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Optimal Siting and Sizing of Dg in Distribution Networks for Power Loss Saving

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Abstract: *This paper presents a methodology to determine optimal location and size of DG so as to minimize real/active power loss in the distribution network. For this purpose, suitable expressions have been derived to compute the active power loss saving associated with placement of the DG units. The proposed method is applicable for sizing and siting of single DG unit at a time. Moreover, the proposed method requires only the results of base case load flow to determine the optimal size of DG unit. The proposed method is tested on 33-bus and 69-bus radial distribution test systems. The comparison of results obtained by the proposed method with those of reported methods validate the suitability and importance of proposed method in determining the optimal size and site of DG unit.*

Keywords*: Power Distribution Network, Distributed Generation (DG), Optimal Siting-Sizing, Power Loss Saving.*

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I. Introduction

Integration of DG into an existing distribution system has many impacts on the system with loss saving being one of the major issues. A number of works has been reported in literature for optimal allocation of DG in distribution networks to minimize power loss [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]. In references [19, 20, 21, 22, 23], the effect of DG penetration level on distribution losses has been presented.

Power injected from DG units to distribution feeders change network power flow modifying annual energy loss. Although DG reduces system energy losses, annual energy loss in distribution networks varies as a U-shape trajectory with increase in DG penetration level [2, 22, 24]. Hence, regulators attempt is to set DG installed capacity equal to minimum point on the U-shape trajectory curve. The U-shape trajectory curve is obtained by varying the DG size in a fixed step and performing load flow analysis corresponding to each step size of DG capacity. This requires several load flow solutions and hence becomes computationally demanding. Therefore, a computationally efficient method is required to determine the power loss reduction after DG placement in the radial distribution network requiring only base case load flow solution.

This paper presents an approach based on active power loss saving for optimal siting and sizing of DG units in radial power distribution networks considering DG operation at a given fixed power factor. Suitable expressions have been derived to compute the active power loss saving associated with placement of the DG unit. The proposed method is applicable for sizing and siting of single DG unit at a time. Moreover, the proposed method requires only the results of base case load flow to determine the optimal size of DG unit. The proposed method is tested on 33-bus and 69-bus radial distribution test systems. The comparison of results obtained by the proposed method with those of published methods validates the suitability and importance of proposed method in determining the optimal size and site of DG unit.

This paper is organized as follows: Section 2 discusses the problem formulation of proposed method, Section 3 presents the solution algorithm, and Section 4 presents the results and discussion of the proposed work. Finally, in Section 5, conclusions are summarized.

II. Proposed Methodology

In this section, the mathematical formulation of the proposed active power loss saving based approach is presented. The mathematical formulation begins with the following assumptions:

a. The radial distribution network under consideration is balanced.

b. The power factor of DG is known.

Consider a typical *N*-bus radial distribution system as shown in Fig. 1 in which $\boldsymbol{I}_k$ is representing the phasor current in branch *k* while $\boldsymbol{I}_{Lk}$ is representing the phasor current of load connected at node *k*.

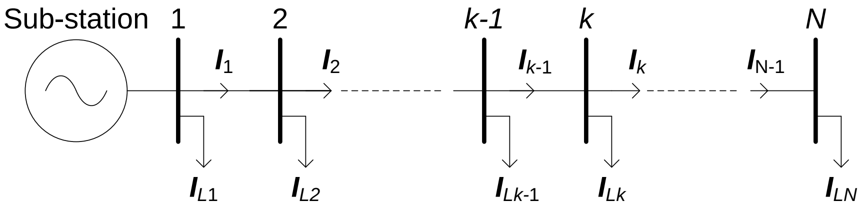

Fig. 1: A typical *N*-bus radial distribution system

The total active power losses, P_L in a typical N-bus radial distribution system as shown in Fig. 1 can be given as:

$$P_L = \sum_{i=1}^{N-1} I_i^2 R_i = \sum_{i=1}^{N-1} \left(I_{ai}^2 + I_{ri}^2 \right) R_i \tag{1}$$

where, I_i is the current through branch i with I_{ai} and I_{ri} being its real and imaginary components, respectively; and R_i is the resistance of the branch i.

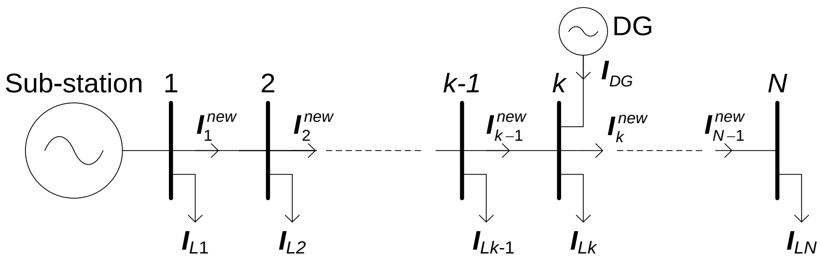

Fig. 2: A typical *N*-bus radial distribution system with DG placed at bus *k*

When a DG is placed at a bus (say bus k) as shown in Fig. 2, it injects current $\boldsymbol{I}_{DG}$ into the network and there by alters the currents in all the branches connected between sub-station (bus 1) to bus k. However, the currents in the remaining branches are unaffected by the DG placed at bus k. The injected current by DG placed at bus k can be written as:

$$\boldsymbol{I}_{DG} = I_{aDG} + jI_{rDG} = I_{aDG}\left(1 + j\tan\phi\right) \tag{2}$$

where, I_{aDG} and I_{rDG} are the real and reactive components, respectively, of $\boldsymbol{I}_{DG}$ and ϕ is the phase angle of $\boldsymbol{I}_{DG}$.
Now, the modified current in branch i due to DG placement at bus k can be given as:

$$\boldsymbol{I}_i^{new} = \boldsymbol{I}_i - D_i \boldsymbol{I}_{DG} = \left(I_{ai} - D_i I_{aDG}\right) + j\left(I_{ri} - D_i I_{aDG}\tan\phi\right) \tag{3}$$

where, $\boldsymbol{I}_i$ is the phasor current in branch i before DG placement and $\boldsymbol{I}_i^{new}$ is the modified phasor current in branch i after DG placement. The value of D_i is given by following relation:

$$D_i = \begin{cases} 1, & \text{if branch } i \text{ is between bus 1 and bus } k \\ 0, & \text{otherwise.} \end{cases}$$

The real power losses in a radial distribution network depend on the current and resistance of different branch as given in eq. (1). Since placement of DG at bus k in the network alters the currents in all the branches connected between sub-station (bus 1) to bus k, it also causes the change in active power losses. Now, the total modified active power loss, $P_{L,\,new}$ can be given as:

$$P_{L,new} = \sum_{i=1}^{N-1} \left(I_i^{new}\right)^2 R_i = \sum_{i=1}^{N-1} \left[\left(I_{ai} - D_i I_{aDG}\right)^2 + \left(I_{ri} - D_i I_{aDG}\tan\phi\right)^2 \right] R_i \tag{4}$$

Then the percentage active power loss saving, ΔP_L associated with placement of DG is given as:

$$\Delta P_L = \frac{P_L - P_{L,new}}{P_L} \times 100\% \tag{5}$$

Substituting the values of P_L and $P_{L,\,new}$ from eqs. (1) and (4), respectively, in eq. (5); and simplifying the expression yields the following:

$$\Delta P_L = \frac{\sum_{i=1}^{N-1}\left[2D_i I_{aDG}\left(I_{ai}+I_{ri}\tan\phi\right)-\left(D_i I_{aDG}\sec\phi\right)^2\right]R_i}{P_L}\times 100\% \tag{6}$$

Equation (6) can be used to compute the active power loss saving associated with single DG placement of a given size and power factor. The developed expression for loss saving requires the active component and angle of injected current by DG. However, the DG capacity is generally expressed in terms of VA rating and power factor. Hence, the following expressions can be used to compute the active component and angle of injected current by DG:

$$I_{aDG} = \frac{V\sec\phi}{S_{DG}} \tag{7}$$

$$\phi = \theta - \cos^{-1}(PF_{DG}) \tag{8}$$

where, V and θ are the magnitude and angle, respectively, of bus voltage at which DG is connected, S_{DG} is the VA rating of DG and PF_{DG} is the power factor of DG.

III. Solution Algorithm Of Proposed Method

The computational procedure of proposed algorithm can be given in the following steps:

1. Read the data regarding number of buses (N), configuration/connectivity, resistance and reactance of different branches, real and reactive power demand at different buses of distribution network under consideration.
2. Perform the load flow to calculate the branch currents, bus voltages and active power losses.
3. Assume the power factor of DG and initialize bus counter, i = 2 (the source bus is numbered as 1 and not considered for DG placement.
4. Initialize DG size, j = 5% of total system load.
5. Compute the the active component and angle of injected current by DGusing eqs. (7) and (8), respectively. Also calculate active power loss saving using eq. (3.6) and store the results.
6. Check whether j = 100% of total system load ? If yes, go to Step 7, otherwise j = j + 5% of total system load and go to Step 5.
7. Check whether i = N ? If yes, go to Step 8, otherwise i = i + 1 and go to Step 4.
8. Identify the values of i and j corresponding to maximum power loss saving. The value of i gives the optimal bus for DG placement and the value of j gives the near optimal DG capacity at bus i. The optimal DG capacity lies in between j-1 and j+1, which can further be optimized.
9. Initialize DG size at bus i, k = j - 1.
10. Compute the the active component and angle of injected current by DGusing eqs. (7) and (8), respectively. Also calculate active power loss saving using eq. (6) and store the results.
11. Check whether k = j+1? If yes, go to Step 12, otherwise k = k + 1% of total system load and go to Step 10.
12. Compare the active power loss savings at bus i and find out the overall maximum value of active power loss saving. Also identify the value of k corresponding to maximum power loss saving, which gives the optimal DG capacity at bus i.

IV. Results And Discussion

The developed algorithm is implemented under MATLAB environment and applied on 33-bus and 69-bus test distribution systems for the optimal placement and sizing of DG. For each test system, two different values of DG power factors are considered as [10]:

a) DG is operated at a power factor equal to the power factor of total load of the system,
b) DG is operated at unity power factor.

4.1. 33-Buses Radial Distribution System

The single line diagram of a 12.66 kV, 33-bus radial distribution system is illustrated in Fig. 3. The relevant data for this test system are acquired from reference [25].This test system is having the total demand of (3715 + j2300) kVA with the power factor of total load as 0.85 lagging. The base case losses in the system are 202.68 kW and 135.14 kVAR.

The proposed method is applied to different buses of 33-bus network by varying the size of DG from 0 to 100% of total load in a step of 5%, when DG is operated at load power factor (LPF), which is 0.85 lagging. The maximum loss saving and corresponding DG size is recorded at each bus and is plotted in Fig 4.

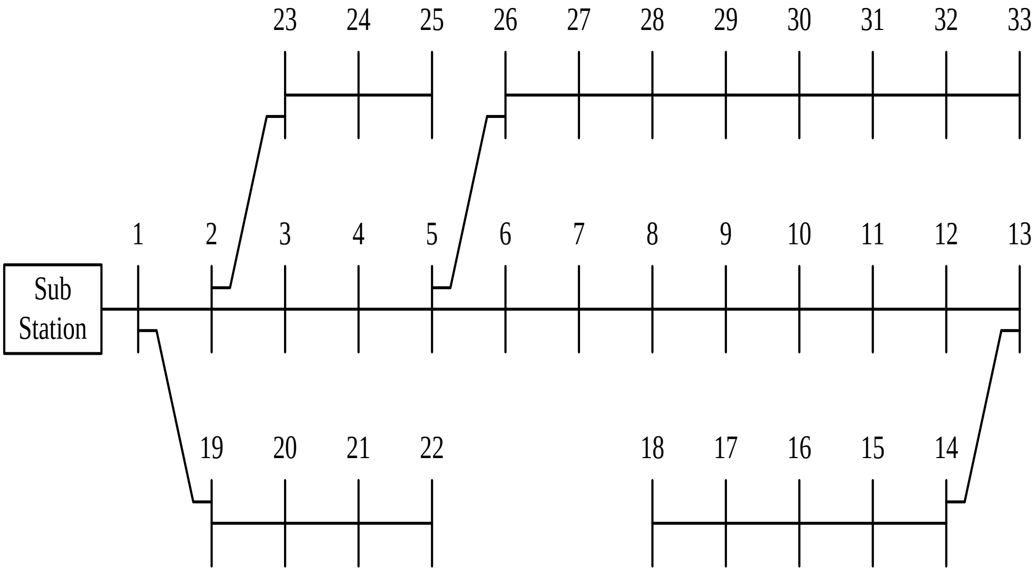

Fig. 3: Single line diagram of 12.66 kV, 33-bus radial distribution system

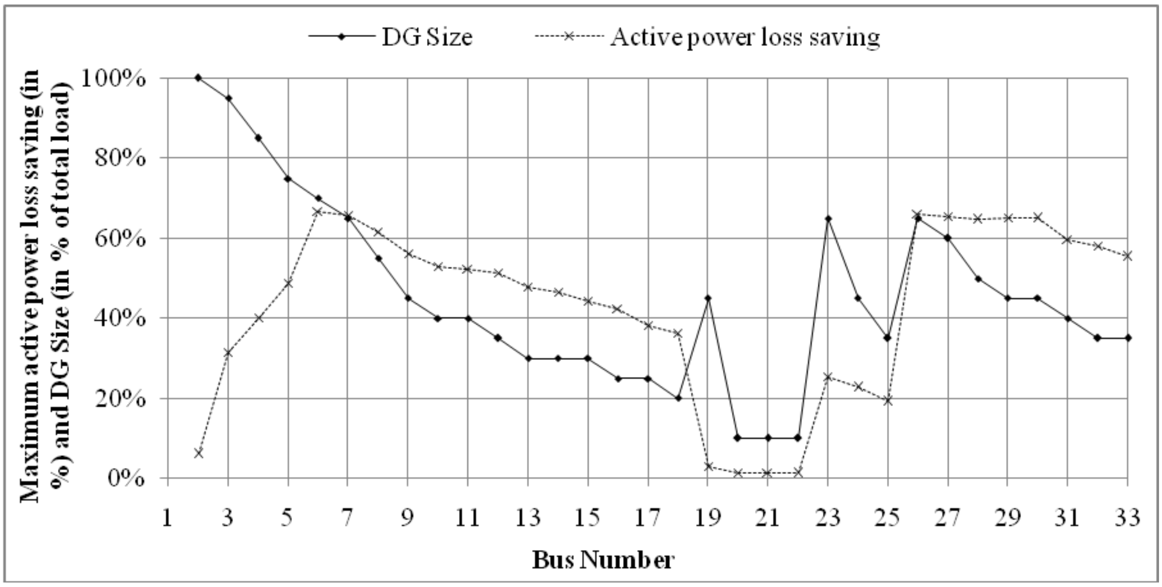

Fig. 4: Maximum active power loss saving and corresponding size of LPF DG at different buses of 33-bus system

From Fig. 4, it is clear that both the maximum active power loss saving as well as corresponding DG size vary from bus to bus. Among different buses, DG placement at bus 6 offers maximum active power loss saving of about 67% with DG capacity of 70% of total load. The results shown in Fig. 4 can also be used to define maximum permissible size (penetration level) of DG at different buses. For example, if anyone wishes to connect DG at bus 10 due to some location constraint, then the DG size at 0.85 lagging power factor cannot exceed 40% of total system load.

In order to validate the suitability of the proposed method, first the loss savings obtained by proposed method are compared with those obtained by the repeated load flow method by varying the DG size. For this purpose, bus number 6 of 33-bus system is selected because this bus is resulting in maximum active power loss saving. Fig. 5 shows the variation in active power loss saving by proposed method as well as repeated load flow method with DG capacity, when a LPF DG is placed at bus number 6. From this figure, it can be observed that the loss saving computed by proposed method is in close agreement to that computed by running load flow and

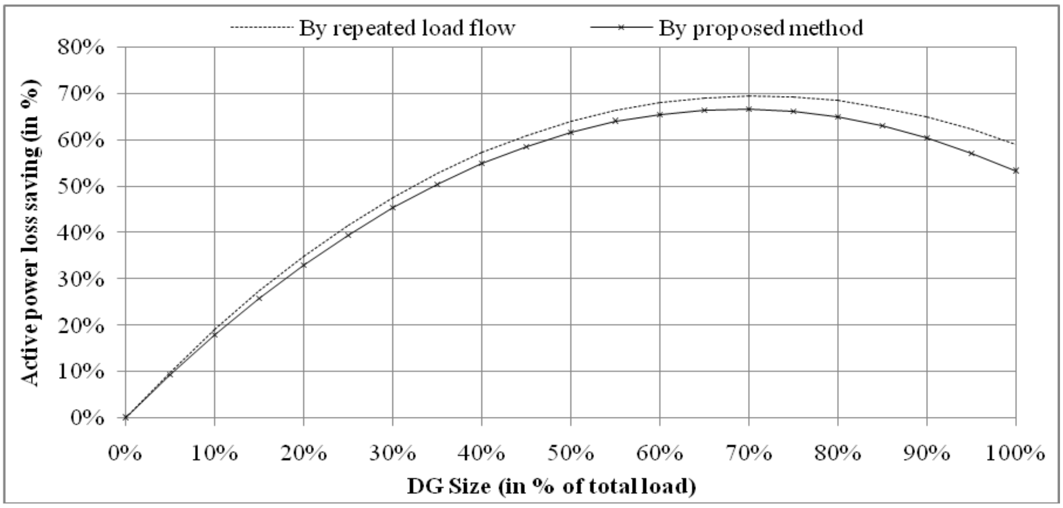

Fig. 5: Comparison of active power loss saving with LPF DG connected at bus 6 of 33-bus system

both are following similar trends. However, there is always a small difference, because DG placement reduces the current flowing through different branches in the radial distribution network. This reduction in branch current reduces the voltage drops in different branches which in turn improves the voltage profile of the system. This phenomenon is well reflected by load flow solution. Thus, repeated load flow methodestimates the active power loss saving precisely. On other hand, the proposed derivation computes the active power loss saving due to the changes in branch currents only caused by DG placement. Hence, the active power loss saving by it is slightly less as compared to that by repeated load flow method. But the proposed method requires only base case load flow solution, while repeated load flow method requires as many load flow solutions as the number of DG sizes.

The maximum active power loss saving is observed by proposed method as well as repeated load flow method, when DG size is 70% of total load. By proposed method, maximum active power loss saving is 66.69%, whereas, it is 69.57% in the case of repeated load flow method. Though the active power loss saving calculated by proposed method is slightly less as compared to that calculated by repeated load flow method, DG sizes corresponding to maximum active power loss savingidentified by proposed method as well as repeated load flow method are same.

Again from Fig. 5, it is observed that the optimal capacity of LPF DG at bus 6 lies in the range of 65-75% of total load. In order to determine the exact optimal size of LPF DG at bus 6, its capacity is varied from 65% to 75% of total load in a step of 1% and obtained results are shown in Fig 6. From this figure, it observed that the optimal size of LPF DG is 69% of total load at bus 6.

A similar exercise is also carried out with unity power factor (UPF) DG and obtained results are shown in Fig. 7. Among different buses, DG placement at bus 6 still offers maximum active power loss saving. However, placement of unity power factor DG at bus 6 results about 45% active power loss saving with DG capacity of 55% of total load. By comparing the results shown in Figs. 4 and 7, it is concluded that placement of

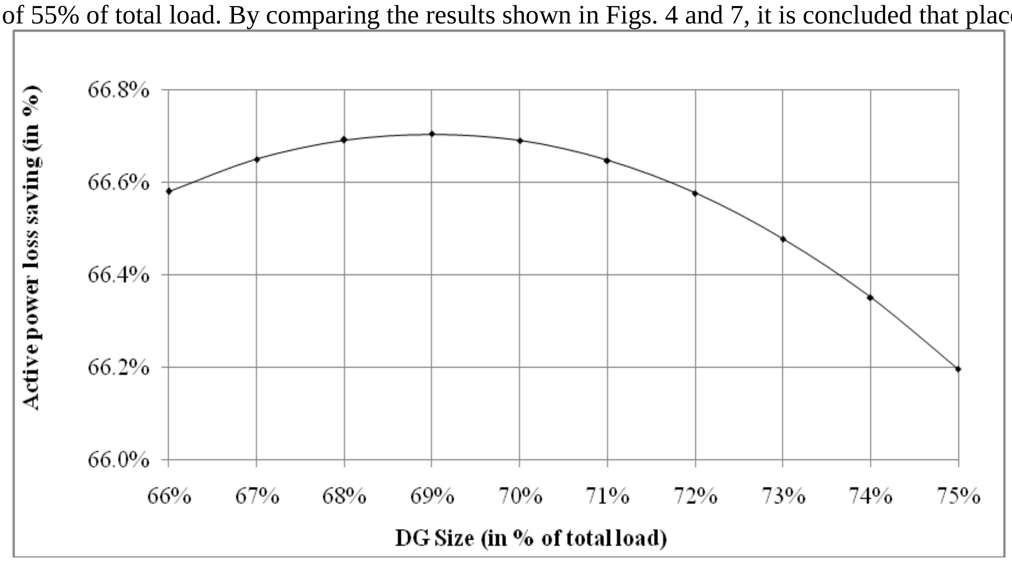

Fig. 6: Active power loss saving with LPF DG connected at bus 6 of 33-bus system

LPF DG results more real power loss saving as compared to the placement of UPF DG. In addition, with power factor of DG, the optimal DG capacity at a bus also varies. The placement of LPF DG at bus 6 with capacity as 70% of total load offers about 67% active power loss saving, whereas the placement of UPF DG at same bus with capacity as 55% of total load offers about 45% active power loss saving. Hence, DG power factor plays an important role in deciding the loss saving and capacity of DG.

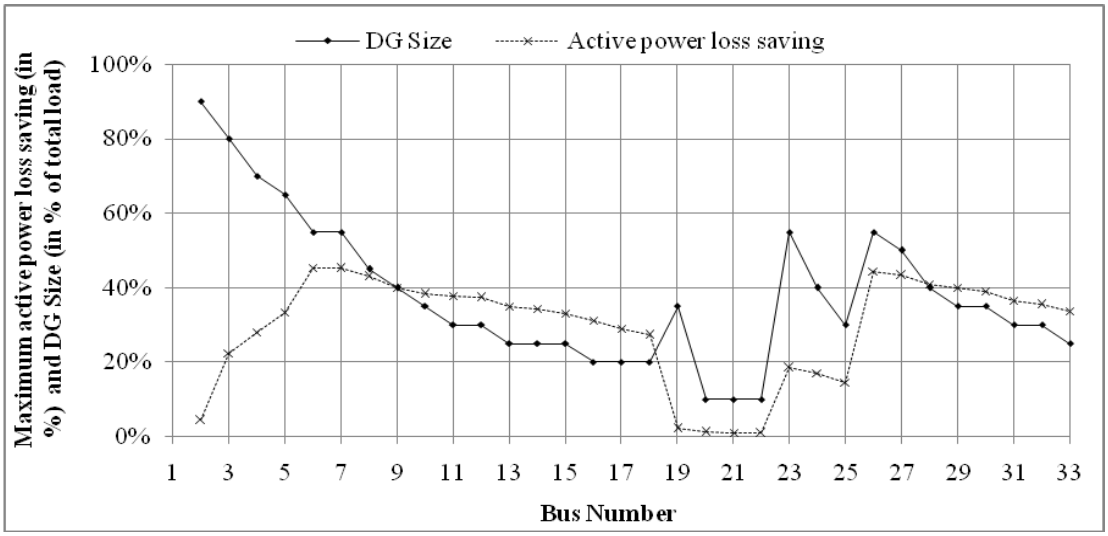

Fig. 7: Maximum active power loss saving and corresponding size of UPF DG at different buses of 33-bus system

In order to validate the results obtained by the developed expression, bus number 6 of 33-bus system is selected because this bus is resulting real power loss saving with UPF DG as shown in Fig. 7. The real power loss saving obtained by the developed expression is compared with that obtained by performing the repeated load flow by varying the UPF DG size at bus 6. Fig. 8 shows the variation in real power loss saving by proposed method as well as repeated load flow method with DG capacity.

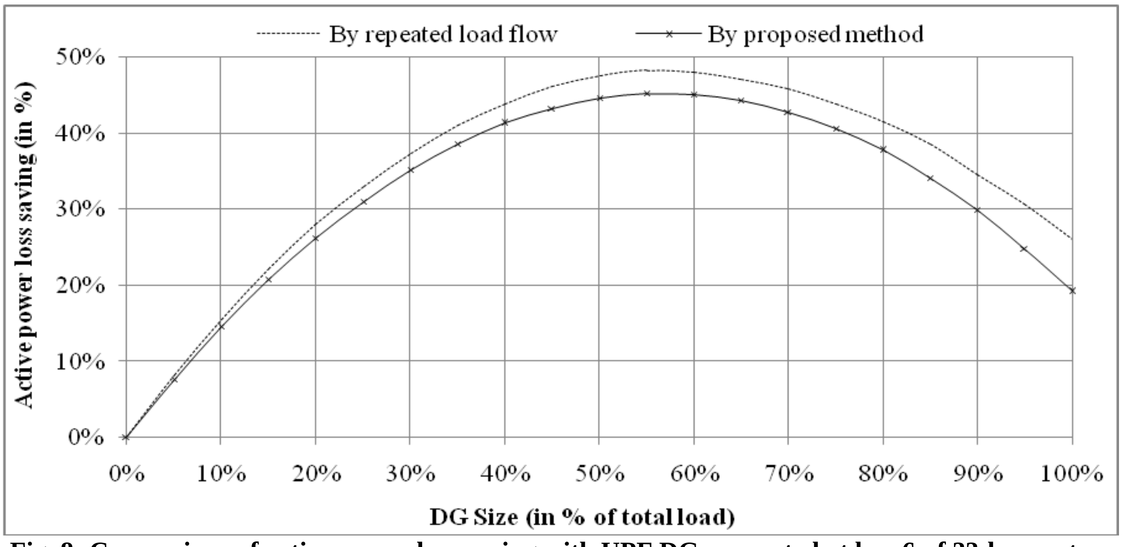

Fig. 8: Comparison of active power loss saving with UPF DG connected at bus 6 of 33-bus system

By proposed method, maximum real power loss saving is 45.25%, whereas, it is 48.31% in the case of repeated load flow method. Though the real power loss saving calculated by proposed method is slightly less as compared to that calculated by repeated load flow method, DG sizes corresponding to maximum real power loss saving identified by proposed method as well as repeated load flow method are same. The maximum real power loss saving is observed by proposed method as well as repeated load flow method, when DG size is 55% of total load.

Again from Fig. 8, it is observed that the optimal capacity of DG at bus 6 lies between 50-60% of total load. In order to determine the exact optimal size of DG, Steps 9 to 12 of Section 3 is used and obtained results are shown in Fig 9. From this figure, it observed that the exact optimal size of UPF DG at bus 6 is 57% of total load.

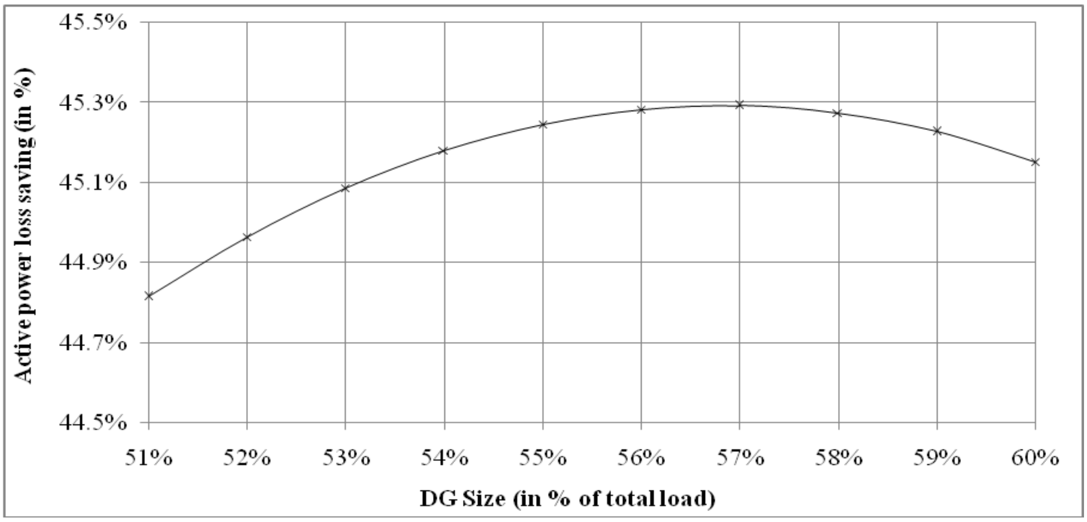

Fig. 9: Active power loss saving with UPF DG connected at bus 6 of 33-bus system

Finally, to validate the proposed method, the results obtained by it are compared with those by the methods reported in the literature for 33-bus test system and presented in Table 1. From this table, it is evident that more active power loss saving is possible by the proposed method as compared to the other methods reported in the literature. Though the proposed method gives approximate results, the DG size obtained by it is closely matching with that by other methods given in literature.

Table 1: Comparison of results for 33-bus test system

Particulars	DG operation at UPF			DG operation at other than UPF	
	Acharya *et al.* [2]	Murthy *et al.*[27]	Proposed Method	Murthy *et al.* [27]	Proposed Method
DG size (MVA)	2.49	2.5	2.5	3.01	3.02
DG Power Factor	UPF	UPF	UPF	0.9 lag	0.85 lag
Location	6	6	6	6	6
Active Power Loss Saving (%)	47.33	47.32	45.3 (by developed expression) 48.65 (by load flow)	66.39	66.7 (by developed expression) 69.55 (by load flow)

4.2. 69-Bus Radial Distribution System

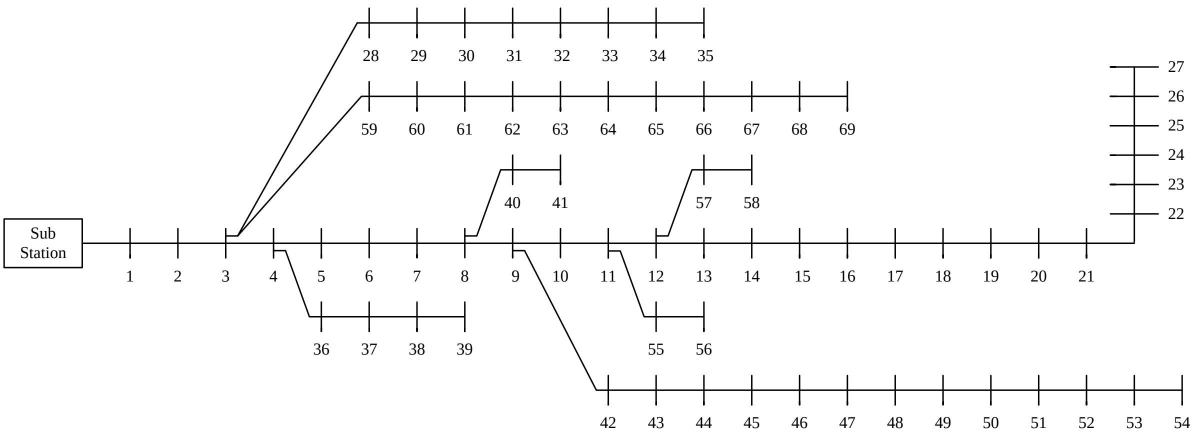

Fig. 10: Single line diagram of 12.66 kV, 69-bus distribution system

The single line diagram of a 12.66 kV, 69-bus distribution test system is shown in Fig. 10. The necessary data for 12.66 kV, 69-bus distribution test system are obtained from reference [26].This test system is having the total demand of (3802.19+ *j*2694.6) kVA with the power factor of total load as 0.82 lagging. . The base case losses in the system are 225 kW and 102.17 kVAR.

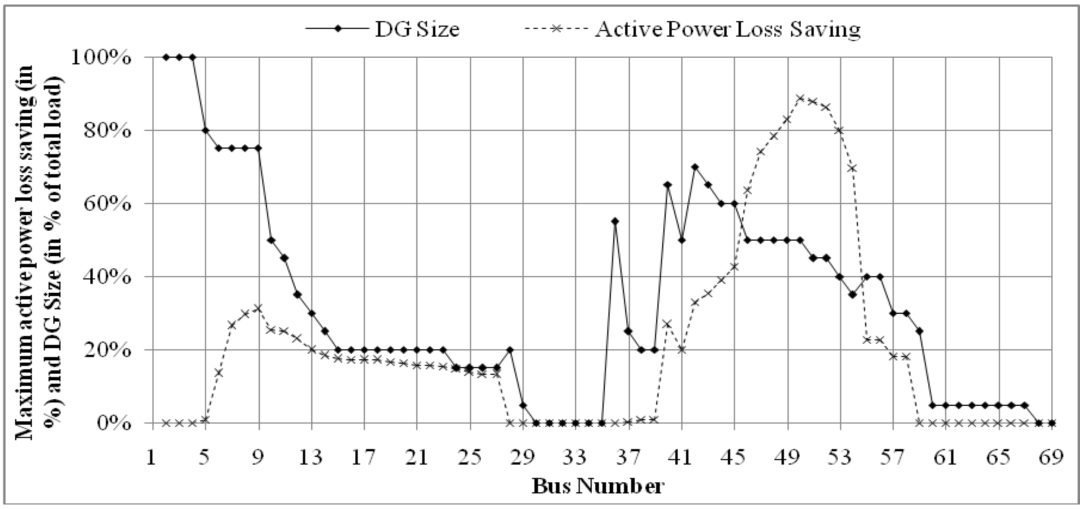

Fig. 11: Maximum active power loss saving and corresponding size of LPF DG at different buses of 69-bus system

The proposed method is applied to different buses of 69-bus network by varying the size of DG from 0 to 100% of total load, when a DG is operated at LPF (0.82 lagging) and the maximum loss saving and corresponding DG size is recorded at each bus. The same is illustrated in Fig 11. From this figure, it is clear that both the maximum active power loss saving as well as corresponding DG size vary from bus to bus. Among different buses, DG placement at bus 50 offers maximum active power loss saving of about 89% with DG capacity of 50% of total load.

In order to validate the results of the proposed method, the loss savings obtained by it are compared with those obtained by the repeated load flow method by varying the DG size. For this purpose, bus number 50 of 69-bus system is selected because this bus is resulting in maximum active power loss saving. Fig. 12 shows the variation in active power loss saving by proposed method as well as repeated load flow method with LPF DG capacity. From this figure, it is observed that the loss saving computed by proposed method is in close agreement to that computed by running load flow and both are following similar trends in case of 69-bus system also. The maximum active power loss saving is observed by proposed method as well as repeated load flow method, when the DG size is 50% of total load. By the proposed method, maximum active power loss saving is 89.1%, whereas, it is 89.59% in the case of repeated load flow method.

Again from Fig. 12, it is observed that the optimal capacity of DG at bus 50 lies in the range of 45-55% of total load. In order to determine the exact optimal size of DG, Steps 9 to 12 of Section 3 is used and obtained results are shown in Fig. 13. From this figure, it observed that the exact optimal size of LPF DG is 48% of total load at bus 50.

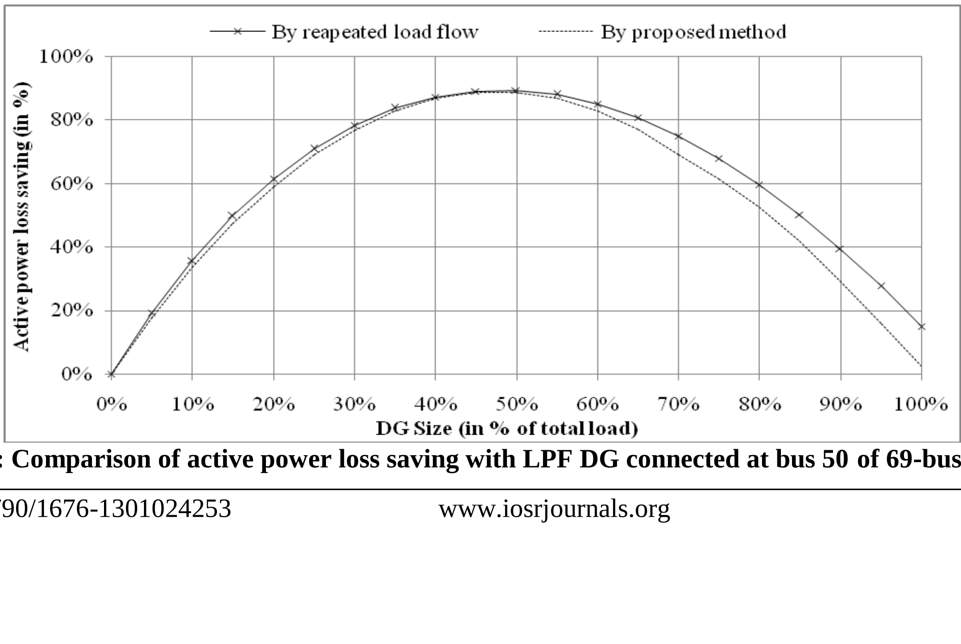

Fig. 12: Comparison of active power loss saving with LPF DG connected at bus 50 of 69-bus system

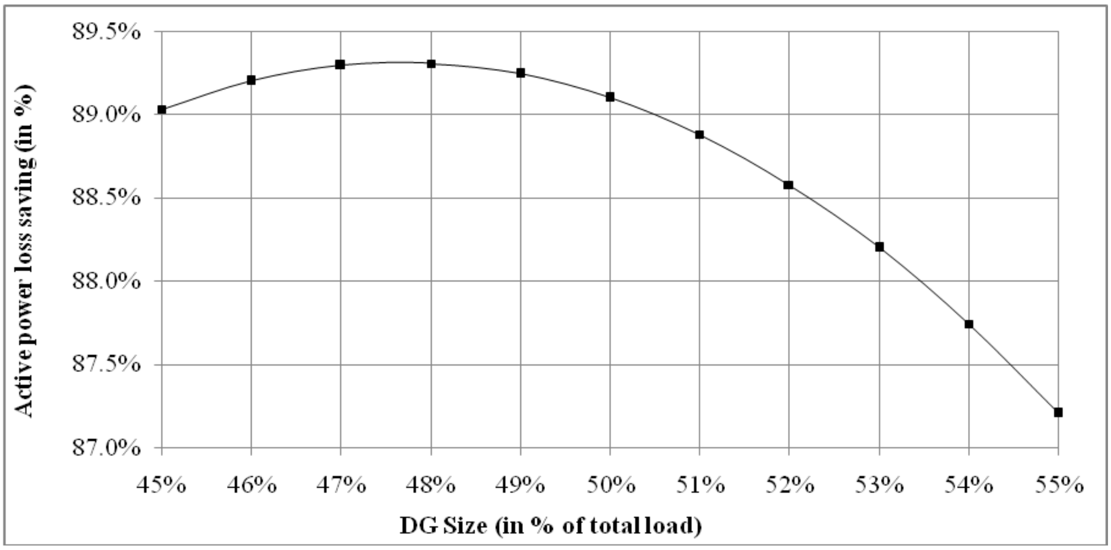

Fig. 13: Active power loss saving with LPF DG connected at bus 50 of 69-bus system

A similar exercise is also carried out with unity power factor (UPF) DG and obtained results are shown in Fig. 14. Among different buses, DG placement at bus 50 still offers maximum active power loss saving. However, placement of unity power factor DG at bus 50 results about 59% active power loss saving with DG capacity of 40% of total load. By comparing the results shown in Figs. 11 and 14, it can be concluded that placement of LPF DG results more real power loss saving as compared to the placement of UPF DG but with different sizes.

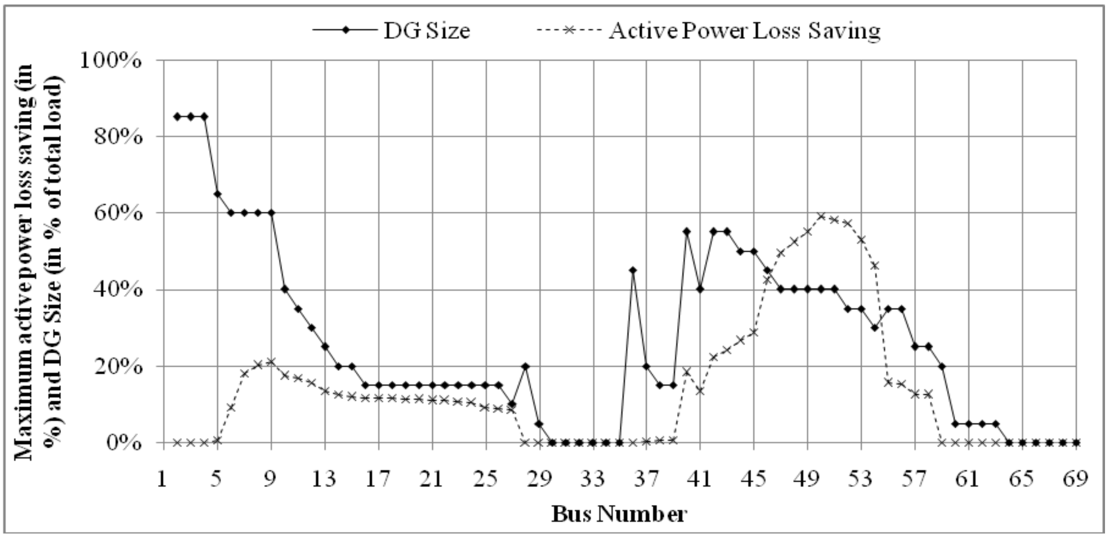

Fig. 14: Maximum active power loss saving and corresponding size of UPF DG at different buses of 69-bus system

Further, the real power loss saving obtained by the developed expression is compared with that obtained by performing the repeated load flow by varying the UPF DG size at bus 50. Fig. 15 shows the variation in real power loss saving by proposed method as well as repeated load flow method with DG capacity.

By proposed method, maximum real power loss saving is 59.06%, whereas, it is 63.01% in the case of repeated load flow method. Though the real power loss saving calculated by proposed method is slightly less as compared to that calculated by repeated load flow method, DG sizes corresponding to maximum real power loss saving identified by proposed method as well as repeated load flow method are same. The maximum real power loss saving is observed by proposed method as well as repeated load flow method, when DG size is 40% of total load.

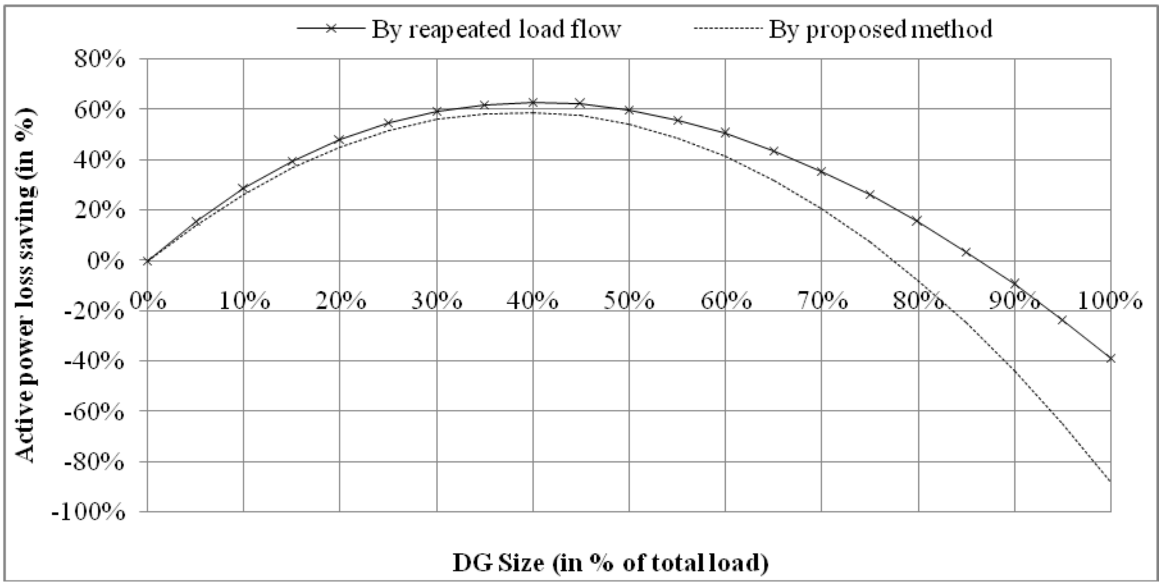

Fig. 15: Comparison of active power loss saving with UPF DG connected at bus 50 of 69-bus system

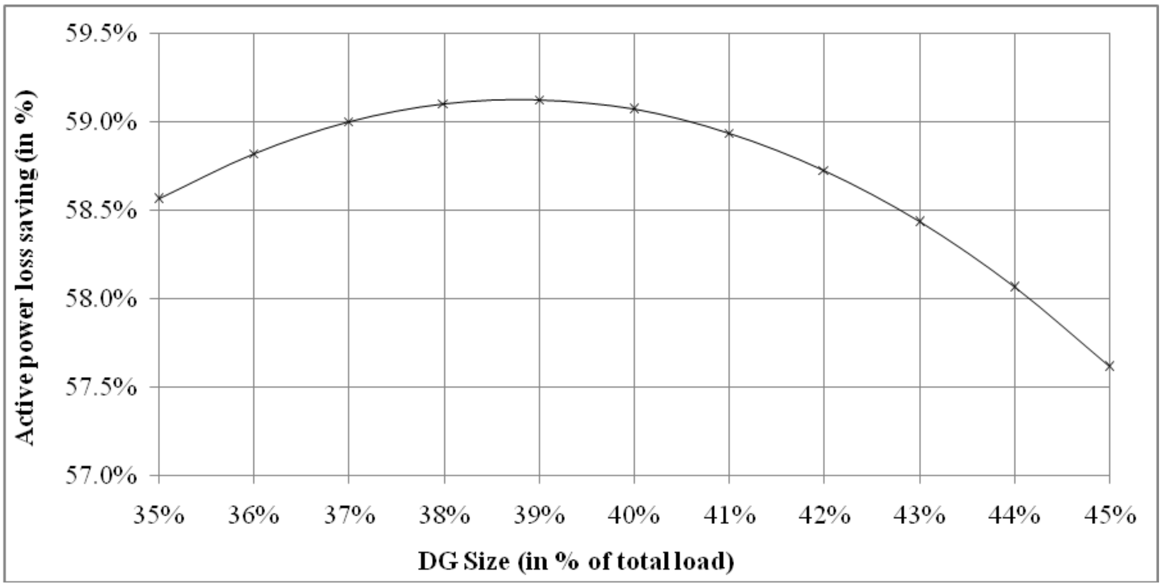

Fig. 16: Active power loss saving with UPF DG connected at bus 50 of 69-bus system

Again from Fig. 15, it is observed that the optimal capacity of DG at bus 50 lies between 35-45% of total load. In order to determine the exact optimal size of UPF DG, its capacity is varied in the range of 35% to 45% of total load in step of 1% and obtained results are shown in Fig, 16. From this figure, it observed that the exact optimal size of UPF DG is 39% of total load at bus 50.

Finally, to validate the proposed method, the results obtained by it are compared with those by the methods reported in the literature for 69-bus test system and presented in Table 2. From this table, it is evident that more active power loss saving is possible by the proposed method as compared to the other methods reported in the literature. The optimal size and location identified by the proposed method are closely matching with those reported in [2] and [27].

Table 2: Comparison of results for 69-bus test system

Particulars	DG operation at UPF			DG operation at other than UPF	
	Acharya *et al.* [2]	Murthy *et al.*[27]	Proposed Method	Murthy *et al.* [27]	Proposed Method
DG size (MVA)	1.81	1.85	1.82	2.20	2.24
DG Power Factor	UPF	UPF	UPF	0.9 lag	0.82 lag
Location	50	50	50	50	50

Active Power Loss Saving (%)	62.86	63.02	59.91 (by developed expression) 62.96 (by load flow)	87.59	89.31 (by developed expression) 89.7 (by load flow)

Further, an analysis has also been carried out for the computational burden involved in determining the optimal location and size of DG. The proposed method takes only base case load flow solution, while on the other hand the repeated load flow method requires a number of load flow solutions which depends on the system size (number of buses in the system) and incremental step-size for DG. The number of load flow solutions required is plotted in Fig. 17 as a function of system size with different values of incremental step-size for DG. The number of load flow solutions required varies linearly with the system size for a given value of incremental step-size for DG. Though the proposed method gives approximate results, it requires less computation burden in comparison to repeated load flow method. Since the trends of active power loss saving calculated by proposed method and repeated load flow method are same, the results obtained by proposed method can also be used to reduce the search space, if proposed method is used with an optimization technique.

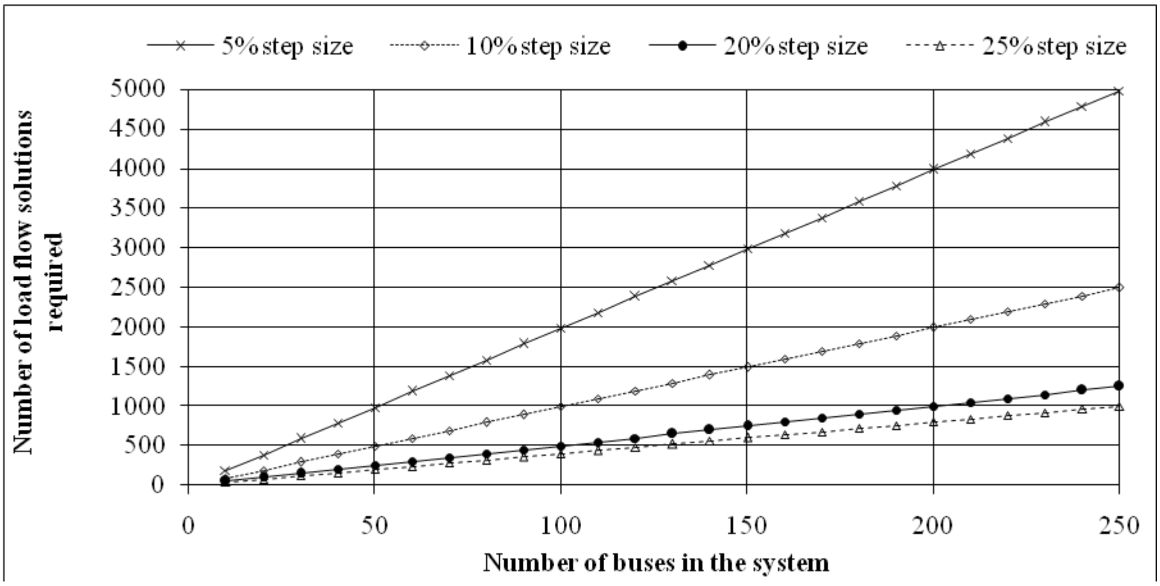

Fig. 17: Variation in number of load flow solutions required with system size and incremental step-size for DG

V. Conclusions

This chapter presents an expression to analyze the impact of DG of a given size and power factor on active power loss in a distribution system. On the basis of developed expression, an algorithm has been presented to determine the optimal location and size of DG in a distribution system for minimization of active power loss. This method requires only base case load flow solution. The proposed method has been implemented under MATLAB environment. The active power loss saving by proposed method has been compared with that by the repeated load flow method. The comparison shows that the results of the proposed method is in close agreement to that by repeated load flow and both are following similar trends. The proposed algorithm has been applied to 33-bus and 69-bus radial distribution test systems considering DG operation at two different power factors, one at unity power factor and another at load power factor. There is significant saving in the real power loss of system with DG placement by proposed method. However, in case of load power factor DG, it is better as compared to the case with unity power factor DG. Hence, the DG power factor also plays an important role in obtaining this maximum real power loss saving. Comparison of the proposed method with those reported in literature shows that more active power loss saving is possible by the proposed method compared to the other methods.

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