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Optimal Placement of Distributed Generation in Distribution Networks

N. Anjani Pavani[1], K. Swarnasri[2]

swarnasrik@gmail.com

Abstract

Due to the restructuring in electricity market and environmental concerns penetration level of DG unit has been increased rapidly. It is also playing a significant role in minimization of line losses of a power system network. So it is very important to define the size and location of distributed generation unit to be allocated in a power system network. On the other hand, due to radial distribution systems basic inherent features such as radial structure, a wide range of □/□ratios, and a large number of nodes. The optimal sizing and sitting problem of a DG unit cannot be determined by the conventional techniques, which are used for transmission systems. A novel method for the estimation as well as minimization of losses in a radial distribution system with DG unit has been presented in this paper. An algorithm is presented in this paper to obtain the optimum position of DG units in the distribution network based on the available amount of DG using Fuzzy logic. Test results on a 34-bus system reveal the superiority and simplicity of the proposed algorithm. It is observed that placement of DG at appropriate location results in loss reduction and improved voltage regulation of the system.

Keywords: Distribution network, Distributed Generation, optimal placement, Newton Raphson method, Fuzzy logic.

Introduction

Distribution systems hold a very significant position in the power system since it is the main point of link between bulk power and consumers. A planned and effective distribution network is the key to cope up with the ever increasing demand for domestic, industrial and commercial load. Electrical distribution networks have gained an overwhelming research interest in the academics as well as in the industries community nearly from last three decades.

[1,2] R.V.R. & J.C. College of Engineering, Guntur, Andhra Pradesh, India.

The requirements are mandatory to maintain the supply of electrical power within the requirements of many types of consumers. Availability of power demand, Reliability, Reliable automatic control system, providing additional reserve facilities and Proper voltage, Loading, Efficiency are the necessary requirements of a good distribution system. The renewable energy based generation resource in the distribution grid has already started. By using the renewable energy source, we can produce the electrical power in an effective and efficient way. Distributed generation (DG) systems are not new phenomena. Prior to the advent of alternating current and large-scale steam turbines, all energy requirements—heating, cooling, lighting, motive power—were supplied at or near their point of use. Technical advances, environmental issues, inexpensive fuel, the expanding role of electricity in life, and its concomitant regulation as a public utility, all gradually converged around gigawatt-scale thermal power plants located far from urban centers, with high-voltage transmission and lower voltage distribution lines carrying electricity to every business, facility, and home in the country.

Load flow studies are used to ensure that electrical power transfer from generators to consumers through the grid system is stable, reliable and economic. The increasing presence of distributed alternative energy sources, often in geographically remote locations, complicates load flow studies and has triggered a resurgence of interest in the topic.

In order to obtain a reliable power system operation under normal balanced three phase steady state conditions, it is required to have the following:

- Generation supplies the load demand and losses.
- Bus voltage magnitudes remain close to rated values.
- Generator operates within specific real and reactive power limits.
- Transmission lines and transformers are not overloaded.

Power flow analysis is used to determine the steady state operating condition of a power system. Power flow analysis is widely used by power distribution professional during the planning and operation of power distribution system. Acharya et al. [14] proposed an analytical method to determine the optimal capacity of DG. The optimal sizes corresponding to each network bus were calculated using a direct equation derived from the sensitivity factor equation. In addition, an effective methodology based on an exact loss formula was applied to determine the optimal site of DG that minimizes total power losses. The method carried out the load flow two times, for the base case, without DG, and with DG, and considered installing only a single DG that injects active power. Borges and Falcao [15] gave a new methodology for optimal distributed generation allocation and sizing in distribution systems, in order to minimize the electrical network losses and to guarantee acceptable reliability level and voltage profile. The optimization process was solved by the combination of genetic algorithms techniques with methods to evaluate DG impacts in system reliability, losses and voltage profile.

The losses and voltage profile evaluation were based on a power flow method for radial networks with the representation of dispersed generators. Kashem et al. [16] developed a deterministic methodology based on the SQP algorithm to identify the optimal size and placement of DG in distribution systems. The authors proposed a combined objective function that aimed to reduce power loss at minimal DG cost. Beromi et al. [17] presented a method for optimal allocation of DG for voltage profile improvement and loss reduction. GA was used as the optimization technique. Load flow was applied for decision-making which combined appropriately with GA. Gozel and Hocauglu [18] formulated a loss sensitivity factor for the distribution systems, based on the equivalent current injection. The calculated sensitivity factor was employed for the determination of the optimum size and location of distributed generation to minimize total power losses by an analytical method without the use of admittance matrix, inverse of admittance matrix or Jacobian matrix. It was shown that, the proposed method was in close agreement with the classical grid search algorithm based on successive load flows.

Distributed Generation

The purpose of distributed generation is to provide a source of active electric power. The location of distributed generation is defined as the installation and operation of electric power generation units connected directly to the distribution network or connected to the network on the customer site of the meter. Distributed Generation (DG) is predicted to play an increasing role in the electric power system of the near future. Distributed generation is by definition that which is of limited size (roughly 10 MW or less) and Interconnected at the substation, distribution feeder or customer load levels. Benefit is to have a lower capital cost because of the small size of the DG (although the investment cost per kVA of a DG can be much higher than that of a large power plant). It may reduce the need for large infrastructure construction or upgrades because the DG can be constructed at the load location. The challenges associated are safety, power quality and reliability for small distributed generation systems.

Optimal Placement of DG in Distribution Network

The optimal allocation and sizing of a DG unit is one of the important factors for loss reduction in a distribution system. Fig. 1 shows a three dimensional plot between power losses and DG size at each buses in a distribution system. It reveals that as the DG size is increased for a particular bus the losses of a distribution network are reduced. However the loss is increased if the DG size is increased beyond the optimal DG size at that particular location. So whenever the DG size is increased more than the optimal value, the loss is increased and it may go beyond the loss of the base case loss. It is also important that minimization of losses are directly depends on location of DG.

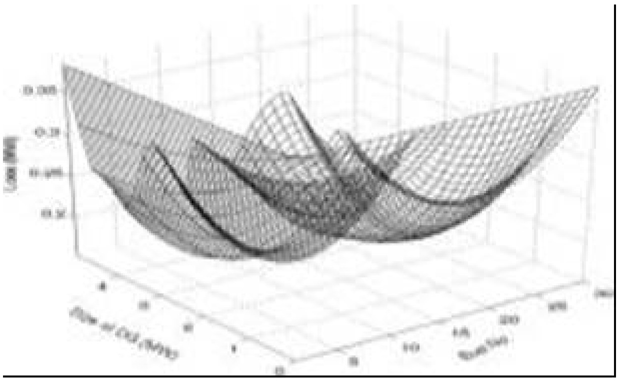

Fig. 1. Effect of different DG size and their location on losses [14]

From the Fig. 1 it can be concluded that for a particular distribution system it is irrelevant to construct very high capacity DG unit. Allocation of a high capacity DG unit will cause very high system losses. So the size selection process of DG unit is carried out based on the size of distribution system (based on load in MW). The reason for the relation between higher DG unit capacity with higher losses can be explained that the distribution system is designed in such a way that such the power flows initially from sending end to the receiving end. The conductor sizes are generally reduced from sending end towards the receiving end. So without change of network any installation of a large size DG unit will make excessive power flow in small size conductors and as a result it causes higher losses.

The DG placement problem is solved by location issue first then followed by the sizing issue.

DG Model and their types

Based upon different point of view such as; type of connection, types, different operation mode DG unit can be modelled as PV bus or DG unit can also be modelled as PQ bus [18]. A DG unit which is already modelled as PQ bus can also modelled into three other types such as: DG unit has constant P and Q [19], DG unit having a certain specified value of P and power factor (PF) [19]. As a varying Q generator DG unit can also be modelled [19]. A DG unit having specified real power and bus voltage magnitude is modelled as PV bus DG unit [19]. DG units are many times modelled as PV node without considering dummy branch; they can inject reactive power to the distribution system and support the voltage profile [20].

DGs with smaller capacity and in the form of constant PQ model are very much sufficient for the loss minimization of a radial distribution system. DG unit as negative load is assumed in this study.

Objective function:

‘Exact loss’ formula [16] can be used for the estimation of total real power losses of a radial distribution system by equation (5.1).

Min $P_L = \Sigma\Sigma[\alpha_{ij}(P_iP_j+Q_iQ_j)+\beta_{ij}(Q_iP_j-P_iQ_j)]\ N_j=1\ N_i=1$ ---------------------- 1

Where $\alpha_{ij}=r_{ij}V_iV_j\cos(\delta_i-\delta_j)$, $\beta_{ij}=r_{ij}V_iV_j\sin(\delta_i-\delta_j)$

and $r_{ij}+jx_{ij}=z_{\square j}$; is the impedance of ij^{th} matrix.

Optimal Node Using Fuzzy Expert System (FES)

For a given single source radial distribution system it is not possible to reduce the losses which are associated with real and reactive component of the branch currents because all these real and reactive power is supplied by the single source at the source node. This limitation can be overcome by placing DG units at different nodes of the system for loss reduction. So the real and reactive powers are generated locally by installed DG unit. The location of DG is chosen based on fuzzy expert system. The location must be one that gives minimum losses along with the best voltage profile.

The fuzzy expert system (FES) consists of a set of rules. These rules are developed in a standard way. Different rules are designed and defined to determine the suitable node at which DG could be placed in fuzzification process. In the fuzzification process, the power loss index (PLI) and voltage index (VI) are converted into fuzzy. Linguistic terms for PLI is described by low (L), medium low (LM), medium (M), high medium (HM), high (H) and linguistic terms for voltage index is described as low (L), low normal (LN), normal (N), high normal (HN), high (H). Different membership functions are generated to represent all these linguistic terms. Triangular and Trapezoidal type membership functions are used in the following fuzzy expert system and they are shown in the Fig. 2 and Fig. 3 respectively.The power loss factor (PLI) and the voltage index (VI) are the two inputs to the fuzzy (FIS), which determines the optimal position for allocation of DG by fuzzy inferencing. The inference involves heuristic rules for the determination of output decisions. In this fuzzy inference system there are two input variables (PLI, VI) and (5, 5) fuzzified variables respectively so that the fuzzy inference system has a set of 25 rules.

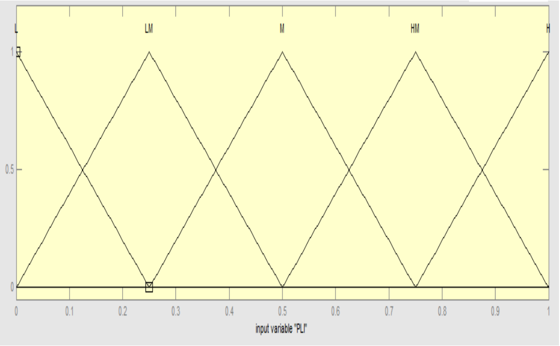

Fig.2. Power loss factor membership functions.

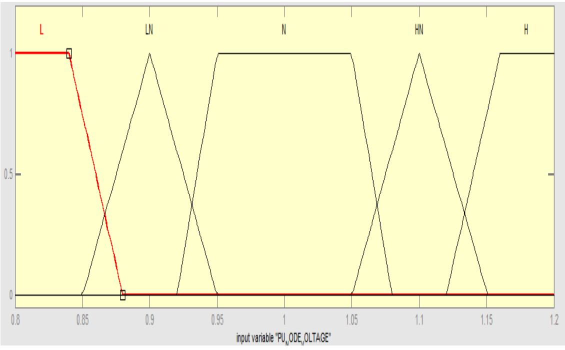

Fig.3. Voltage Index (pu node voltage) membership functions.

The DG unit is allocated in a radial distribution system in such a way that power loss index should be maximum and the voltage index should be minimum. These two objectives are more important while designing the heuristic rules for fuzzy inference system (FIS). All these rules are expressed as the following way:

IF premise (antecedent).THEN conclusion (consequent).

To determine the DG suitability at a node a set of fuzzy rules have been employed. The rule base for optimal DG placement is presented in the fuzzy decision matrix shown in Table 1 and illustrated in Fig. 5. The output of fuzzy inference system is DG placement suitability index and it is also described by the linguistic terms very low (VL), low (L), medium low (ML), medium (M), medium high (MH), very high (VH). These linguistic terms are also represented by membership functions and it is shown graphically in Fig. 4.

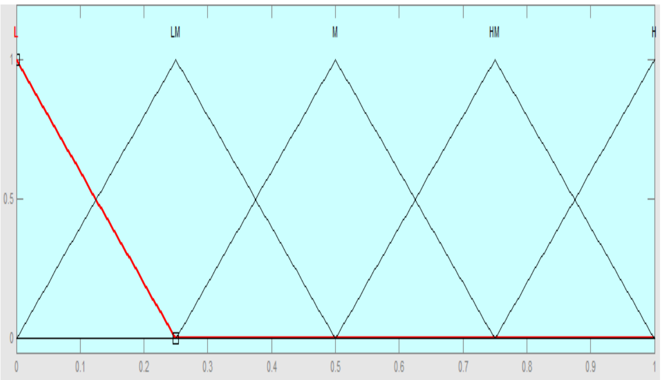

Fig. 4. DG placement suitability index membership functions

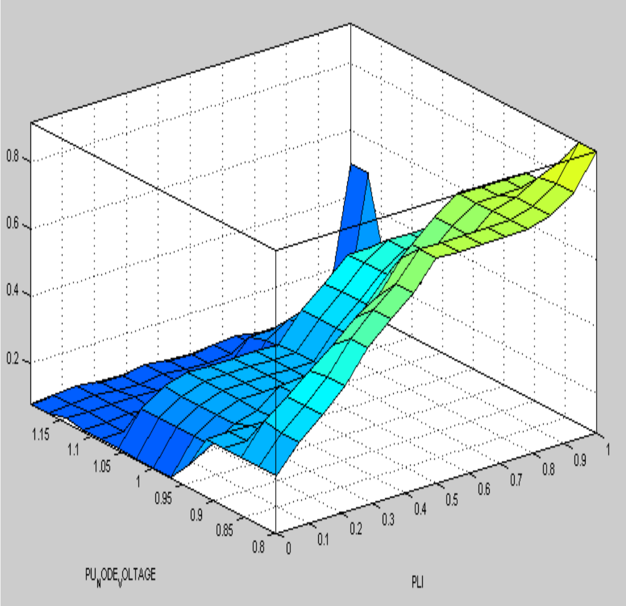

Fig.5. Fuzzy rules in graphical representation

Table 1: FUZZY DECISION MATRIX

AND		**Voltage index (VI)**				
		L	**LN**	**N**	**HN**	**H**
Power loss Index (PLI)	**L**	LM	LM	L	L	L
	LM	M	LM	LM	L	L
	L	HM	M	LM	L	L
	HM	HM	HM	M	LM	L
	H	H	HM	M	LM	LM

Fuzzy Inference and Defuzzification Technique:

Several rules are implemented with some degree of membership after the inputs are given to the fuzzy expert system (FES) which is obtained from the load-flow program i.e. power loss factor and voltage index. In this fuzzy expert system method Mamdani's maximum-minimum method of inference has been used. Regarding the DG placement problem, the DG suitability membership function, μs of node *i*for *k* fired rules are given by the equation

$\mu s(i)$**=max [min [**$\mu p(i)$**,**$\mu v(i)$**]** **------- 2**

The two membership functions of power loss factor and voltage index are represented by μp and μv respectively. After the calculation of DG suitability membership function for a particular node it must be defuzzified to a scalar value. This defuzzification method helps to determine the ranking of different node's suitability. To defuzzify the fuzzified values a centroid method has been used. DG suitability index can be determined as,

$$S - \frac{\int \mu_s(z).zdz}{\int \mu_s(z)dz}$$ **--------------- 3**

IV. OPTIMAL DG SIZING BY ANALYTICAL METHOD

The active power and reactive power injected at bus *i*by a DG can be given by the following equation (4) and (5).

$Pi{=}Pdgi{-}Pdi$ ------- 4

$Qi{=}Qdgi{-}Qdi{=}aPdgi{-}Qdi$ ------5

We are considering

a = $(sign)$tan (cos$^{-1}PF_{dg}$) [14] for optimal positioning of a DG unit in a radial distribution system. The reactive power generated by a DG unit can be expressed by the following equation as: $Q_{dgi}{=}aP_{dgi}$

In which

$sign$ = +1: reactive power supplied by a DG.

$sign$ = −1: reactive power absorbed by a DG.

PF_{dg} = Power factor of DG

From equations (1), (4), (5) the active power loss which occurred in the distribution system can be computed in the following way

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}[\alpha_{ij}[(P_{dgi} - P_{di})P_j + (aP_{dgi} - Q_{di})Q_j] + \beta_{ij}[(aP_{dgi} - Q_{di})P_j - (P_{dgi} - P_{di})Q_j]] \quad \text{---- 6}$$

The partial derivative of Eq. (6) with respect to the active power injection from DG at bus '*i*' becomes zero to obtain reduced active power loss.

$$\frac{\partial P_L}{\partial P_{dgi}} = 2\sum_{j=1}^{N}[\alpha_{ij}(P_j + aQ_j) + \beta_{ij}(aP_j - Q_j)] = 0$$

-------------- **7**

Equation (7) can be written in the following way:

$$\alpha_{ii}(P_i + aQ_i) + \beta_{ii}(aP_i - Q_i) \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j) + a\sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j) = 0$$

------ **8**

$$\text{Now Let } X_i = \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)$$

$$\text{And} \quad Y_i = \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}Q_j + \beta_{ij}P_j)$$

------- **9**

From the equation (5.4), (5.5), (5.8) and (5.9) we can obtain the equation (5.10) as below :

$$\alpha_{ii}(P_{dgi} - P_{di} + a^2P_{dgi} - aQ_{di}) + \beta_{ii}(Q_{di} - aP_{di}) + X_i + aY_i = 0$$

----- 10

Rearranging the above equation we can obtain equation (11) to get the formulae to compute the best size of a DG to be placed in distribution system to reduce losses

$$P_{dgi} = \frac{\alpha_{ii}(P_{di}+aQ_{di})+\beta_{ii}(aP_{di}-Q_{di})-X_i-aY_i}{a^2\alpha_{ii}+\alpha_{ii}}$$

-------------- 11

The power factor of a DG unit is very important to minimize the total system losses and it also depends upon the DG type and its operating condition. When the power factor of a DG unit is specified then its size can be determined in the following way:

The DG considered in the paper is injecting only active power such as fuel cells, photovoltaic system, micro-turbines. Power factor is unity for this type i.e. $PFdg$=1, a=0. By reducing the equation (5.11) we can get the size of Type 1 DG.

$$P_{dgi} = P_{di} - \frac{1}{\alpha_{ii}}[\ \beta_{ii}P_{di} + \sum_{\substack{j=1\\ j\neq i}}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)$$

------------ 12

Algorithm

The procedure to allocate a DG unit for loss minimization in a radial distribution system represented as below:

Step 1) Run the load-flow for base case and find each branch as well as total losses and node voltages for the specified test system.

Step 2) Find the optimal node to allocate a DG unit.

(a) Compute Power loss Index

(b) Develop the two input membership functions based on power loss index and pu node voltages and one output membership function of DG suitability index.

(b) Develop fuzzy rules (5×5) using Mamdani’s method and defuzzify that to get optimal node for DG placement.

Step 3) Obtain the optimal size of DG and compute the losses using the following steps:

(a) Allocate the DG unit at the appropriate position obtained from step 2, and vary the DG sizes in a very small steps using equation (5.4,5.5,5.11,5.12) by updating the values of ‘α’ and ‘β’ and finally compute the total real power losses

(b) Select and store the DG size which gives minimum losses and discard other results.

Step 4) Update load data which is obtained in step 2, after allocating the DG unit with optimal size.

Step 5) Stop the procedure if the following occurs:

(a) If the voltage value at a particular node violate its upper limit.

(b) If the loss obtained in new iteration is greater than the previous iteration loss then the previous iteration loss is saved (or) repeat steps 1 to 4.

Implementation & Results

Test system: In order to evaluate the proposed algorithm described in Chapters 4 and 5, 34 bus test system, taken from the literature is used. Accordingly, optimum size and place of DG for the 34 bus distribution test system [11] are determined with the adapted method.

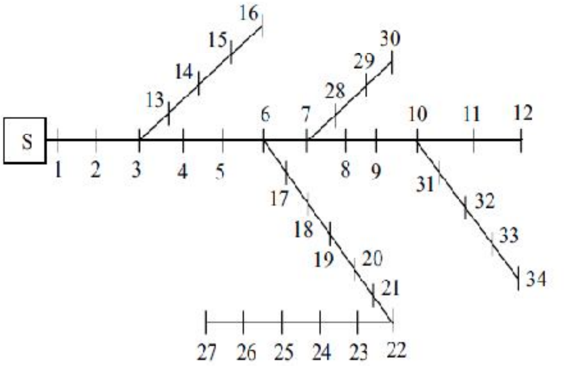

Fig 6. 34 - bus distribution network configuration

This test system has real and reactive load of 4636.5 MW and 2873.5 MVAR respectively. It is found that combined load PF of the system is about 0.85 lagging. Details of the test system are given in Annexure.

Based on the proposed method the base case power flow gives the total real power loss 222 kW and the fuzzy expert system gave the optimal node 20 for DG placement. By the analytical method the optimal size of PV DG unit is found to be 564kW. The percentage of loss reduction after the allocation of DG is found to be 69.8%.

Table 2 NODE VOLTAGES OF TEST SYSTEM WITH/WITHOUT DG UNIT

Node No.	Node voltages without DG	Node voltages with DG
1	1	1
2	0.9904	0.9942
3	0.9819	0.989
4	0.9697	0.9821
5	0.9589	0.9761
6	0.9485	0.9705
7	0.9446	0.9667
8	0.9424	0.9646
9	0.9399	0.9621
10	0.9387	0.961
11	0.9382	0.9605
12	0.9381	0.9604
13	0.9815	0.9887
14	0.9812	0.9884
15	0.9811	0.9883
16	0.9811	0.9883
17	0.9384	0.966
18	0.9295	0.9623
19	0.9189	0.9582
20	0.9097	0.9549
21	0.9067	0.9521
22	0.9033	0.9488
23	0.9004	0.9461
24	0.8978	0.9436
25	0.8965	0.9424
26	0.896	0.9419
27	0.8959	0.9418
28	0.9442	0.9663
29	0.944	0.9661
30	0.9439	0.966
31	0.9383	0.9606
32	0.938	0.9603
33	0.9378	0.9601
34	0.9378	0.9601

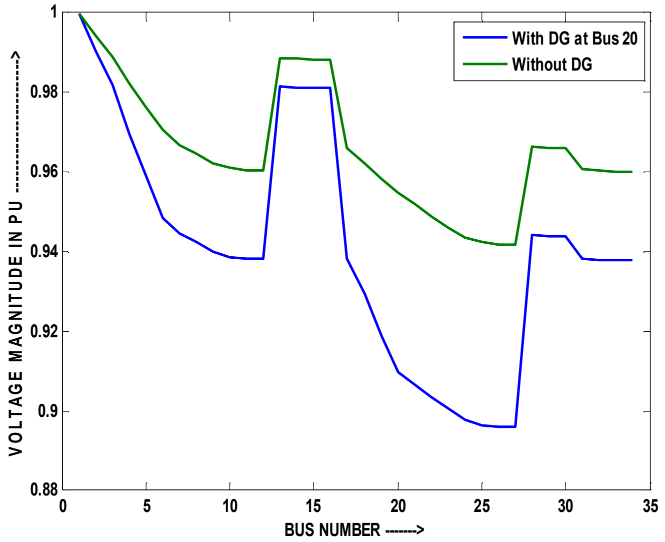

Fig 7: Voltage profile with/ without DG

A graphical representation of voltage profile improvement is shown in fig 7. Fig 8 shows the variation of real power losses in the system when DG unit of various capacities is connected at optimal location.

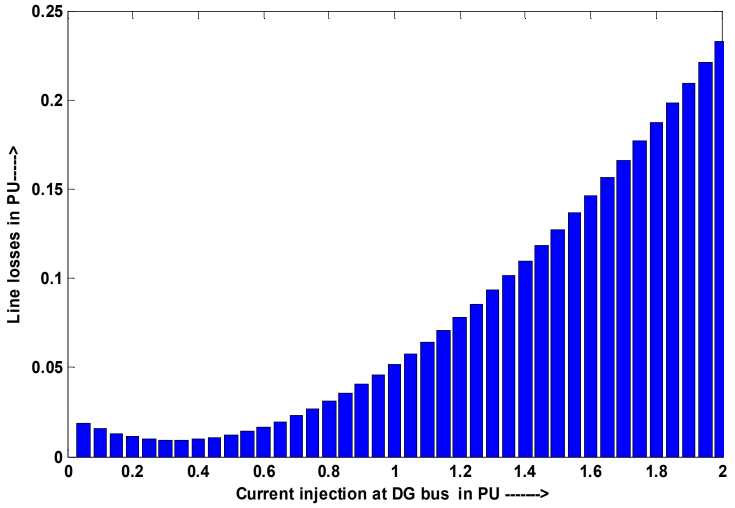

Fig 8 Variation of Real power losses with DG installation

The computer program has been implemented in MATLAB 2014 for estimation of losses with/without DG for the given test system. The fuzzy toolbox is also used to solve the optimal position problem of DG unit.

Results obtained are compared for the same test system with the results presented in [21] by analytical approach for both location and sizing of DG.

Table 3 Comparison of Results

Test system	Real power losses in kW (Without DG)	Real power losses in kW (With DG)	%Loss reduction
34 – Bus	222.0	69.0	69.8%
34 – bus [21]	229.76	108.6	52.7

Conclusion

A method has been proposed to determine most sensitive buses to place DG unit using fuzzy logic and its size is calculated using index based method in radial distribution systems. The FES considers loss reduction and voltage profile improvement simultaneously while deciding potential buses for DG placement. Hence, a good compromise of loss reduction, voltage profile improvement and net saving is achieved when compared to existing methods. Validity of the method is tested on IEEE 34-node radial distribution system. Results showed that appropriate size, location and power factor of a DG unit will lead a significant role to minimize the losses in distribution system.

Future Scope

The algorithm may be implemented for 3-phase distribution network with unbalanced loading conditions. Various types of loads may be considered other than PQ model.

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Annexure

Details of 34 - bus distribution network

Line No.	From Bus	To Bus	Resistance in Ohm	Reactance in Ohm	P in kW	Q in kVAR
1	1	2	0.117	0.048	230	142.5
2	2	3	0.10725	0.044	0	0
3	3	4	0.16445	0.04565	230	142.5
4	4	5	0.1495	0.0415	230	142.5
5	5	6	0.1495	0.0415	0	0
6	6	7	0.3144	0.054	0	0
7	7	8	0.2096	0.036	230	142.5
8	8	9	0.3144	0.054	230	142.5
9	9	10	0.2096	0.036	0	0
10	10	11	0.131	0.0225	230	142.5
11	11	12	0.1048	0.018	137	84
12	3	13	0.1572	0.027	72	45
13	13	14	0.2096	0.036	72	45
14	14	15	0.1048	0.018	72	45
15	15	16	0.0524	0.009	13.5	7.5
16	6	17	0.1794	0.0498	230	142.5
17	17	18	0.16445	0.04565	230	142.5
18	18	19	0.2079	0.0473	230	142.5
19	19	20	0.189	0.043	230	142.5
20	20	21	0.189	0.043	230	142.5
21	21	22	0.262	0.045	230	142.5
22	22	23	0.262	0.045	230	142.5
23	23	24	0.3144	0.054	230	142.5
24	24	25	0.2096	0.036	230	142.5
25	25	26	0.131	0.0225	230	142.5
26	26	27	0.1048	0.018	137	85
27	7	28	0.1572	0.027	75	48
28	28	29	0.1572	0.027	75	48
29	29	30	0.1572	0.027	75	48
30	10	31	0.1572	0.027	57	34.5
31	31	32	0.20856	0.036	57	34.5
32	32	33	0.1572	0.027	57	34.5
33	33	34	0.1048	0.018	57	34.5