A Proposed Economical Based Approach for Optimal Sizing and Placement of Distributed Generation

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***Abstract*— Distributed Generation (DG) is a small capacity generating units connected to the distribution network close to the consumers. It can provide a promising future for power generation in electric networks. In recent years, the demand for distributed generation into the electrical networks is rapidly increasing. Connecting DG units into the distribution networks can offer environmental, economic and technical merits. Those merits can be optimized if the DG unit site and size is properly determined. In this paper, a new approach for optimal allocation and sizing of DG based on reducing the simple payback period is presented. The goal of this paper is to provide a complete study of the impact of connecting DG units in the distribution networks on power loss based on economical point of view. Also, a mathematical approach is used for calculating the loading center of the IEEE 33 bus system. Genetic Algorithm is used to solve the optimal DG allocation problem in the distribution system. The Proposed solution methodology has been tested on IEEE 33 standard bus system using MatLab software.**

Keywords*— *Distributed generation, Genetic algorithm, Loss reduction, Radial distribution network, Simple payback period.

I. Introduction

The Distributed generation is a small capacity generating units connected to the distribution network close to the consumers. Distributed generators include wind turbines, solar photovoltaic, small hydro power, Reciprocating Engine, etc., with or without storage elements. DG terminology has several definitions and there are no consistent definition defining it.

At first the electricity generation was relaying on very large centralized power plants and their huge output power is transmitted to the loads, so that every load in the end must be connected to one centralized plant. But over the years it became possible to generate electricity at the distribution area by small generating units and connect them to the utility. The first philosophy in electricity generation, centralized generation, has some shortcomings, so that some researchers predicted that the power system tends to be more distributed [1]. Connecting DG units into the distribution networks can offer environmental, economical and technical merits [2]. Now it is the right of the private sector and small investors to invest their money in the electricity generation sector. Some consumers can purchase small generating units to cover their need from electricity. They can also be connected to the utility and sell their rest to it. In addition to what was mentioned, a huge amount of the harmful emissions as CO_2 and SO_2 which were coming from the centralized plants are disposed. Our environment became cleaner. The philosophy of DG also enabled us to more exploitation of the renewable resources, as most of the DG units are renewable resources. On the other hand, there are very far areas need electricity. Delivering electricity through overhead feeders to them from the centralized plants is more expensive. While using DG to feed them is more economic.

One important merit is that the presence of generation in the distribution network can lead to reduction in power losses. Power losses in the power system are caused by active and reactive power flows through the line resistances. The amount of current flow and the line resistance are the two factors affecting the magnitude of the power losses [3]. Connecting DG units to the distribution network will reduce the magnitude of electric current passes through the lines which reduces the power losses.

The merits of connecting the DG into the distribution network could be maximized by optimal selection of the DG units' placement, and size. Improper size and site can affect the distribution system negatively [4-5]. Most of the literatures in distributed generation allocation were done with the objective of real power loss minimization [5].

In addition, other objectives can be taken into account as voltage profile improvement, reactive power loss minimization, and voltage stability improvement. Financial objectives can also be considered. The most common objectives are summarized in Fig. 1 [5].

Several researchers have examined the impact of DG on the system power loss. There are many optimization techniques for optimal distributed generation allocation [6-15]. However, in some literatures the impact of DG is studied without using optimization techniques [16-18].

Genetic Algorithm (GA) technique is presented in [8,11,14], but in [12] a hybrid GA with artificial neural network technique is used, and in reference [13] a combination of analytical and GA methods is used. Particle swarm optimization technique is presented in [9], but in the literature [6] a selective particle swarm optimization technique is presented. Artificial bee colony technique is used in [15]. The impact of DG on other technical issues, for example voltage profile, besides the power loss is presented in [6-9,16-18]. However, in some references financial objectives are considered [10-11].

In this paper, first, a technical-based study for the impact of DG on total active power loss of the distribution network is presented by determining once the optimal size of the DG units, and once by determining both of the optimal size and site of the DG units to minimize the total active power loss of the distribution system.

The next part of the paper presents the proposed economical-based approach for determining the optimal size and site of the DG units to minimize the Simple Payback Period (SPBP). The SPBP is the duration required to recover the cost of an investment. The SPBP provides a clear signal to the distribution company about the economic feasibility of connecting DG units into the distribution network. The SPBP does not take into consideration the time value of money. It can be calculated the fixed cost over the annual saving. This paper gives an economical and practical solution for the distribution companies to use the DG units for supplying some of the loads connected to the distribution network instead of the centralized paradigm.

The problem is formulated using the power flow studies, and the simultaneous non-linear equations in power flow calculations are solved by Newton Raphson method. GA is presented to solve the optimal DG allocation problem in the distribution system.

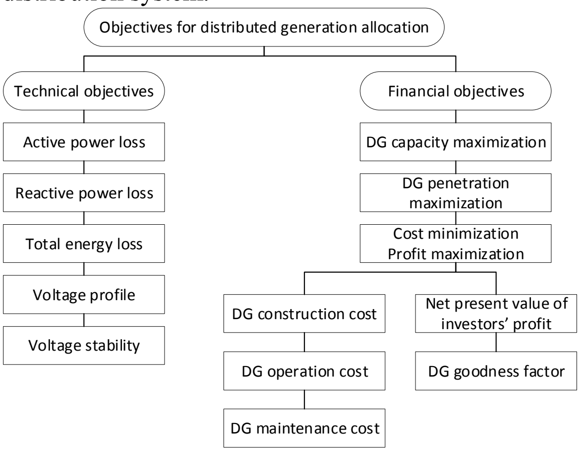

Fig. 1. The most common objectives in distributed generation allocation

The proposed solution methodology has been tested on the IEEE 33 standard bus system using MatLab software.

The problem formulation is described in section 2. Both of equality and inequality constraints are considered. The system analysis and case study are described in section 3. In section 4, the obtained results and the discussion are presented and the conclusions of the paper are summarized in Section 5.

II. PROPLEM FORMULATION

Power-flow, or load flow, studies are of great importance in studying power system operation, planning, and protection in steady state. The power flow problem, mainly, is the computation of voltage magnitude and phase angle at each bus in the system. As a result of this calculation, active and reactive power flows in transmission lines, as well as losses, can be computed. At each bus, there are four variables: voltage magnitude, phase angle, net injected active power, and reactive power [14,19].

A. Power loss formulation

The total active power loss is formulated as in [14]:

$$P_{loss} = \sum_{k=1}^{nb} G_{ij}[V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j) \quad (1)$$

The first objective function is then to be:

Minimize (P_{loss})

Where "nb" is the total number of branches, "G_{ij}" is the conductance of the branch between the two buses i and j, "V_i" is the ith bus voltage magnitude, "V_j" is the jth bus voltage magnitude, "δ_i" is the ith bus voltage angle, and "δ_j" is the jth bus voltage angle.

B. Simple payback period formulation

The SPBP is the duration required to recover the cost of an investment. The SPBP provides a clear signal to the distribution company about the economic feasibility of connecting DG units into the distribution network. The SPBP does not take into consideration the time value of money, unlike other techniques of capital budgeting such as net present value, and accounting rate of return. In the second part of this paper, the objective function is to minimize SPBP.

The SPBP is formulated as follows:

$$SPBP = \frac{FC}{NAS} \quad (2)$$

Where,

$$AES = \left(P_{loss}^{base} + \sum_{i=1}^{n} P_{D_i}\right) * \rho_P * H - \left(P_{loss}^{DG} + \sum_{i=1}^{n} P_{D_i} - \sum_{i=1}^{N} P_{DG_i}\right) * \rho_P * H \quad (3)$$

$$ARC = \left(\sum_{i=1}^{N} c_{2_i} * P_{DG_i} * H\right) + \left(\sum_{i=1}^{N} R_i * \rho_f * H\right) \quad (4)$$

$$NAS = AES - ARC \quad (5)$$

$$FC = \sum_{i=1}^{N} c_{1_i} * P_{DG_i} \quad (6)$$

The second objective function is then to be:

Minimize $(SPBP)$

Where, AES is the annual saving in energy cost ($/year), ARC is the annual running cost of the DGs ($/year), NAS is the net annual saving ($/year), FC is the fixed, or installed, cost of the DGs ($), P_{loss}^{base} is the total active power loss for the base case (without DG) (kW), P_{loss}^{DG} is the total active power loss when one or more DG units are connected (kW), P_{D_i} is the active power demand at bus i (kW), ρ_P is the energy market price ($/kWh), H is the period of operation per year (hrs/year), P_{DG_i} is the rated power of the DG unit i (kW), c_{1_i} is the installed cost of the DG unit i per kW of the rated power ($/kW), c_{2_i} is the operation and maintenance cost per kwh for the DG unit i ($/kWh), R_i is the fuel input for the DG unit i (Mbtu/hr), ρ_f is the fuel market price ($/Mbtu), n is the total number of buses, and N is the total number of DG units.

Equation (3) calculates the distribution company annual saving in the cost of the electrical energy consumption by the loads. The first and second terms calculate the annual cost of the electrical energy supplying the loads of the distribution system for one year before and after using DG, respectively. The cost of electrical energy which the distribution company must bear to supply the loads will be reduced after connecting the DGs because the DG units will reduce the total active power loss in the lines and also these DG units will supply the close loads.

Furthermore, equation (4) calculates the annual running cost of the DG units. This cost contains the annual operation and maintenance cost (the first term), and the annual fuel cost (the second term). Then, the net annual saving cost is calculated from equation (5) which is the difference between the annual payments and the annual saving. While the fixed cost of the DG units is calculated from equation (6). The SPBP is calculated from equation (2).

Both of the total active power loss and the SPBP objective functions are subjected to the following constraints:

1. Equality Constraints:

The load flow equations must be satisfied as follows:

$$P_i = P_{DG_i} - P_{D_i} \tag{7}$$

$$= V_i \sum_{k=1}^{n} V_k [\, G_{ik}\cos(\delta_i - \delta_k) + B_{ik}\sin(\delta_i - \delta_k)]$$

$$Q_i = Q_{DG_i} - Q_{D_i} \tag{8}$$

$$= V_i \sum_{k=1}^{n} V_k [\, G_{ik}\sin(\delta_i - \delta_k) - B_{ik}\cos(\delta_i - \delta_k)]$$

Where "G_{ik}" is the conductance of the branch between the two buses i and k, "B_{ik}" is the susceptance of the branch between bus i and bus k, "P_i" is the net injected active power at bus i, and "Q_i" is the net injected reactive power at bus i.

2. Inequality Constraints:

The inequality constraints considered in this paper are the following:

- *Voltage profile constraints:*

$$V_i^{min} \le V_i \le V_i^{max} \tag{9}$$

The voltage of all buses must be within the allowable range as shown in (9). The maximum allowable variation is considered as 5% in some references, which will be considered here, and 10% in other references [5].

- *DG unit generation power capacity constrains:*

$$P_{DGi}^{min} \le P_{DGi} \le P_{DGi}^{max} \tag{10}$$

The active power consumed from the DG unit i must be within its maximum and minimum limits of generation.

III. SYSTEM ANALYSIS AND CASE STUDY

The system under study is the IEEE 33 bus radial distribution system which is shown in figure 2. The system has 100 MVA and 12.66 kV base values. The system has total load of 3.715 MW and 2.30 MVAr. The line data, load data, and line lengths of the IEEE 33 bus system are stated in [21]. The total active power loss for this system is calculated at the base case (without DG). It was approximately 135.597 kW.

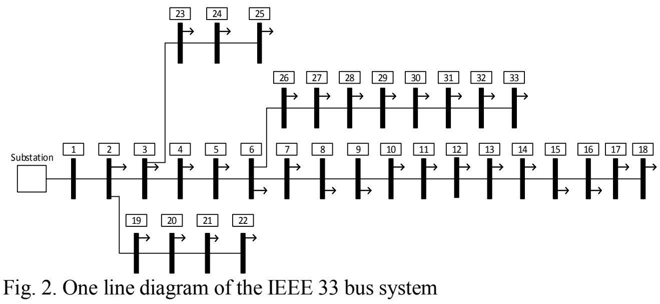

Fig. 2. One line diagram of the IEEE 33 bus system

In this literature, the IEEE 33 bus system center of load and Loss Sensitivity Factor (LSF) of all buses are calculated to be used for allocation of the DG units. the center of load can be calculated by different ways.

The method of load moments based on the static moment's law is selected to determine the center of load. In this method the masses are replaced with loadings active power as shown in the following two equations [17]:

$$X_o = \frac{\sum_{i=1}^{n} P_{D_i} x_i}{\sum_{i=1}^{n} P_{D_i}} \tag{11}$$

$$Y_o = \frac{\sum_{i=1}^{n} P_{D_i} y_i}{\sum_{i=1}^{n} P_{D_i}} \tag{12}$$

Where (X_o, Y_o) are the coordinates of the center of load, and (x_i, y_i) are the coordinates of the loading active power at bus i. The axes are selected to be at bus 1 (the slack bus). The loading center is located at bus 28.

The loss sensitivity factor method is based on the concept of linearization of the original nonlinear equation around the initial operating point. For computing the LSF at the ith bus, the exact formula of total active power loss is partially differentiated to the net injected power at bus i.

The LSF can be formulated as [20]:

$$\alpha_i = \frac{\partial P_{loss}}{\partial P_i} \tag{13}$$

$$= 2\sum_{j=1}^{n} [\frac{r_{ij}}{V_i V_j}\cos(\delta_i - \delta_j)]\, P_j - [\frac{r_{ij}}{V_i V_j}\sin(\delta_i - \delta_j)]Q_j$$

Where "r_{ij}" is the real part of the ijth element in [Zbus] matrix.

The LSF technique determines how sensitive the total active power loss is to the real power injection at any bus. The higher negative LSF value at a specific bus, the less the total active power loss achieved if the DG connected to it. Wherefore, the LSFs of all buses are arranged in descending order, and the DG unit is connected to the buses that has high sensitivity. The LSFs of all buses of the IEEE 33 bus system is shown in figure 3. The highest negative six buses are 18,32,33,31,17, and 30.

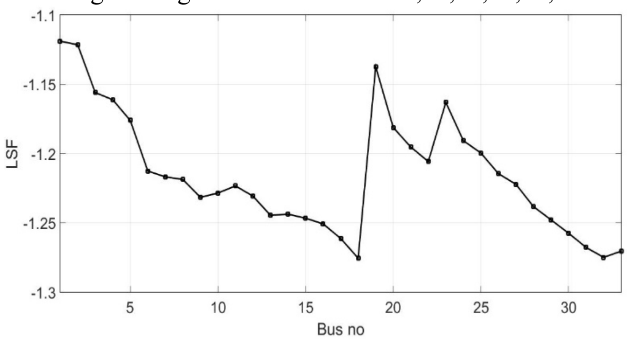

Fig. 3. The LSFs of all buses of the IEEE 33 bus system

IV. RESULTS AND DISCUSSION

The computer simulation study is performed to demonstrate the proposed algorithm using the IEEE 33-bus test network. Two objective functions are considered as follows:

A. Total active power loss reduction

The first objective function considered in this paper is the total active power loss. This objective function is minimized once by determining only the size of the DG units and the site is selected by different scenarios, and once by determining both of the optimal size and site of the DG units.

1) Optimal sizing of Distrusted Generation units for total active power loss reduction

In this section, the problem is studied for one, two, and three DGs. All the results can be seen in table I.

The optimal size of the DG unit in the case of using one DG is determined by the GA. While the location of the DG unit is selected by the following different scenarios: Scenario 1: locate the DG unit at the center of load (bus 28). Scenario 2: locate the DG unit at the inner bus (bus 6). Scenario 3: locate the DG unit at the bus that has the highest LSF (bus 18). Scenario 4: locate the DG unit at the bus which has the minimum voltage at the base case (bus 32).

As shown in table I, Connecting the DG unit to bus 32 (the minimum bus voltage) achieves minimum total active power loss and the best voltage profile. While, the minimum optimal size of the DG unit is achieved at bus 18 (highest LSF) with proper total active power loss. Scenario 2 is very bad because the optimal size of the DG unit is very high. Such that solution is not preferred with economically.

The voltage profile of the 33-bus system at the base case and after connecting one DG unit with all scenarios is presented in figure 4. This figure illustrates that connecting the DG unit into the distribution network enhances the voltage profile. The voltage of some buses is under the lower allowable limit at the base case, but connecting the DG unit enhances the voltage profile and the voltage of all buses becomes accepted.

Table I. The results of sizing optimization for total active power loss reduction

		DG location	DG optimal size (kW)	Sum. Of DG optimal sizes (kW)	Total active power loss (kW)	Min. bus voltage (bus no.) in p.u.
Without DG		-	-	-	135.6	0.942 (32)
With one DG unit	Scenario 1	Bus 28 (loading center)	1797.32	1797.32	80.99	0.9682 (18)
	Scenario 2	Bus 6 (inner bus)	2483.59	2483.59	78.06	0.964 (32)
	Scenario 3	Bus 18 (highest LSF)	1391.16	1391.16	78.44	0.969 (30)
	Scenario 4	Bus 32 (the minimum bus voltage)	1536.9	1536.9	75.45	0.974 (29)
With two DG units	Scenario 1	DG1 (bus 32) DG2 (bus 28)	1486.47 656.7	2143.17	71.31	0.979 (25)
	Scenario 2	DG1 (bus 32) DG2 (bus 6)	1525.96 1024.44	2550.4	65.07	0.980 (25)
	Scenario 3	DG1 (bus 32) DG2 (bus 18)	1053.54 531.57	1585.11	73.45	0.974 (29)
With three DG units	Scenario 1	DG1 (bus 32) DG2 (bus 6) DG3 (bus 28)	915.29 1402.7 20.42	2338.4	60.92	0.975 (30)
	Scenario 2	DG1 (bus 18) DG2 (bus 32) DG3 (bus 33)	722.2 751.6 59.4	1533.2	73.63	0.973 (30)
	Scenario 3	DG1 (bus 2) DG2 (bus 3) DG3 (bus 6)	429.7 1144.8 2157.7	3795.2	73.5	0.965 (32)

For the case of using 2 DGs, the location of the first DG unit is fixed at bus 32 at which the minimum total active power loss for one DG achieved. The optimal size of the two DG units is determined by GA, while the location is selected by the following different scenarios:

Scenario 1: locate the first DG unit at bus 32 and the second DG unit at bus 28 (the load center). Scenario 2: locate the first DG unit at bus 32 and the second DG unit at bus 6 (inner point). Scenario 3: locate the 2 DG units at the higher two buses in LSF (bus 18 and bus 32).

The results in table I illustrate that connecting the two DG units at the buses 32 and 6 respectively achieves the minimum total active power loss, but with higher size of the DG. Such that solution is not preferred with economic point of view.

While the summation of the sizes of the two DG units is the lowest in scenario 3. Figure 5 presents the voltage profile of the 33-bus system at the base case and after connecting two DG units with all scenarios. The voltage profile is accepted for all these three scenarios. The best scenario in voltage profile is scenario 2.

For the case of connecting three DG units, they are located by the following different scenarios: Scenario 1: locate DG1 and DG2 at bus 32 and 6 respectively (the best scenario in 2 units part), and locate DG3 at bus 28 (the load center). Scenario 2: locate the three units at the three buses that have the higher LSF (bus 18, 32,33 respectively). Scenario 3: locate the three units at the branched points (bus 2, 3, 6 respectively).

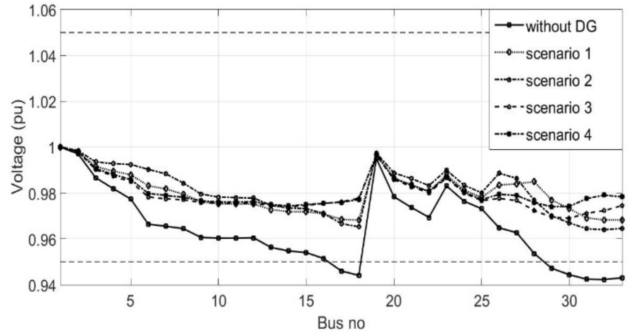

Fig. 4. Voltage profile of the 33-bus system at the base case and after connecting one DG unit with different scenarios

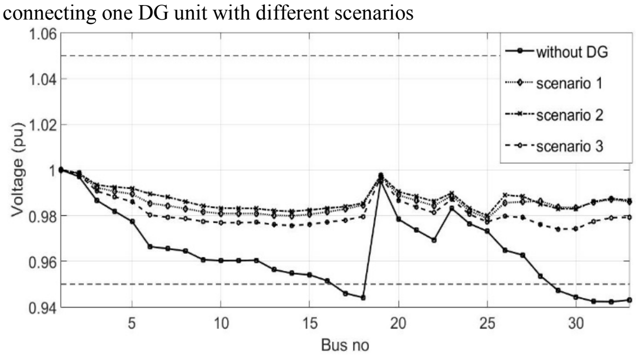

Fig. 5. Voltage profile of the 33-bus system at the base case and after connecting two DG units with different scenarios

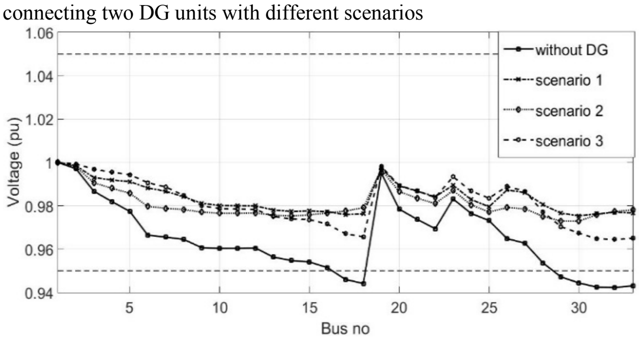

Fig. 6. Voltage profile of the 33-bus system at the base case and after connecting three DG units with different scenarios

Table I illustrates that connecting the three DG units at buses 32, 6, and 28 achieves the lowest total active power loss compared with the other scenarios. While, scenario 2 has the lowest sizes of the DG units. scenario 3 is very bad because it achieves high losses with higher DG size. Figure 6 presents the voltage profile at the base case and after connecting three DG units for all scenarios. As shown in the figure, the voltage profile is accepted for all scenarios. The first scenario has the best voltage profile.

It is worth noting the results in all scenarios in table I that the scenario which has the minimum summation of the DG optimal sizes is always based on the LSF.

2) optimal sizing and site of Distrusted Generation units for total active power loss reduction

In this section the problem is studied for one, two, and three DGs. In this section, the optimal location of the DG unit is determined by the GA besides the size. The results of this section are summarized in table II.

Table II. The results of sizing and site optimization for total active power loss reduction

Number of DG units	DG units' optimal site	DG units' optimal size (kW)	Sum. Of DG optimal sizes (kW)	Total active power loss (kW)	Min. bus voltage (bus no.) in p.u.
One DG unit	DG1 (bus 32)	1536.9	1536.9	75.45	0.9740 (29)
Two DG units	DG1 (bus 32) DG2 (bus 24)	1435.7 1026.2	2461.9	59.55	0.9750 (30)
Three DG units	DG1 (bus 32) DG2 (bus 24) DG3 (bus 8)	1056.5 1009.9 1078.5	3144.9	48.9	0.9770 (30)

From the results of table II it can be noticed that the greater the number of DG units, the less total active power loss until connecting 33 DG unit at the 33 bus each of a size equals the load at each bus, at this case there will be no current passes through lines and the total active power loss will be zero. In this literature, the highest number of the buses connected to DG is assumed to be 3 buses.

Furthermore, if the size of the DG unit exceeds the optimal size mentioned in table II, the total active power loss will increase. On other words, the minimum total active power loss of the IEEE 33 bus system can be achieved by one DG unit is 75.45 kW, and if you want to reduce it, you must insert another DG unit, while increasing the size of that one DG above the optimal size will not decrease the total active power loss, but it will increase it.

In addition, the optimal site of one DG achieving the minimum total active power loss is bus 32, which is the bus that has the minimum voltage at the base case, and the same results obtained as scenario 4 in table I.

The voltage profile of all buses is improved and becomes within the allowable range in all of the three cases (after inserting one, two, and three DG units with the optimal site and size) as shown in figure 7. It is illustrated that the greater the number of DG units the better voltage profile.

From the comparison of the results in tables I and II, it can be noticed that using the GA to search for the optimal site is preferred. It can achieve more reduction in the total active power loss compares to locating the units at fixed locations.

B. Simple Payback Period (SPBP) reduction

The second objective function considered in this paper is the SPBP reduction by determining the optimal sizing and site of the DG units. These assumptions are considered in the cost calculations:

1- The distribution company is the owner of the DG units.

2- The candidate DGs are microturbines produced by capstone company. The rated power, the installed cost, the operation and maintenance costs, and the fuel flow input of the microturbines produced by capstone company are presented in table III [22].

3- The maximum number of buses can be connected to DG is three buses, each bus can have one microturbine unit or more than a unit.

4- The optimal size of the DG unit is restricted to be one of the capstone units standard ratings, or multiplication of them.

5- The electricity price= 19.9 cent/kwh [23].

6- The microturbine fuel type is natural gas.

7- The price of the natural gas in united states=3.25 dollar/MBTU [24].

8- The load factor is assumed to be unity.

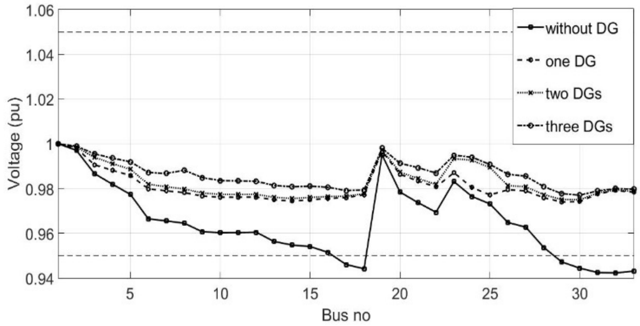

Fig. 7. Voltage profile of the 33-bus system at the base case and after DG placement with the optimal size and site for loss reduction

All the results can be seen in table IV. It is obvious that connecting one microturbine of 323 kW rated power at bus 32 is the best solution which achieves the shortest SPBP. Such that solution achieves not preferred, but accepted, voltage profile as shown in figure 8.

Table III. The data of capstone microturbine

Description	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Net Electric Power (kW)	61	190	242	323	950
Installed Cost ($/kW)	3220	3150	2700	2560	2500
O&M, not including fuel (¢ /kWh)	1.3	1.6	1.2	0.8	1.2
Fuel Input (MBtu/hr)	0.84	2.29	3.16	3.85	11.43

During the calculations it is noticed that some solutions have no economic feasibility. For example, when connecting 9 units each of 190 kW at bus 9, and 10 units each of 950 kW at bus 3, the annual running cost of that DGs will be greater than the annual saving in energy cost and the SPBP will have a negative value.

Table IV. The results of sizing and site optimization for SPBP reduction

Number of buses that has DG units	DG units' optimal site	DG units' optimal size (kW)	Total active power loss (kW)	SPBP (years)	Min. bus voltage (bus no.) in p.u.
One bus has DG	DG1 (bus 32)	1*323	112.347	1.729	0.9501 (31)
Two buses have DG	DG1 (bus 18)	1*323	94.87	1.760	0.9570 (30)
	DG2 (bus 31)	1*323			
Three buses have DG	DG1 (bus 17)	1*323	81.727	1.780	0.9628 (31)
	DG2 (bus 30)	1*323			
	DG3 (bus 32)	1*323			

Wherefore, determining the optimal size and location of the DG units for reducing the SPBP is very important. It is also worth noting that the unit 4, which has 323 kW rating, has the minimum operation and maintenance costs with proper installed cost and fuel input. Wherefore, the GA selected it at minimizing the SPBP as shown in the results in table IV. One of the important things that can be inferred from the results in table IV that the optimal location of the DG units was obtained to be at the buses 18, 32, 33, 31, 17, and 30 which are the higher six buses at LSF. Such that technique which has the minimum summation of the optimal sizes of the DG units as shown in table I for all scenarios.

Figure 8 illustrates the voltage profile of the IEEE 33 bus system before and after connecting the DGs with the optimal size and location for reducing the SPBP. The voltage profile is accepted for all of these three solutions, but preferred for the third solution.

All these results will be given to the distribution company, and it can take the decision based on these data. The first solution is preferred in the cost objective as it achieves the shortest SPBP, while the third solution is preferred in the technical objectives, as it achieves lower total active power loss and the best voltage profile.

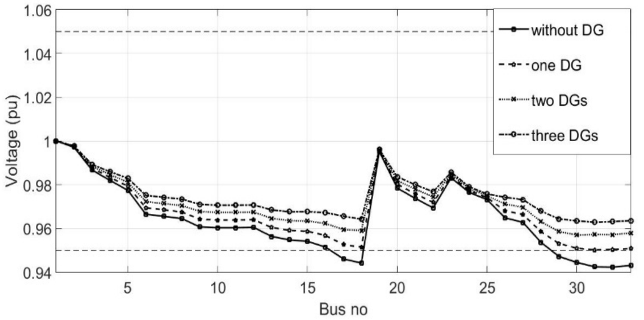

Fig. 8. Voltage profile of the 33-bus system at the base case and after DG.

V. CONCLUSION

This paper presented both of technical and economical based studies of the impact of the DG on the distribution system. A novel objective function, the Simple Payback Period (SPBP) reduction, is considered, and a feasibility study to determine the optimal size and location of the DG units based on reducing the SPBP is presented to the distribution company. All the calculations are conducted on the IEEE 33 bus system, and the candidate DGs are microturbines produced by capstone company. GA is used to solve the optimal DG allocation problem using MatLab software. It is noticed that the optimal locations of the DGs for reducing the SPBP are the buses that have higher Loss Sensitivity Factor (LSF). The proposed solution satisfies the permissible voltage limits.

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