y) \mid \sum_{j=1}^{n} \lambda_j X_j \le X \ , \sum_{j=1}^{n} \lambda_j Y_j \ge Y \ , \\ \lambda_j \ge 0 \ ; \ \forall j = 1, \ldots, n \end{array} \right\} \qquad (15)$$

where X is the input variables vector, Y is the output variables vector and λ can be any real number greater than or equal to zero. Given the production possibility set, T_c, the question is to investigate whether the considered decision making unit is located on the boundary of production possibility sets or not. If it is not located on the boundary it can be propelled to the boundary using following method:

- **Input oriented nature of CCR model.**

The aim of this method is to propel DMU_o, with input X_o and output Y_o , towards PPS boundary in which input X_o is contracted to θX_o in a way that with maximum contraction, X locates on the boundary.

$$\begin{array}{ll} Min & \theta \\ s.t & (\theta X_o, Y_o) \in T_c \end{array} \qquad (16)$$

According to Eq.12, the membership conditions in T_C are:

$$\sum_{j=1}^{n} \lambda_j X_j \le \theta X_o \ ; \ \sum_{j=1}^{n} \lambda_j Y_j \ge Y_o \qquad (17)$$

Hence, Eq.12 can be rewritten as following:

$$
\begin{aligned}
& Min \quad \theta \\
& s.t \quad \sum_{j=1}^{n} \lambda_j x_{ij} \le \theta x_{io} \;\; ; i = 1,...,m \\
& \quad \sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{ro} \quad ; r = 1,...,s \\
& \quad \lambda_j \ge 0 \quad ; j = 1,...,n
\end{aligned} \tag{18}
$$

This problem is known as CCR envelopment model in the input oriented nature. Dual form of Eq.14 is the mathematical solution of the same equation and it is known as multiple form of CCR in the input oriented nature.

$$
\begin{aligned}
& Max \quad \sum_{r=1}^{s} u_r y_{ro} \\
& s.t \quad \sum_{i=1}^{m} v_i x_{io} = 1 \\
& \quad \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0 \;\; , \; j = 1,...,n \\
& \quad u_r \ge 0 \quad , \; r = 1,...,s \\
& \quad v_i \ge 0 \quad , \; i = 1,...,m
\end{aligned} \tag{19}
$$

3.3. Ranking

By implementing the CCR model of DEA on DMUs and comparing the efficiency scores of them, they can be ranked based on these efficiency scores. DMUs that their efficiency scores equal to 1 are defined as efficient DMUs.

In order to ranking the efficient DMUs, we need to use the fundamental models of DEA such as AP model proposed in [15]. In [15] to rank efficient DMUs, first, one of them is excluded from DMUs sets and then AP model is applied to calculate the excluded DMU's efficiency score. The AP model of data envelopment analysis is represented as following:

$$
\begin{aligned}
& Max \quad \sum_{r=1}^{s} u_r y_{ro} \\
& s.t \sum_{i=1}^{m} v_i x_{io} = 1 \\
& \sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0 \;\; , \; j = 1,...,n \; , \; j \ne o \\
& \quad u_r \ge 0 \quad , \; r = 1,...,s \\
& \quad v_i \ge 0 \quad , \; i = 1,...,m
\end{aligned} \tag{20}
$$

This procedure is repeated for all efficient DMUs.

4. SYSTEM STUDY

The simulation is carried out on the radial network of 33 buses. Single-line diagram and the network specification are given in Fig. 2 and Table 1, respectively. The rated voltage level of the substation is 12.66 KV and the capacity of the feeder is 8 MVA. The peak loads are 6012 kW and 3012 KVAR. The DG investment cost is considered to be $500,000 per each MW [11, 6, and 9]. The base price to purchase of energy by DISCO is considered $45 / MWh [6, 11]. Also, the interest rate is considered equal to 6% and the invested and the return time of the investment is 5 years. The generation and maintenance cost are considered equal to 50$ / MWh [4, 11]. The sale price of active power ratio to the sale price of reactive power by DISCO is considered three to one. The pollution coefficient of energy absorption by the transmission network and the pollution coefficient of DG is assumed to be equal $\gamma_T = 0.55$, $\gamma_{DGi} = 0.40$, respectively.

Table 1. 33 Bus distribution system data

Number of Branch	Sending Node	Receiving Node	R(ohm)	X(ohm)	Active Power Injected (KW)	Reactive Power Injected (Kvar)
1	0	1	0.0922	0.0470	100	60
2	1	2	0.4930	0.2511	90	40
3	2	3	0.3660	0.01864	120	80
4	3	4	0.3811	0.1941	60	30
5	4	5	0.8190	0.7070	60	20
6	5	6	0.1872	0.6188	200	100
7	6	7	0.7114	0.2351	200	100
8	7	8	1.03	0.74	60	20
9	8	9	1.044	0.74	60	20
10	9	10	0.1966	0.0650	45	30
11	10	11	0.3744	0.1238	60	35
12	11	12	1.4680	1.1550	60	35
13	12	13	0.5416	0.7129	120	80
14	13	14	0.5910	0.5260	60	10
15	14	15	0.7463	0.5450	60	20
16	15	16	1.2890	1.7210	60	20
17	16	17	0.7320	0.5740	90	40
18	1	18	0.1640	0.1565	90	40
19	18	19	1.5042	1.3554	90	40
20	19	20	0.4095	0.4784	90	40
21	20	21	0.7089	0.9373	90	40
22	2	22	0.4512	0.3083	90	50
23	22	23	0.8980	0.7091	420	200
24	23	24	0.8960	0.7011	420	200
25	5	23	0.2030	0.1034	60	25
26	25	26	0.2842	0.1447	60	25
27	26	27	1.0590	0.9337	60	20
28	27	28	0.8042	0.7006	120	70
29	28	29	0.5075	0.2585	200	600
30	29	30	0.9744	0.9630	150	70
31	30	31	0.3105	0.3619	210	100
32	31	32	0.5032	0.5302	60	40

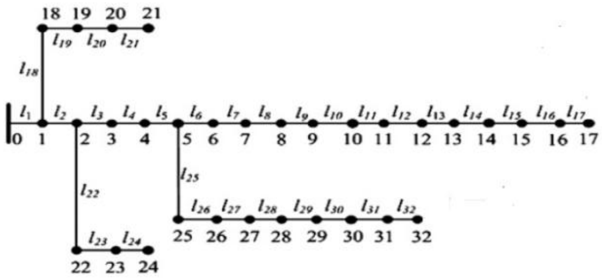

Fig. 2. Single line diagram of 33 buses distribution system

As we know it is difficult to express the DG placement mathematically in a way that it can express losses, voltage profiles, the environmental pollution problem and energy which is not supplied to comprehensively.

Using the proposed DEA methodology, the relative efficiency scores are used to solve the DG placement problem. In order to achieve this purpose, busses which have the maximum amount of efficiency will be found and then, it will be ranked according to their efficiency scores. The optimal value of DG for minimum network loss is calculated according to Eq.3 and the related power losses are reported in Table 2. Also According to the computed DG values, the installation and operation cost using Eq.8, the VPI according to Eq.5, the ENS value refers to Eq.6 also the environment pollution levels using Eq.7 are calculated and given in Table 2.From Fig. 2, it is observed that the installation of appropriate DG value with a capacity of 2.71 MW at bus 5^{th} will minimize the network losses. Whereas by installing this DG, voltage profile improvement, reliability and environmental pollution rate are 0.6789, -0.2375 and 590.11 respectively. Using the results of Table 2 it is shown that the maximum VPI will be obtained in busses 6, 25 and 7. According to maximum reliability (or minimal ENS) index, the buses 24, 23 and 17 are suitable. Also, installing the calculated value of DG in first, second and third buses will have minimum pollution emission. Therefore, optimal establishment of all parameters for the installation of DG units at a specific bus is not possible. Then to solve the DG placement issue it is better to be considered effective placement instead of only optimization placement. To determine the convenient and effective bus, the proposed method, ranks the buses using the concept of DEA ranking. The variable input values which is used in evaluating the performance of each bus, is the total installation cost. The output variables values include the network loss reduction, environmental pollution emissions, the voltage profile improvement and reliability. It can be seen that the cost of DG installation at bus 1 is contains. Ranking results and the relative efficiency values of CCR model, by using DEA is presented in the right half of Table 2. It is observed that for the complete and accurate ranking, the buses which their CCR efficiency score is equal to one will be used to participate in efficiency value of AP model. Also the buses with lover value of CCR efficiency scores will have the lower rank. Ranking the buses with CCR score equal to one, using AP model are shown in Table 2. The final ranking of buses is shown in the last column of Table 2.

As a result of Table 2, the buses 5, 6, 25, 26 and 7 are the best buses which have the most loss reduction along with the DG installation. But according to Table 2, it is observed that the ENS value and pollution from the installed DG in these buses are not desirable. According to the results of the case study, the more suitable bus is 26 that its AP efficiency is 1.17. The amount of DG is 2.45 MW and its cost 25.39 M$. Losses is 70.17 kW, the voltage profiles index is 0.7069 per unit , the amount of pollution and ENS value are 599.66 kilo-tons and 0.2456 MW, respectively. Ranking carried out for all buses and if there is no possibility to install DG on bus 26, we could go look for the next ranks.

Table 2. Result of ranking and sizing and sitting

No . Bus	Size of DG	Loss	Voltage Profile	Reliability Index	Emis sion Index	Cost	DEA Efficienc y	DEA Rank	AP Efficie ncy	AP Rank	Rank
1	4.54	197.321	1.7024	0.6343	545.8	26.44	1.00		1.04	10	10
2	3.824	141.401	1.3222	-0.2295	562.6	26.01	1.00		1	23	23
3	3.52	121.73	1.1307	-0.2328	570.6	25.85	0.99	27	0.99		27
4	3.15	103.89	0.9909	-0.2336	581.0	25.70	1.00		1.131	4	4
5	2.71	68.35	0.6789	-0.2375	590.1	25.40	1.00		1.11	5	5
6	2.76	68.60	0.5605	-0.2370	588.4	25.41	1.00		1.145	2	2
7	1.83	80.88	0.6533	0.2368	623.8	25.39	1.00		1.04	9	9
8	1.56	86.36	0.6736	-0.2369	634.5	25.39	1.00		1.0081	22	22
9	1.34	90.77	0.7093	-0.2368	643.1	25.40	1.00		1.0087	21	21
10	1.32	91.31	0.7097	-0.2368	643.9	25.40	1.00		1.0132	19	19
11	1.27	92.82	0.723	-0.2367	646.0	25.40	1.00		1.0146	18	18
12	1.05	100.24	0.8141	-0.2363	655.6	25.43	1.00		1.0154	17	17
13	0.96	103.48	0.8554	-0.2361	659.2	25.44	1.00		1.016	16	16
14	0.91	106.83	0.8839	-0.2358	661.8	25.46	1.00		1.018	15	15
15	0.84	111.28	0.9284	-0.2355	665.1	25.48	1.00		0.9	25	25
16	0.72	119.56	1.0182	-0.2347	671.1	25.53	1.00		1.1	6	6
17	0.68	123.17	1.0512	-0.2823	673.2	25.55	0.74	30	0.74		30
18	1.90	199.43	1.6967	0.0734	642.5	26.19	0.96	29	0.96		29
19	0.31	196.36	1.6903	-0.2265	699.7	26.00	0.98	28	0.98		28
20	0.27	196.29	1.6897	-0.2271	701.3	26.00	1.00		0.99	24	24
21	0.21	196.36	1.6911	-0.2274	703.4	25.99	0.57	33	0.57		33
22	2.51	152.97	1.4267	0.1431	612.6	25.95	1.00		1.03	11	11
23	1.37	159.47	1.5301	-0.3660	654.7	25.87	1.00		1.06	8	8
24	0.98	165.86	1.5721	-0.4140	670.2	25.87	1.00		1.137	3	3
25	2.70	68.42	0.6487	-0.2237	590.2	25.40	1.00		1.17	1	1
26	2.45	70.17	0.7069	-0.2456	599.6	25.39	1.00		1.02	13	13
27	1.82	74.49	0.8518	-0.1773	623.2	25.35	1.00		1.019	14	14
28	1.50	77.45	0.9428	-0.0068	635.4	25.33	1.00		1.02	12	12
29	1.30	81.65	1.0155	0.0619	643.2	25.34	1.00		1.009	20	20
30	1.20	88.06	1.036	0.0800	648.0	25.37	0.71	31	0.71		31
31	1.18	90.47	1.0436	0.0768	649.4	25.39	0.70	32	0.7		32
32	1.15	94.12	1.0547	0.0752	651.2	25.41	1.00		0.39	26	26

5. CONCLUSION

In this paper, a new method is proposed for bus ranking using the values of relative efficiency CCR and AP models of DEA to determine the appropriate and effective DG location. In this method, using the analytical approach, the optimal size of DG at each bus is calculated to obtain the minimum loss. Then, using the calculated DG values, the values of the investment costs, voltage profiles improvement, energy not Supplied value and the pollution emissions reduction indices are calculated. The proposed method, using the combined process of the concepts of efficiency and optimization is able to rank the network buses for installation. The results of the case study show the advantages of the proposed method.

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