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A Novel Algorithm for Distributed Generator Placement and Sizing for Distribution Systems

M.Venkateswarlu, M.Tech
Sr.Assistant Professor
Department of EEE,
G.Pullaiah College of Engineering & Technology,
Kurnool.

Y.Hazarathaiah, M.Tech
Assistant Professor,
Department of EEE,
G.Pullaiah College of Engineering & Technology,
Kurnool.

Abstract

Distribution grids the number of distributed generation units is increasing rapidly. Combined heat and power (CHP) plants and wind turbines are most often installed. Integration of these DG units into the distribution grid leads to planning as well as operational challenges. In this paper proposed a new algorithm for Distributed Generator (DG) placement and sizing for distribution systems based on a novel index. This paper proposes a new algorithm for Distributed Generator (DG) placement and sizing for distribution systems based on a novel index. The index is developed considering stable node voltages referred as power stability index (PSI). A new analytical approach is adopted to visualize the impact of DG on system losses, voltage profile and voltage stability. The proposed algorithm is tested on 12-bus, modified 12- bus and 69-bus radial distribution networks. The test results are also compared and found to be in close agreement with the existing Golden Section Search (GSS) algorithm.

INTRODUCTION

With the Distributed Generation (DG), many power companies are investing in small scale renewable energy resources such as wind, photo-voltaic cells, micro-turbines, small hydro turbines, CHP or hybrid. In England and Wales for example, DG was only 1.2 GW during 1993–1994, however today this figure has increased substantially and reached up to over 12GW [1]. It is also expected with the KYOTO protocol commitment by various countries to reduce CO2 emission, the market for DGs as a ‘‘Clean Energy’’ resource is promising. According to Energy Network Association (ENA) report [2], the UK government is targeting to achieve 15% of electricity from renewable sources by 2015, implying rapid growth in DG and investment in the power infrastructure. However there are several issues concerning the integration of DGs with existing power system networks; that needs to be addressed [3–5]. The integration of DG changes the system from passive to active networks, which affects the reliability and operation of a power system network [4]. Furthermore, the non-optimal placement of DG can result in an increase of the system losses and thus making the voltage profile lower than the allowable limit [6]. Since utilities are already facing technical and non-technical issues, they cannot tolerate such additional issues. Hence an optimum placement of DG is needed in order to minimize overall system losses and therefore improve voltage profiles. In the past, different methodologies have been developed to determine the optimum location and optimum size of the DG.

These methodologies are either based on analytical tools or on optimization programming methods. Analytical approaches have been proposed by several authors. In [7], the authors presented analytical approach to determine the optimal location for the DG with an objective of loss minimization for distribution and transmission networks. In [8], the author used the loss sensitivity equation to determine the optimum size of DG and the exact loss equation to determine the optimum location of DG based on minimum losses. In [9], the author presented the loss sensitivity factor based on equivalent current injection using two Bus-Injection to Branch-Current (BIBC) and Branch-Current to Bus-Voltage (BCBV) matrix. A simple search algorithm is proposed in [10] for optimal sizing and placement of DG for a network system, based on losses and cost function as an objective function. The method is simple but time consuming for searching both the best location and optimum size. In [11], the author considered the minimum loss and generation cost as a parameter in addition to DG power limits to determine the optimal size and location of the DG. The author developed two programs named ''Bloss'' and ''dpslack'' for optimum sizing of DG, considering DG min–max limits also. Later-on, site is decided by considering the minimum total power losses considering DG on each bus. The method is accurate but very tedious and mathematical computation need much computation time.

In [12] authors have evaluated the effect of DG placement on network reliability, power losses reduction and power quality using the simple analytical approach and has shown the optimum DG allocation affects the system reliability and system losses. Optimization based algorithms have also been proposed by different authors. In [13], ACS (Ant Colony Search Algorithm) is used here to find the optimal placement of DG and recloses based on system reliability. Particle Swarm Optimization algorithm is used in [14,15] for optimum placement considering the minimum electricity cost for consumers. In [16], authors have presented the dynamic based programming approach to find the best location for DG with maximum profit as an objective function. Genetic Algorithm (GA) based methods are proposed in [17–19] for optimal sizing and placement of DG, considering different objective functions. GA-Fuzzy based optimal placement of DG is discussed in [20], considering multi-objective functions including system losses, system loading as well as the profit for DISCOs (Distribution Companies). In [21], the author has presented the combine GA and PSO based approach for optimal location and capacity of DG, considering multi- objective constraints like voltage stability, losses and improved voltage regulations. GAs based methods are slow in computation and convergence [11], particularly useful when multi-objective conditions are considered. This paper proposes a new method for DG placement and sizing based on the line voltage stability index. Previously the author in [22] has used the continuation power flow method to determine the most voltage-sensitive bus in the distribution system which could results in voltage instability in the system. DG is placed on the identified sensitive bus and the size of DG on that bus is increased gradually till the objective function (voltage constraints) is achieved. The proposed algorithm is also working on the same objective function for DG allocation. The developed index is used to identify the most critical bus in the system that can lead to system voltage instability when load increase above certain limit. The DG is placed at the identified bus. The search algorithm is used for estimating the size of DG considering minimum network losses. Overall, this proposed method is simpler and requires less computational time for determining the optimum placement and size of DG as compared to classical search algorithms. The paper is organized as follows:

In Section 2, the impact of DG placement on system losses, voltage profile and stability is discussed. A new analytical approach is used here. Section 3 presents a new algorithm for optimum placement and sizing of DG based on a novel index. In Section 4, the proposed algorithm is applied on 12, modified 12 and 69 bus radial distribution test systems. The results are shown and discussed in detail. To test the effectiveness of proposed method; results are compared with GSS Algorithm.

IMPACT OF DG PLACEMENT

- For obtaining the maximum benefit from the placement of DG, it is necessary to consider the impact of DG on a power system. The following factors are considered in the placement and sizing of DG.

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- Reduction in line losses.
- Improvement in voltage profile and stability.

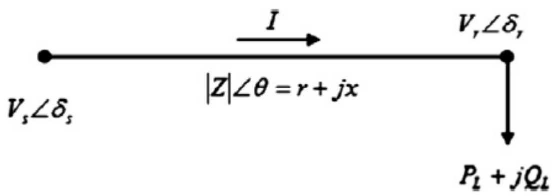


Fig. 1 A two bus network

Consider a simple two bus network shown in Fig. 1 and its corresponding phasor diagram in Fig.2.

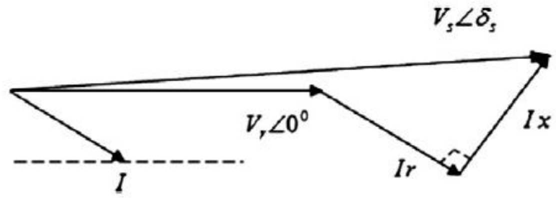


Fig.2 Phasor diagram of a simple two bus network

From the fig.2 phasor diagram, we can write:

$\bar{V}_r = \bar{V}_s - \bar{I}\bar{Z}$ (1)

Where Z is the r + jx is the impedance of the line.

If we reduce the IZ component in the eqn. (1), the receiving end voltage can be improved. There are three ways to reduce the IZ components.

1. Provide active power support to the system locally using renewable energy or distributed resources or FACTS (in the present case we are considering the impact of DG only).
2. Provide reactive power support to the system locally using static condensers or FACTS.
3. Use of Anti Z element, which is only possible through series capacitance.

The first two methods will result in reduction in I component, while the third method will decrease the Z.

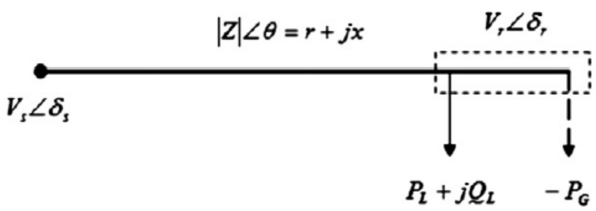


Fig.3Active power support

Fig.3 shows the scenario when we provide active power support ($-P_G$) to the system locally. The phasor diagram is shown in Fig.4, which shows that the introduction of DG will reduce the active line component of the current from I to I' to I" (I>I'>I") asthe DG size will increase. This will result in lesser I_r and $I_x$drop (for simplicity I' and I" drops are not shown in the phasor diagram).

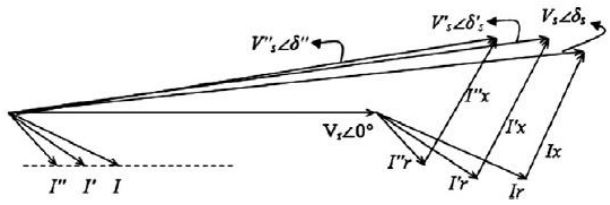


Fig.4 Phasor diagram for Active Power Support.

DG is mostly used for providing active power support to the system. However results could be seen for partially injecting reactive power support at that bus. Fig.5 shows the scenario when we provide reactive power to the system. This will reduce the reactive current component from I to I' to I"(I"<I'<I) shown in phasor diagram Fig. 6, which will results in lesser I_r and I_x drop.

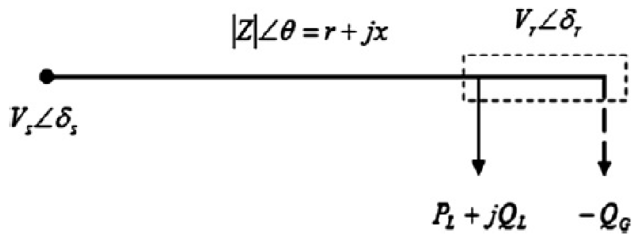


Fig.5 Reactive Power Support.

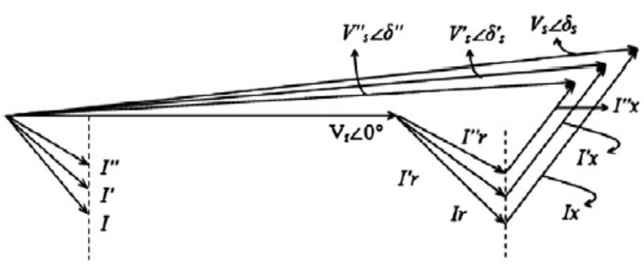


Fig.6 Phasor Diagram for Reactive Power Support

For a simple two bus network, the losses that occurs in the line is given by,

$$P_e - jQ_e = I^2(r + jx) \quad (2)$$

Where
Pe is the active power loss;
Qe the reactive power loss; and
I is the line current, given by:

$$I = \frac{V_s\angle\delta_s - V_r\angle\delta_r}{r+jx} \quad (3)$$

Where

$$V_s\angle\delta_s = V_s(\cos\delta_s + j\sin\delta_s)$$
$$V_r\angle\delta_r = V_r(\cos\delta_r + j\sin\delta_r)$$

From (3.3) and (3.2) results in,

$$[V_r\angle\delta_s - V_s\angle\delta_r]^2 = (P_e - jQ_e)(r + jx) \quad (4)$$

PROPOSED METHOD FOR DG PLACEMENT AND SIZING

The important factor in maintaining the voltage between two buses is the drop in the line connecting the two buses, commonly known as voltage regulation.

Ideally voltage regulation should be zero, but there are drops due to resistance and reactance of a line. In transmission lines resistance is much less than the reactance of the transmission lines (r_x) while in overhead distribution system reactance is much less than the resistance of the line (x_r).There is no anti-resistance element which could improve the voltage regulation. The series capacitor is commonly connected in long transmission lines having high reactance than a distribution net work in order to improve the voltage profile and increasing the system efficiency. However by supporting the active and reactive power demands locally could significantly reduced the voltage drop in the line by reduction in line current and losses and thus improves the system efficiency.

3.1 DEVELOPMENT OF AN INDEX FOR DG PLACEMENT

An index is derived for finding the most optimum site of DG based on the most critical bus in the system that can lead to system voltage instability when the load increases above certain limit.

Consider a simple two bus network without and with DG shown in Figs.1 and.3, with their phasor diagram also presented in Figs.2 and .4.
From Fig.1 we can write,

$$S_L = P_L + jQ_L = V_r I_r^* \quad (5)$$
$$\overline{V_r} = \overline{V_s} - \overline{I_r Z} \quad (6)$$

Where

$$I_r = \frac{P_L - jQ_L}{V_r^*} \quad (7)$$

From figs. 3.3 and 3.5 we can write

$$I_r = \frac{(P_L - P_G) - j(Q_L - Q_G)}{V_r^*} \quad (8)$$

Substitute I_r from Eqn. (4) into Eqn. (2) and separate into real and imaginary parts will give:

$$P_L - P_G = \frac{|V_r||V_s|}{V_r^*}\cos(\theta - \delta_s + \delta_r) - \frac{|V_r|^2}{Z}\cos(\theta) \quad (9)$$

$$Q_L - Q_G = \frac{|V_r||V_s|}{V_r^*}\sin(\theta - \delta_s + \delta_r) - \frac{|V_r|^2}{Z}\sin(\theta) \quad (10)$$

Rearranging Eq. (5) will give:

$$|V_r|^2 = \frac{|V_r||V_s|\cos(\theta-\delta)}{\cos(\theta)} + \frac{Z(P_L - P_G)}{\cos(\theta)} = 0 \quad (11)$$

Where

$$\delta = \delta_s - \delta_r$$

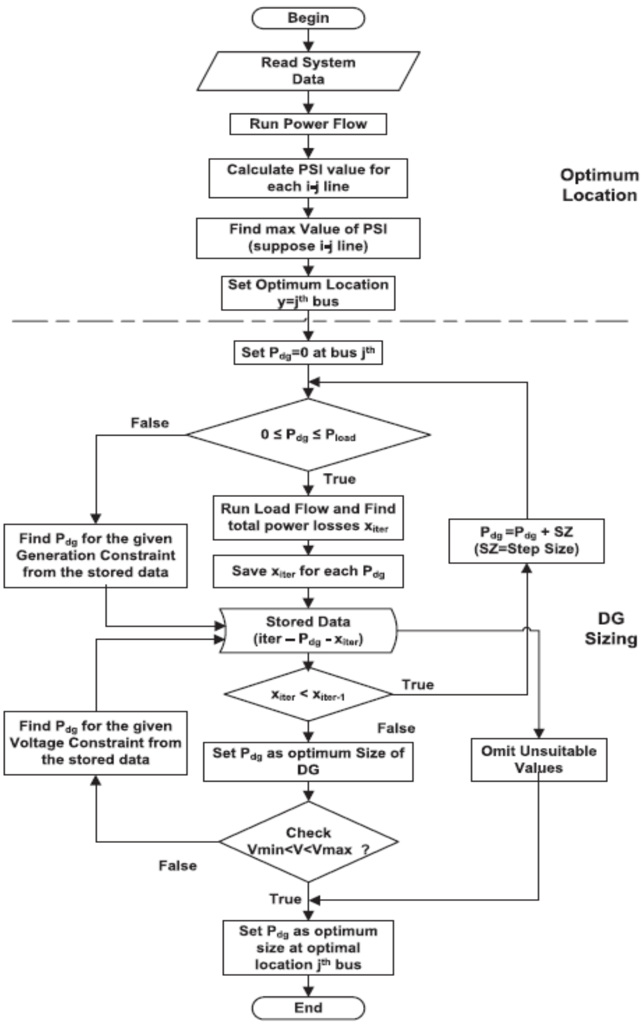
The Eq. (11) is a quadratic equation. For stable bus voltages Eq. (11) should have real roots, i.e. discriminant B2 - 4AC > 0,which results in the proposed index referred as Power Stability Index (PSI) given by Eq. (12):

$$PSI = \frac{4r_{ij}(P_L - P_G)}{[|V_i|\cos(\theta-\delta)]^2} \le 1 \quad (12)$$

Under stable operation, this value should be less than unity closer the value of PSI to zero, more stable will be the system .The above index is used to find the optimum placement of DG. The PSI value is calculated for each line in the given network and sorted from the highest to the lowest value. For the i - j line having the highest value of PSI, the DG should be placed at j-bus. For multi DG placement, the location of the second DG will be based on the effect of first DG on PSI using Eq. (12). PSI value for each line will be re-calculated and sorted in the same fashion from highest to lowest. The DG will be placed at the end of the line having the highest value of PSI.

PROPOSED ALGORITHM FOR DG PLACEMENT AND SIZING

For a radial distribution network, load flow analysis is carried out and PSI value is computed for each line using Eq. (12). For i - j line having the highest value of PSI, the DG will be placed at j^{th} bus. The search algorithm is used for finding the optimum size of DG at optimum location based on a minimum total power loss, with constraints given in eqns. (1-8). The complete flow chart for DG allocation and sizing is represented in Fig.7



5.1 CASE STUDIES AND ANALYSIS

5.1. TEST SYSTEMS

The test system of 12-bus [25] and 69-bus [26] radial distribution test systems are shown in Figs. 5 and 6 respectively. In modified 12-bus system, the active load on each bus is multiplied by 5 for better visualization of results, as the actual value of load is very small. The single line diagrams are given in the fig.8 and fig. 9 respectively for 12-bus and 69-bus of radial distribution system. The line and load data is given in the Tables A1, A2 and B1 for 12-bus, modified 12-bus and 69-bus of radial distribution system respectively. The base MVA is 100 and whereas the base kV is 11 for the 12-bus and modified 12-bus of radial distribution system and 12.66 kV for 69-bus of radial distribution system respectively.

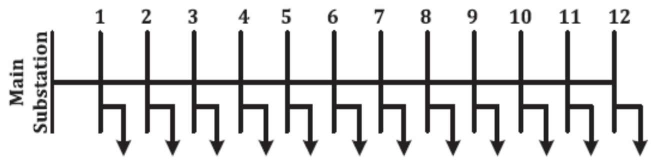


Fig.8 Single line diagram of 12-bus radial network.

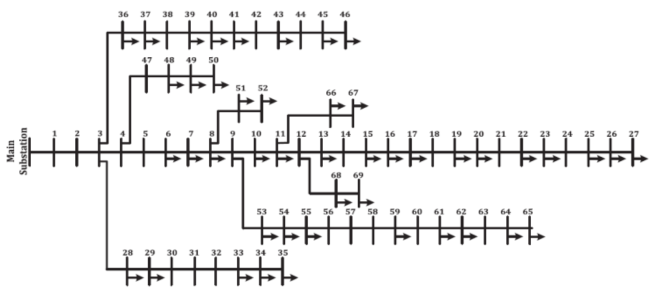


Fig. 9 Single line diagram of 69-bus radial network.

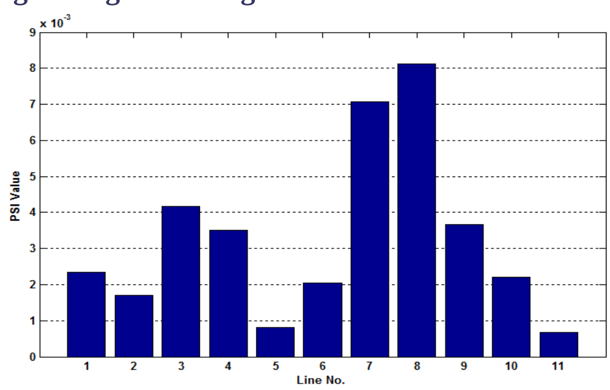


Fig. 10 PSI value for each line for 12-bus Radial Distribution System

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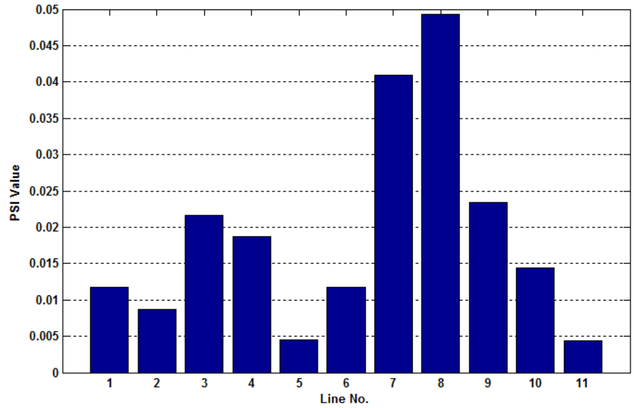

Fig. 11 PSI value for each line for modified 12-bus Radial Distribution System

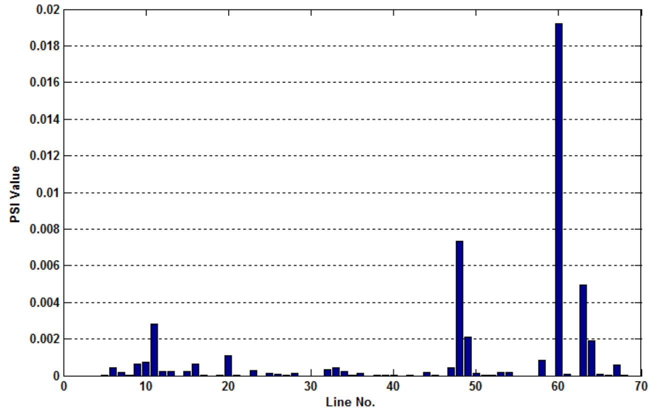

Fig.12 PSI value for each line for 69-bus Radial Distribution System

The PSI value for each line is shown in Fig. 10 for 12-bus radial distribution system. It could be observed that the 8th line connecting bus 8 and bus 9 have the highest value i.e. 0.0081 than the others for 12-bus system. So the installation of DG at bus 9 will be the optimum place. The same approach is carried out for modified 12-bus and 69-bus test system; PSI graph for each system is shown Fig. 11 and 12 respectively.

From Fig. 13 and14, it could be observed that the 8th and 60th line in modified 12-bus and 69-bus radial distribution system has the highest value of PSI i.e. 0.0494 and 0.0192 respectively. Hence, the optimum location of DG is at bus 9 and bus 61 for modified 12-bus and 69-bus distribution systems respectively.

5.1.3 Effect of DG on Voltage Stability

In order to see the effects of DG on voltage stability on any bus ,the load at that bus is increases gradually to find out the maximum load that cause instability.

Table 1 Effect of Load on PSI

S. No.	Load at bus 7 (MW)	Voltage at bus 7	DG at bus 7 in MW	Active power loss in kW	Reactive power loss in kW	PSI
1	0.04	0.8574	0	326.09	122.98	0.0476
2	0.5	0.7996	0	569.52	221.84	0.2514
3	1.0	0.7159	0	1070.6	424.99	0.5854
4	1.1909	0.6682	0	1438.0	572.95	0.6377
5	1.2909	0.6281	0	1798.7	716.81	0.6963
6	1.3206	0.5968	0	2122.7	844.07	0.7434
7	1.33	NC	0	NC	NC	NC
8	1.33	0.7485	0.5	855.05	337.72	0.5552
9	1.33	0.7954	0.8	590.67	230.43	0.2518
10	1.33	0.8469	1.2	138.36	363.97	0.0482

For example, in the modified 12-bus system when there is no DG, bus 7 reaches its maximum value of load at 1.3206 MW, after that voltage collapse could be observed as shown in Table 5.1. The PSI value calculated using Eq. (4.8) is also shown in Table 1.

From Table 5.1, it could be seen that:
(1) More the value of PSI approach to the unity, more the link will be weak and additional load could result in voltage collapse
(2) Adding DG on bus 7th will result in stable voltage operation.
(3) The system capacity has increased, more load could be added.

5.1.4 Effect of DG on Reactive Power

Although DGs are mostly used for active power support, reactive power could also be injected to supply reactive load in the system. To see the effect of reactive power support ($-Q_G$) to the system, the 12-bus system is used. The summary of the test result is shown in Figs. 5.6 and 5.7.

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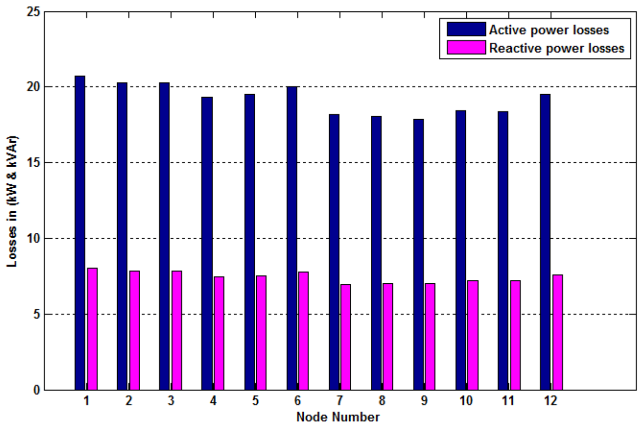

Fig. 13 Effect of Q_G on system losses of 12-bus system.

Fig. 13 shows the results when a reactive power equal to the reactive load on each bus is injected by the DG. It could be seen the active and reactive power losses have reduced as compared to without reactive power support on i^{th} bus.

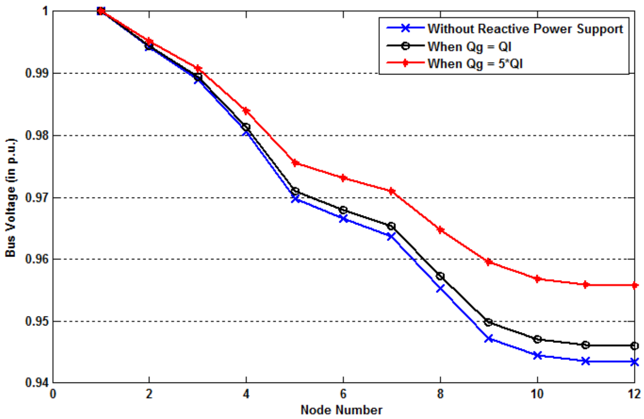

Fig. 14 Effect of Q_G on system voltage profile of 12-bus system.

Fig. 14 shows the effect of reactive power support on system voltage profile. When a reactive power is supplied on bus 9 from the DG, the overall voltage profile has improved.

Similarly the reactive power could also be injected to supply reactive load in the modified 12-bus and 69-bus distribution systems. To see the effect of reactive power support ($-Q_G$) to the system, the modified 12-bus and 69-bus systems are also used.

Figs. 14 and 17 show the results when a reactive power equal to the reactive load on each bus is injected by the DG. It could be seen the active and reactive power losses have reduced as compared to without reactive power support on i^{th} bus for modified 12-bus and 69-bus systems respectively.

Figs. 16 and 18 show the effect of reactive power support on system voltage profile. When a reactive power is supplied on bus 9 for modified 12-bus system and bus 61 for 69-bus system from the DG, the overall voltage profile has improved

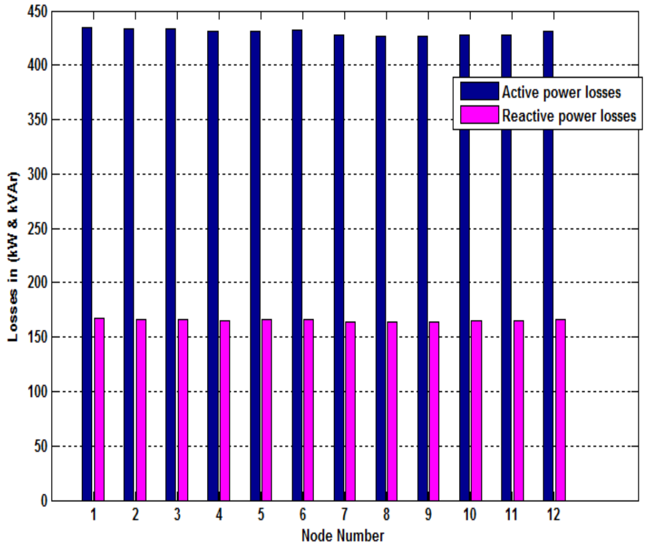

Fig. 15 Effect of Q_G on system losses of modified 12-bus system.

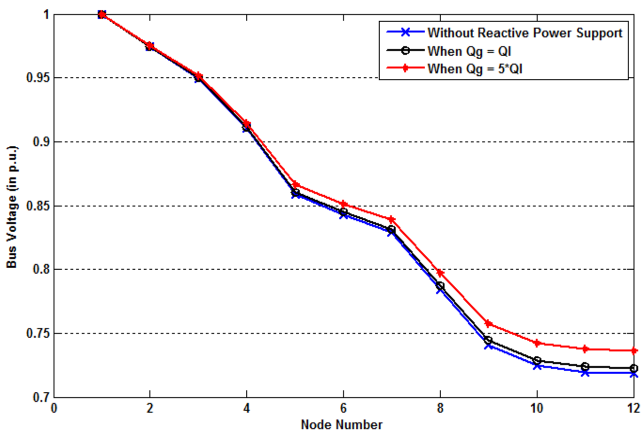

Fig. 16 Effect of QG on system voltage profile of modified 12-bus system.

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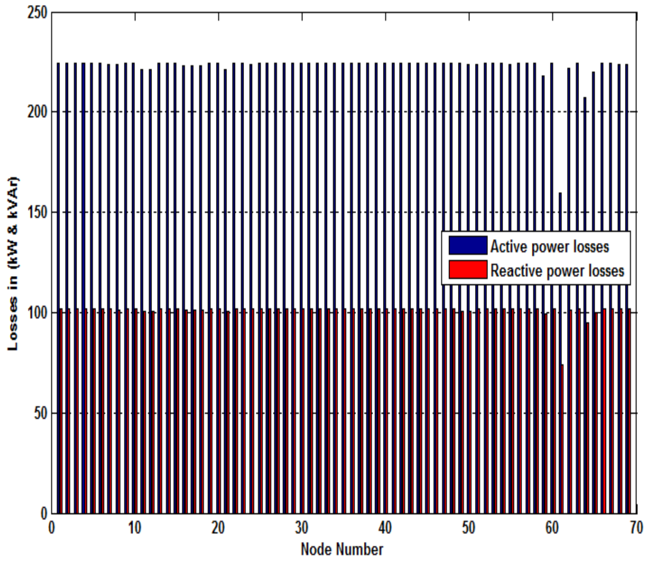

Fig. 17 Effect of Q_G on system losses of 69-bus system

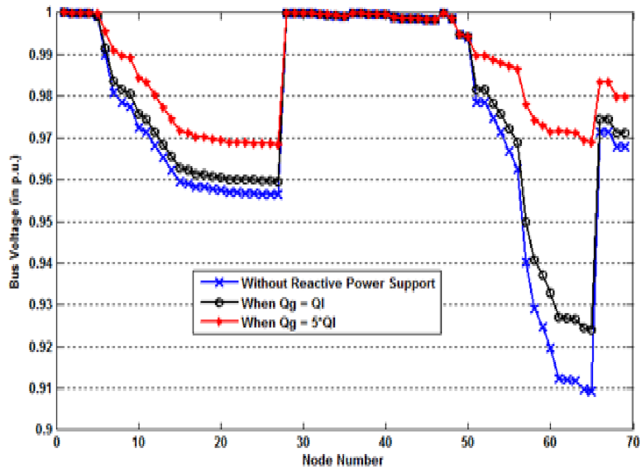

Fig.18 Effect of QG on system voltage profile of 69-bus system.

5.1.5 Optimum DG Size

To determine the optimum size of DG, the proposed algorithmis applied on all test systems and the results are tabulated in Table5.2. The proposed algorithm is also compared with the GSS Algorithm, implemented using VS&OP power tool [27]. The results are shown in Table 2, from where it could be seen the close agreement of the propose method with the existing one. From the Table 3, it is also observed that the base case minimum voltage and losses with respect to proposed algorithm.

Table 2 Application of proposed algorithm on radial distribution networks

Bus System	Proposed Algorithm				Golden Section Search Algorithm		
	Max PSI Value	Bus No	OptimumSize, MW	CPU Time (s)	Bus No	Optimum Size, MW	CPU Time (s)
12-Bus	0.0081	9	0.2349	0.302	9	0.23545	0.892
12-Bus Modified	0.0494	9	1.1963	0.336	9	1.19119	0.897
69-Bus	0.0263	61	1.8959	9.047	61	1.87270	26.681

Table 3 Comparison of base case to proposed algorithm on radial distribution networks

Bus System	Base Case			Proposed Algorithm		
	Minimum Voltage	Active Power Loss, kW	Reactive Power Loss, kVAr	Minimum Voltage	Active Power Loss, kW	Reactive Power Loss, kVAr
12-Bus	0.9434	20.71	10.77	0.9835	8.04	4.12
12-Bus Modified	0.7187	434.07	54.48	0.9573	166.82	19.27
69-Bus	0.9098	317.17	111.60	0.9683	143.49	54.25

From Tables 2 and 3, it could be observed that:

- The proposed method results are in close agreement with GSS algorithm
- The computation time has been decreased considerably for three test systems (53.6%, 52.39%, 58.45% respectively with the 12-bus, modified 12-bus and 69-bus).
- The minimum voltage is improved in all the test cases and also observed the system losses also reduced.

The DG size vs. loss-curves follow a parabolic curve, first decreases and then increases Thus the size of DG should be carefully selected, above optimum size of DG the system losses increases which results in poor efficiency and voltage regulation.

5.1.6 Effect of DG on System Losses and Voltage Profile

In chapter 3, it has seen the impact of DG on system losses based on analytical analysis. To verify the derived analytical equations, the effect of DG on

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modified 12-bus system studied by injecting optimum active power of 0.2349 MW on each bus. The total active and reactive losses occurring due to different DG location is shown in Fig. 19. It can be observed that the most suitable location of DG in terms of losses is at bus 9, which is in agreement with the result in Fig.19.

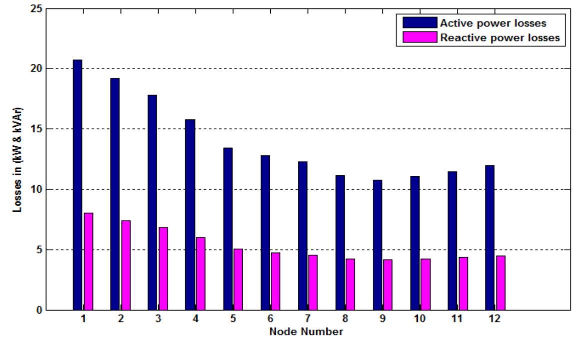

Fig. 19 System losses profile of 12-bus with optimum DG size = 0.2349 MW

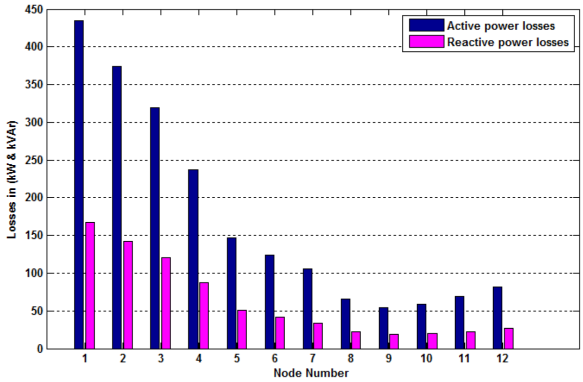

Fig.20 System losses profile of modified 12-bus with optimum DG size = 1.1962 MW

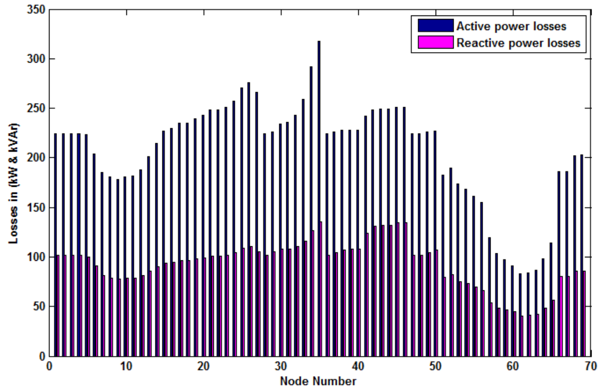

Fig.21 System losses profile of 69-bus with optimum DG size = 1.8580 MW

The effect of DG on modified 12-bus and 69-bus systems studied by injecting optimum active power of MW on each bus. The total active and reactive losses occurring due to different DG location is shown in Figs. 20 and 21 for modified 12-bus and 69-bus systems respectively. It can be observed that the most suitable location of DG in terms of losses is at bus 9 and bus 61 for modified 12-bus and 69-bus systems respectively, which is in agreement with the result in Figs.20 and 21.

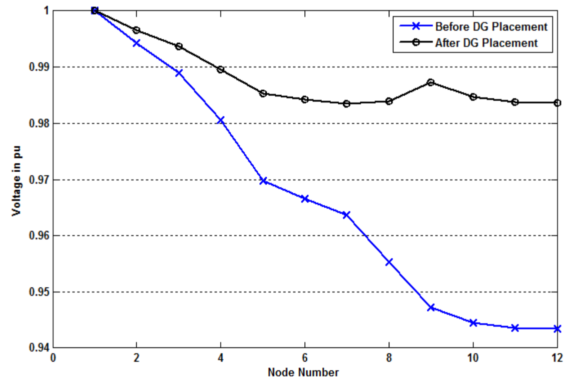

Fig. 22 Effect of DG on system voltage profile of 12-bus system (DG size = 0.2349 MW @ bus 9th)

In chapter 3, it has also been shown that the reduction in active and reactive losses improve the voltage profile. From Figs. 22,23 and 24, this could be visualized whereby the optimum placement of DG at 9th bus, 9th bus and 61st have improved the overall voltage profile for 12-bus, modified 12-bus and 69-bus radial distribution system.

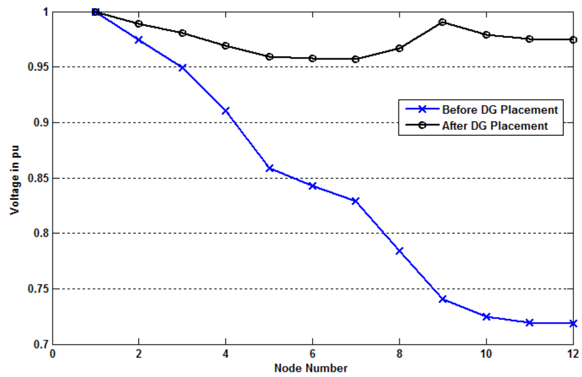

Fig. 23 Effect of DG on system voltage profile of modified 12-bus system (DG size = 1.1962 MW @ bus 9th)

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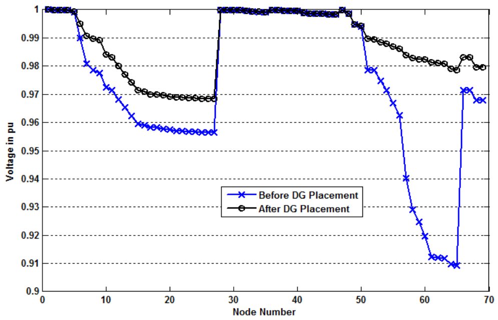

Fig. 24 Effect of DG on system voltage profile of 69-bus system (DG size = 1.8580 MW @ bus 61st)

5.1.7 Overall Findings

From the analysis of the simulation results presented in Section 4,we can conclude the following due to DG placement.

1. The voltage profile has improved and the system voltage stability has increased.
2. Line losses have reduced.
3. The overall system capacity has increased.

The third statement is better presented in Figs. 25, 26 and 27 by connecting the most optimum DG size found out in Table 5.2 to the most optimum location of each system and the nose curve (PV curve) is plotted for 12-bus, modified 12-bus and 69-bus systems respectively. The loading has been done at the 7th bus, 7th bus and 54th bus for 12-bus, modified 12-bus and 69-bus systems respectively. Figs. 25, 26 and 27 demonstrate that the system capacity has increased due to the installation of DG at the best location and of optimum size.

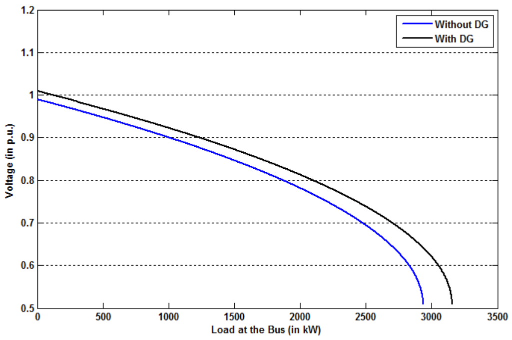

Fig. 25 PV characteristic curve with and without DG for 12-bus system (DG size = 0.2349 MW @ bus 9th)

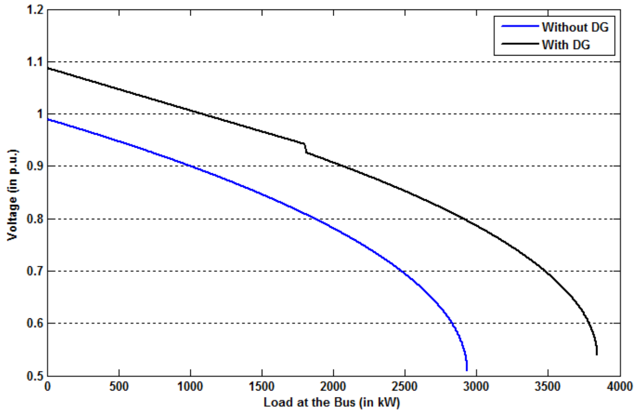

Fig. 26 PV characteristic curve with and without DG for modified 12-bus system (DG size = 1.1962 MW @ bus 9th)

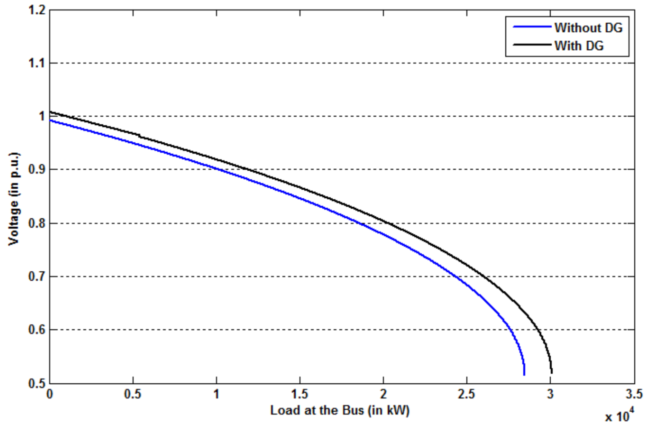

Fig. 27 PV characteristic curve with and without DG for 69-bus system (DG size = 1.8580 MW @ bus 61st)

CONCLUSION

In this chapter, an existing simple and efficient load-flow technique has been presented for solving radial distribution networks. It has been found from the cases with which the method was tested that the method has good and fast convergence characteristics.

In this chapter, a new analytical approach is also presented on the impact of DG in power system. A new algorithm is also proposed for DG location and sizing. The DG allocation and sizing is based on a novel Power Stability Index (PSI) index to determine the most voltage sensitive bus and minimum total power losses. Using the proposed algorithm optimum

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DG allocation and correct sizing results in an improved voltage profile and minimizes the burden of system losses.

The proposed algorithm has also been tested using three different radial distribution test systems and the results are verified using GSS Algorithm. It has been found that overall the proposed algorithm takes less computation time by 50–60% as compared to Golden Section Search (GSS) algorithm.

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