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Impact of Distributed Generation Penetration in Voltage Stability of Radial Distribution System

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Abstract

This paper depicts the effect of distributed generation (DG) location on power system voltage stability, voltage profile and power losses. Different categories of DG types are used to check the effects on power system voltage stability, voltage profile and power losses. The most suitable locations to connect DG sources are identified by a modal analysis. A modal analysis is used to verify both proximity and mechanism of voltage instability. Here, reduced power flow Jacobian is used of full Jacobian to account for dependence of voltage stability on reactive power flow. The weak buses are identified using bus participation factors. Then, DGs are injected at these buses in order to evaluate voltage stability, voltage profile and power losses for different scenarios. For these scenario optimal sizing of the DG units in distribution system given their location is determined by Genetic Algorithm. The analysis is conducted on a well-known IEEE 33 bus radial distribution network. The results show the impact of DG injection in radial distribution system on voltage stability, voltage index and power losses.

Keywords

Modal analysis, voltage stability, eigenvalue, participation factors, genetic algorithm

1. Introduction

In recent years, the use of distributed generation (DG) technologies has remarkably increased worldwide due to their potential benefits. DG units generate power near load centres, avoiding the cost of transporting electric power through transmission lines. Another benefit of DG is cost savings in electricity production compared with large centralized generation stations [1]. Furthermore, renewable DG technologies, such as wind power, photovoltaic (PV), and solar thermal systems, are considered to be one of the fundamental strategies in the fight against climate change, as they can reduce dependence on fossil fuels [2, 3].

With the rapid increase of DG penetration, distribution systems are being converted from passive to active networks. Normally, DG units are small in size and modular in structure. Therefore, their impacts on distribution system operation, control, and stability vary depending on their locations and sizes [4]. Considering that most DGs are located at the distribution level, determination of the best locations for installing DGs to maximize their benefits is very important in system design and expansion.

The problem of voltage stability in a radial distribution networks due to addition of DG units and its analysis from this point of view are rather new concepts with few reported works. A new voltage-stability index is introduced by simplified load-flow equations to recognize the most sensitive buses to voltage collapse in radial networks [5]. However, no DGs are modelled. An equivalent two-bus system of a distribution network is used for the analysis of voltage stability [6]. Linkwise, the reconfiguration of radial distribution networks for voltage-stability enhancement is introduced with no DG penetration [7]. Bus indices for considering the effect of aggregated DGs into the voltage security of a transmission grid are developed by neglecting the behaviour of radial distribution networks [8].

A new method for DG placement in radial distribution networks is introduced which uses continuous power flow to identify the most sensitive bus to voltage collapse. Also, the effects of DG placement on the bus on voltage security margin (VSM) enhancement and loss reduction is analyzed [9]. But these method does not always result in the best choices. It is better if the DG units are installed at suitable locations with suitable size to improve voltage profile, reduced system losses and stability enhanced. In distribution systems, if DGs are placed strategically there may be significant improvement in voltage stability issues and system losses [10]. Unfortunately, the electric utility doesn't have absolute control over installation places neither the sizes of DG since they are usually consumer's property. Inspite of these challenges it is of great interest for the utility to have a methdology for suitable location and size of DGs for overall improvement of voltage profile, system stability along with improvement in losses.

In this paper, a DG placement problem is solved by using modal analysis and sizing of DG to be injected at those locations is optimized by Genetic Algorithm (GA), whose objective function is to minimize active power losses. The next section briefly reviews the methodologies used for impact of DG penetration on voltage-stability problem. Section 3 presents the results and discussions. Finally section 4 concludes this paper.

2. Methodology

2.1 Power Flow Problem

The power-flow analysis of a distribution feeder is similar to that of an interconnected transmission system. The distribution networks are termed as ill conditioned due to following reasons as follows :

- Radial or weakly meshed networks.
- High R/X ratios.
- Multi- phase, unbalanced operation.
- Unbalanced distributed load and/or distributed generation.

Due to the above factors the Newton Raphson (N-R), Gauss Seidel (G-S) and other transmission system algorithms fails to converge the load flow of distribution network. Because a distribution feeder is radial, iterative techniques used in transmission network power-flow studies are not used here. Instead, an iterative technique specifically designed for a radial system is used. The sweeping algorithm is iterative technique and has the advantages of less computation effort and less calculation time compared to the N – R and G – S methods. The sweeping algorithm is used for load flow is as shown below:

Consider a branch that is connected between nodes 1 and 2, having a resistance $R_1$and inductive reactance X_1. From Figure 1, current flowing through the branch is given by,

$$I_1 = \frac{V_1\angle\delta_1 - V_2\angle\delta_2}{R_1 + jX_1} \tag{1}$$

$$= \frac{P_2 - jQ_2}{V_2\angle-\delta_2} \tag{2}$$

where, $V_1\angle\delta_1$ & $V_2\angle\delta_2$ are the voltage magnitudes and corresponding phase angles at sending end node 1 and receiving end node 2 respectively.
P_2 = Sum of the real power loads of all the nodes beyond node 2 plus the real load at node 2 itself plus the sum of real power losses of all branches beyond node 2.
Q_2 =Sum of the reactive power loads of all the nodes beyond node 2 plus the reactive load at node 2 itself plus the sum of reactive power losses of all branches beyond node2.

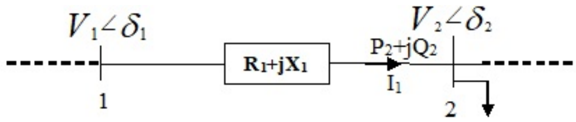

Figure 1: Electrical equivalent of a typical branch connected between two nodes

From equations (1) and (2)

$$\frac{V_1\angle\delta_1 - V_2\angle\delta_2}{R_1 + jX_1} = \frac{P_2 - jQ_2}{V_2\angle-\delta_2} \tag{3}$$

$$|V_1||V_2|[cos(\delta_1-\delta_2) + jsin(\delta_1-\delta_2)] - |V_2|^2 = (P_2 - jQ_2)(R_1 + jX_1) \tag{4}$$

Separating, the real and imaginary parts from above equation, the real part is

$$|V_1||V_2|cos(\delta_1-\delta_2) = |V_2|^2 + P_2R_1 + Q_2X_1 \tag{5}$$

The imaginary part is,

$$|V_1||V_2|sin(\delta_1-\delta_2) = P_2X_1 - Q_2R_1 \tag{6}$$

Squaring and adding equations (5) and (6)

$$|V_2|^4 + 2|V_2|^2(P_2R_1 + Q_2X_1 - 0.5|V_1|^2) + (R_1^2 + X_1^2)(P_2^2 + Q_2^2) = 0 \tag{7}$$

Equation (7) has a straight forward solution and do not depend on the phase angle.
Therefore from equation (7)

$$|V_2|^2 = [(P_2R_1 + Q_2X_1 - 0.5|V_1|^2)^2 - (R_1^2 + X_1^2)(P_2^2 + Q_2^2)]^{1/2} - (P_2R_1 + Q_2X_1 - 0.5|V_1|^2)$$

In general, V_{i+1} can be written as shown in (8)

$$|V_{i+1}|^2 = [(P_{i+1}R_j + Q_{i+1}X_j - 0.5|V_i|^2)^2 - (R_j^2 + X_j^2)(P_{i+1}^2 + Q_{i+1}^2)]^{1/2} - (P_{i+1}R_j + Q_{i+1}X_j - 0.5|V_1|^2)^2 \quad (8)$$

where ,
Node no., i =1,2....n ; Branch no., j = 1,2 ...n-1
n = total number of nodes The active and reactive power losses in branch j are given by

$$P_{loss,j} = R_j \frac{P_{i+1}^2 + Q_{i+1}^2}{|V_{i+1}|^2} \quad (9)$$

$$Q_{loss,j} = X_j \frac{P_{i+1}^2 + Q_{i+1}^2}{|V_{i+1}|^2} \quad (10)$$

The total active and reactive power of the system is

$$TPL = \sum_{i=1}^{n-1} P_{loss,j} \quad (11)$$

$$TQL = \sum_{i=1}^{n-1} Q_{loss,j} \quad (12)$$

Following the above steps, we perform load flow and find the voltage, angle, active and reactive power losses of the distribution system.

2.2 Modal Analysis

The Modal analysis mainly depends on power flow Jacobian matrix of equation 13. Gao and P. Kundur proposed a modal analysis approach to evaluate voltage stability for large power systems in 1992 [11]. Modal analysis is used to compute the smallest eigenvalues and eigenvectors associated it with obtained from the load flow solution. Each eigenvalue represents a mode of V-Q variation. The magnitude of the eigenvalue can be considered as a quantitative measurement of the static voltage stability margin.

The eigen vectors are used to calculate the bus participation factor which indicates the weak areas of the system. The analysis is expressed as follows:

$$\begin{bmatrix} \triangle P \\ \triangle Q \end{bmatrix} = J \begin{bmatrix} \triangle \delta \\ \triangle V \end{bmatrix} \quad (13)$$

Equation 13 can be rewritten as:

$$\begin{bmatrix} \triangle P \\ \triangle Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \triangle \delta \\ \triangle V \end{bmatrix} \quad (14)$$

Let $\triangle P = 0$ in equation 14

$$\begin{bmatrix} 0 \\ \triangle Q \end{bmatrix} = \begin{bmatrix} J_{P\delta} & J_{PV} \\ J_{Q\delta} & J_{QV} \end{bmatrix} \begin{bmatrix} \triangle \delta \\ \triangle V \end{bmatrix}$$

The above equation can be separated as:

$$0 = J_{P\delta} \triangle \delta + J_{PV} \triangle V \quad (15)$$

$$\triangle Q = J_{Q\delta} \triangle \delta + J_{QV} \triangle V \quad (16)$$

Solving equation 15 and 16 we get,

$$\triangle Q = (J_{QV} - J_{Q\delta} J_{P\delta}^{-1} J_{PV}) \triangle V \quad (17)$$

The reduced Jacobian matrix J_R can be defined as:

$$J_R = J_{QV} - J_{Q\delta} J_{P\delta}^{-1} J_{PV}$$

Equation 17 becomes:

$$\triangle Q = J_R \triangle V \quad (18)$$

$$\triangle V = J_R^{-1} \triangle Q \quad (19)$$

The diagonal element of J_R^{-1} is the sensitivity factor at each bus which is also the slope of the Q-V curve. A stable operating point requires all sensitivity factors to be positive. A smaller sensitivity factor magnitude indicates a more stable operating point. The system is unstable if at least one sensitivity factor is negative. The decomposition of J_R and J_R^{-1} are:

$$J_R^{-1} = \xi \lambda^{-1} \eta$$

Where,
ξ is the right eigenvector matrix of the reduced Jacobian matrix
λ is the diagonal eigenvalue matrix of the reduced Jacobian matrix
η is the left eigenvector matrix of the reduced Jacobian matrix
Equation 19 can be written as:

$$\triangle V = \xi \lambda^{-1} \eta \triangle Q \quad (20)$$

Or,

$$\triangle V = \sum_i \frac{\xi_i \eta_i}{\lambda_i} \triangle Q \quad (21)$$

where
ξ_i is the ith column of ξ
λ_i is the ith eigenvalue λ
η_i is the ith row of η
Equation 20 describes the Q-V response of each mode. The sign and magnitude of λ_i provide a qualitative measure of system stability. A positive λ_i indicates that the incremental change in voltage magnitude of bus i is along the direction of the incremental change in reactive power injection at bus i.
Hence, the system is at a stable operating condition if

λ_i is positive. A negative λ_i indicates that the incremental change in voltage magnitude of bus i is along the opposite direction of the incremental change in reactive power injection at bus i. Hence, the system is at an unstable operating condition if λ_i is negative. The incremental change in voltage magnitude is inversely proportional to the magnitude of the λ_i times the incremental change in reactive power injection. A smaller positive λ_i indicates that a small amount of reactive power injection change could result in a dramatically large change in voltage magnitude. Therefore, the larger the λ_i, the more stable the system. A value of λ_i=0 indicates a voltage collapse since any variation in reactive power injection gives infinite change in voltage magnitude.

In equation 21, if the $\triangle$Q is assumed to have only one non-zero element which is the k^{th} element and the value of this non-zero element is unity, then it becomes:

$$\triangle V = \sum_i \frac{\xi_i \eta_i}{\lambda_i}$$

The V-Q sensitivity analysis at bus k gives:

$$\frac{\partial V_k}{\partial Q_k} = \sum_i \frac{\xi_i \eta_i}{\lambda_i}$$

Compared to the V-Q sensitivity analysis, modal analysis is able to capture the voltage magnitude change at all buses due to a reactive power injection change at bus k.
In mode i, the participation of bus k is defined by Bus Participation Factor:

$$P_{ki} = \xi_{ki} \tau_{ki} \tag{22}$$

where,
ξ_{ki} is the kth element of ξ_i
η_{ki} is the kth element of η_i
Recall from equation 22, that $\eta_{ki}\xi_{ki}$ describe the contribution of λ_i to a Q-V response at bus k in mode i. The buses with relatively large bus participation factors for the smallest eigenvalue (mode) determine the weak areas. Reactive power compensation can be applied at buses that have large bus participation factors. Bus participation factors can show the type of the mode. There are two types of modes in general, local modes and non-localized modes. A local mode has few buses with large participation factors and other bus participation factors close to zero. A non-localized mode has many buses that have large bus participation factors and other bus participation factors close to zero.

Calculating only the minimum eigenvalue of J_R is not sufficient because there is usually more than one weak mode associated with different part of the system. Thus, it is seldom necessary to compute more than 5 to 10 of the smallest eigenvalues to identify all critical modes. In this work 5 of the smallest eigenvalues is considered for analysis.

2.3 GA Method

The GA is a method for solving both constrained and unconstrained optimization problems that are based on natural selection, the process that derives biological evolution. The GA repeatedly modifies a population of individual solutions. At each step, the GA selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population “evolves” toward an optimal solution [12].

The GA uses two main types of rules at each step to create the next generation from the current population:

- Selection rules select the individuals, called parents that contribute to the population at the next generation.
- Reproduction is the step used to generate a second generation population of solutions from those selected through genetic operators: crossover (also called recombination), and/or mutation: a- Crossover rules combine two parents to form children for the next generation, b- Mutation rules apply random changes to individual parents to form children. For detailed description of GA refer to reference [12].

The optimum sizing of DG units has been obtained by the GA module which uses the “Global Optimization Toolbox” Ver. 8.1 of MATLAB© R2018a. The input to the GA module is the locations of the DG units obtained from Modal Analysis. The outputs of GA module is the apparent power of each DG unit at each location determined and the optimized real power losses of the system. The fitness function to be minimized is the real power losses as follows:

$$P_{loss} = \sum_{i=1}^{k} P_{loss(i,i+1)}$$

where,
i = number of branch

The main constraint of the optimization problem is the summation of the ratings of DG units which is defined as the "Penetration Level" which can vary from 0 to full rated capacity of the system.

2.4 DG Technologies

Based on capability of injecting real and/or reactive power in the system DG technologies are classified as follows:

- Type 1: Generates both active power (P) and reactive power (Q)
  DG units based on synchronous machine for small hydro, geothermal, and combined cycles fall in this category. The synchronous generators as an DG can either be modelled as constant terminal voltage control (voltage control mode) or with constant power factor control (power factor control). The DGs with the voltage control mode are considered as PV nodes and DGs with the power factor control mode are considered as PQ nodes [13]. In this work, the DG with the power factor control mode at power factor 0.8 is modeled as PQ nodes.

- Type 2: Generates active power (P) only
  Photovoltaic (PV), micro turbines, fuel cells, which are connected to the main grid with the help of power electronic devices [14, 15] fall in this category. In this work, it is assumed that DG units in this category neither absorb nor deliver reactive power to system and operate with unity power factor only.

- Type 3: Generates reactive power (Q) only
  The DG units equipped with synchronous compensator are considered as Type 3 category.

- Type 4: Generates active power (P), but absorbs reactive power (Q)
  Wind farms with wind turbines of the type squirrel cage (SCIG-Squirrel Cage Induction Generator) falls under this category. These are capable of injecting real power in the system whereas it demands reactive power from the system.

Thus, it can be noted that adoptation of different type of DG technologies can have significant bearing on the performance of distribution network. The installation of DG units based on synchronous machine that are close to the loads can lead to beneficial impact on system voltage stability whereas in the case with an induction generator type DG there might negative impact on the system stability. Therefore, it is an very important to analyze the effect of different types of DG technologies on the voltage stability to enjoy the system wide benefits. In this paper Type 1, Type2 and Type 3 DGs are used for analysis purpose.

2.5 Evaluation Indices

Some indices are used as shown in Table 1 to clarify the effect of DG units on the performance of power systems. The penetration level of DG units is defined by PL, where S_{DG} and S_{Load} are the apparent power of DG/DGs and the total apparent load of the network, respectively. ALR and RLR show active and reactive loss reduction after installing DG/DGs, where 0 indicates base case and 1 indicates after DGs installation [16]. Higher the ALR and RLR better the performance of DGs in loss reduction.

To determine the deviation from bus voltage targets, VI index is used, where $V_{i,0}$ is the desired voltage at bus (usually 1 p.u.) and $V_{i,1}$ is the bus voltage when DG is presented in the network, both in per unit. Lower the VI, better the performance of DG units.

Table 1: Evaluation Indices

Index	Formula
DG Penetration Level	$PL = \frac{S_{DG}}{S_{Load}} \times 100\%$
Active Loss Reduction	$ALR = \frac{Re\{losses_0\} - Re\{losses_1\}}{Re\{losses_0\}} \times 100\%$
Reactive Loss reduction	$ALR = \frac{Im\{losses_0\} - Im\{losses_1\}}{Im\{losses_0\}} \times 100\%$
Voltage Index	$VI = \sum_{i=1}^{n} (V_{i,0} - V_{i,1})^2$

3. Result and Discussion

3.1 Study System

The above methodology has been successfully applied to IEEE 33 bus power system, which is shown in Figure 2, is a 33 bus, 12.66 kV radial distribution system. The RDS configuration of IEEE 33 bus system presented in Figure 2 has branches sub-divided from bus 2, bus 3, and bus 6. The bus 2 has branch that includes four buses 19, 20 21, and 22, bus 3 has branch that includes three buses 23, 24, and

25, and bus 6 has branch which includes eight buses from bus 26 to bus 33 as shown in Figure 2. The total load of the system is 3715 kW and 2300 kVAr with maximum active load of 420 kW at bus 24 and bus 25 and maximum reactive load of 600 kVAr at bus 30, and minimum active load of 45 kW at bus 11 and minimum reactive load of 10 kVAr at bus 15.

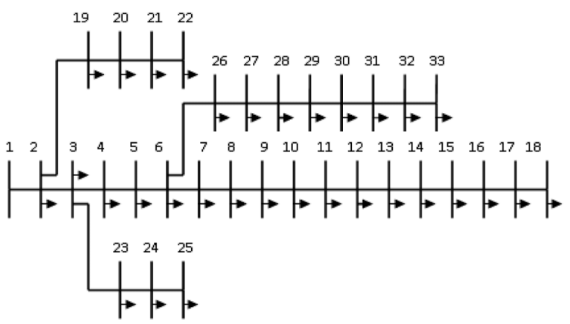

Figure 2: IEEE 33 Test bus System

3.2 Base Case without DG

The base case voltage profile of the test system obtained performing load flow simulation is as shown in Figure 3. The maximum value of bus voltage calculated is 1 pu i.e., refrence bus and lowest bus voltage calculated is 0.92 pu of bus 18 which is located at the farthest end of the RDS. It can be seen that voltage is in decreasing order from bus 1 to bus 18 and again voltage decreases gradually from bus 19 to bus 33 due to radial nature of RDS.

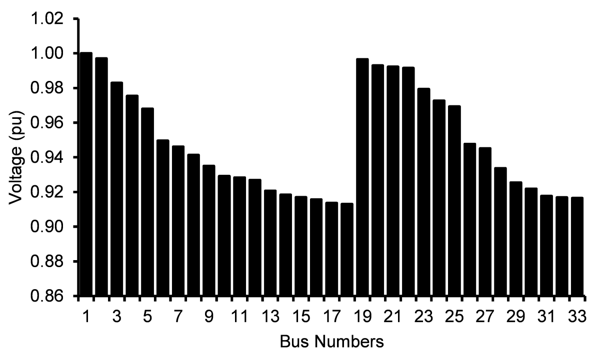

Figure 3: Voltage Profile of IEEE 33 bus for Base Case Load Flow

Also, it can be seen that almost half the number of buses of the system does not satisfy the voltage regulation limit. The total active and reactive power losses after performing the load flow of the RDS is 202.71 kW and 135.17 kVAr respectively.
The lowest voltage compared to the other buses can be noticed in bus number 18. Since there are 33 buses among which there is one swing bus, then the total number of eigenvalues of the reduced Jacobian matrix is expected to be 32 as shown in Table 2.

Table 2: Modes for the base case with eigen values

Mode No.	Eigen Values λ	Mode No.	Eigen Values λ
1	54.2475	17	4.9845
2	54.9571	18	4.7269
3	39.8688	19	4.5466
4	28.2655	20	3.7509
5	16.8542	21	0.0252
6	16.1831	22	0.0741
7	15.6952	23	0.2387
8	14.0323	24	0.2748
9	13.6352	25	0.4367
10	10.8122	26	0.5711
11	9.4184	27	0.8044
12	9.0829	28	1.1714
13	7.9374	29	1.91
14	7.5377	30	2.6202
15	5.8366	31	2.4373
16	5.1774	32	2.5133

Note that all the eigenvalues are positive, which means that the system is voltage stable.

From Table 2, it can be noticed that the minimum eigenvalue, λ = 0.0252, is the most critical mode. The participation factor for this critical mode has been calculated and the result is shown in Figure 4.

The result shows that, the bus 18 has the highest participation factor for the critical mode indicating highest contribution of this bus to the voltage collapse.

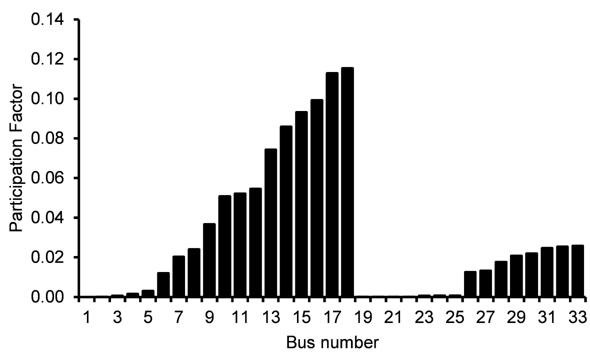

Figure 4: Participation factor of all buses for most critical mode

Similarly, as discussed in Section 2, five smallest eigen values is considered for calculation of bus participation factor. The most participated bus of those modes are identified as Bus 18, Bus 33, Bus 18, Bus 22 and Bus 25 respectively as shown in Table 3.

Table 3: Most participated bus for least mode

Mode	Base Case	Eigen Value	M.P. Bus
21	λ_1	0.0252	18
22	λ_2	0.0741	33
23	λ_3	0.2387	18
24	λ_4	0.2748	22
25	λ_5	0.4367	25

It can be observed that some buses repeatedly contribute to critical modes which represent the non localized behavior of the modes and determine the weak region in the system. Note that bus 18 is the critical bus for two modes. Hence, buses 18, 33, 22, and 25 are the DG placement candidates.

3.3 Determination of type of DG units

The characteristic of three types of DG units for voltage stability enhancement has been discussed in Section 2. Type 1 and Type 3 DG units comprised of synchronous generators and synchronous compensators are modeled to deliver reactive power in normal and emergency condition. Type 1 and Type 2 will operate in constant power factor mode. Type 2 DG unit comprise of solar PV which will neither supply nor absorb any reactive power. Also, DG penetration level is not set in this paper. It is optimized by GA with objective function to minimize active power loss.

To determine the best types of DG for voltage stability enhancement, any one type of DG unit is placed at the candidate buses determined by Modal analysis with DG penetration level of Type 1, Type 2 & Type 3 DGs optimized by GA as 73.70%, 62.60% and 40.19% alternately and its influence on the variation of critical modes have been analyzed. Figure 5 shows the change in eigen value of critical mode obtained for both the systems without and with the placement of different types of DG units on the candidate buses. The results clearly show that the placement of any type of DG unit on all the four candidate buses at a time significantly increases the magnitude of the eigen values of most critical modes towards positive infinity and hence away from instability boundary.

From Figure 5, it is noticed that magnitude of eigen value of the most critical mode has been enhanced greatly with the placement of synchronous generator on those candidate buses. It means that placement of synchronous generator as DG units at those candidate buses can carry more loads before becoming voltage unstable. The capability of Type 1 DGs of delivering both active and reactive power makes it more promising for enhancing the voltage stability. On the other hand from Figure 5, it can be noticed that between Type 2 and Type 3 DGs, Type 2 gives intermediate results than those DG technologies that inject reactive power. This is because of inability of Type 2 DGs to compensate for reactive power locally.

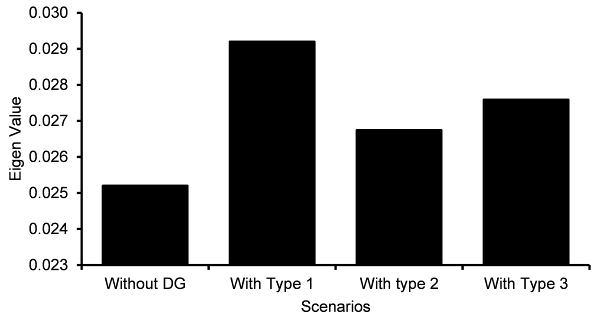

Figure 5: Change in eigen value of critical mode for different scenarios

Figure 6 shows the comparative bus voltage profile for different scenarios. The placement of Type 1 DGs at candidate buses can significantly improve bus voltage profile than that of base cases and other two scenarios. This is generally due to the fact that DGs of Type 1 are capable of injecting both real and reactive power locally so that real power, as well as a reactive power, which is flowing through the line, is decreased which decreases the corresponding current and which basically decrease corresponding losses in the line as seen in Table 4. So, the line losses will also get reduced if the current which is flowing through the feeder is decreasing. Since the current is decreasing, a voltage drop across the system also decreases. Hence the improvement in voltage profile.

The performances of Type 2 DGs and synchronous compensators, the two different scenarios have caused more variations in bus voltages and losses as compared to synchronous generator. Between these scenarios, scenario with Type 2 DGs has good results than Type 3 DGs as seen in Table 4 and Figure 5. This is because our study system has more active load than reactive load so that Type 2 DGs provide more active power locally which has majority in the system. Thus,

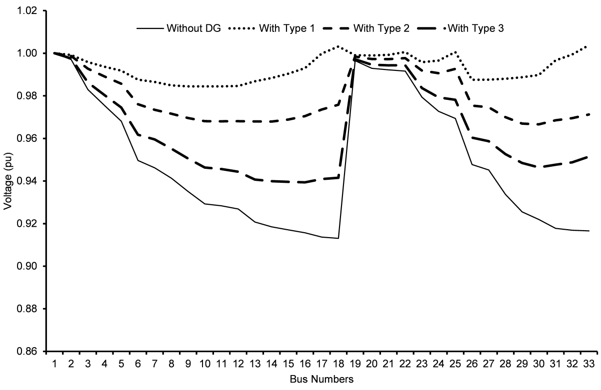

Figure 6: Bus Voltage profiles for Different Scenarios

as seen in Table 4 for scenarios amongst Type 2 & Type 3, Type 2 gives better result in loss reduction as well as voltage deviations. Hence, the placement of Type 1 DGs with 73.30% of DG penetration depicts the best performance for improvement of different performance indices against other DG technologies used for study in this paper.

Table 4: Different performance indices

Scenarios	Active Power Loss (kW)	Reactive Power Loss (kVAr)	% ALR	%RLR	DG Penetration Level	VI
Base Case without DG	202.71	135.17				0.117
With Type 1	28.44	26.33	85.97%	80.52%	73.70%	0.003
With Type 2	81.03	58.71	60.02%	56.57%	62.60%	0.019
With Type 3	141.30	97.39	30.29%	27.95%	40.19%	0.059

From the results obtained in this paper, it is observed that with the injection of DGs at critical buses, magnitude of eigen value of most critical mode for dispatchable sources like Type 1 DGs and Type 3 DGs has better results than non dispatchable sources like Type 2 DGs. Also, from the results of Figure 5 and Table 4, voltage profile and performance indices has improved significantly after injection of Type 1 DGs into the system, then follows the Type 2 DGs and Type 3 DGs respectively as our test system has more active loads than reactive loads. Hence, injecting Type 1 DGs at critical buses has significant performance both in terms of voltage stability enhancement and performance indices presented in Table 4. If constraints like over current protection, protection coordination, design of fuses, harmonics, feeder protection, DG penetration level etc were to be incorporated for this work in this paper, then results might have been different. These constraint can be incorporated in the future studies regarding impact on voltage stability due to injection of distributed generation in distribution system.

4. Conclusion

In this paper, methodology has been proposed to find the locations for DG placement and different type of DG unit which can enhance voltage stability, voltage profile as well as other performance indices. Modal analysis is used to determine candidate buses for DG injection and DG size given their location is optimized using GA whose objective function is to minimize real power loss. The study is executed on the well-known IEEE 33-bus radial distribution network, and the result shows that voltage stability, voltage profile and other performance indices enhanced significantly by injecting synchronous generator (i.e., Type 1 DGs) at candidate buses with optimized DG size than other two types of DG technologies like solar PV, Synchronous Compensator which is used in this paper for study.

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