Study of Distributed Generations in Voltage Sag Mitigation Using Unbalanced Load Flow

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In this paper, a new three-phase unbalanced distribution load flow (DLF) technique is proposed to study the impact of distributed generations (DGs) installed with the distribution networks in mitigating the voltage sag. For analysis purpose, DGs are modeled as variable reactive power and constant power factor source with both wind and solar powered DGs in the case study. The proposed technique is based on the application of classical set theory, where different impedance matrices were formed for the test case with the help of set theory. It enables the method to be more flexible and robust for handling in any situation. Within the defined PSIM matrix, DG modeling is incorporated for the impact study of DGs. Effect of DGs in mitigating voltage sag is mathematically explained with the help of phase diagram. The proposed technique is tested on the standard IEEE 13 bus radial distribution networks with programming done on the MATLAB platform. Different other test networks can be used for analytical purpose. To justify the claims, different cases are studied, such as load increment, an increase in the maximum power limit of DGs. Also, a comparison is drawn between the proposed DLF technique and the traditional backward forward sweep method, where the efficacy of the proposed technique is proved over the traditional method. In overall analysis of the proposed method, it shows better results compared to the traditional backward forward sweep method in terms of execution time and number of iterations.

Keywords: Distribution load flow (DLF), Distributed generations (DGs), Voltage sag, Radial distribution network.

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1. INTRODUCTION

Distribution load flow (DLF) is key mathematical method for analyzing the steady-state response of a power distribution system. Distribution automation needs fast and efficient power flow method for planning and operating condition. Distribution feeders are characterized by unbalanced loading for asymmetrical spacing of conductors and single-phase loads. Conventional DLFs cannot be applicable for distribution systems due to these factors. Number of research articles on optimal DG allocation and can be obtained in [1].

Backward Forward Sweep (BFS) method is mostly used for LF studies like in [2], where Shirmohammadi et al. have performed a compensating power flow method for the weakly meshed radial distribution and transmission systems by using the concept of multiport compensation, where radial part is solved in two steps. In in beginning branch currents are calculated with which the node voltages are updated in second step. In [3] a modified BFS technique has been used where the loop analysis is used to formulate the DLF problem. Another kind of BFS method is proposed in [4] to analyze weakly meshed radial distribution system which involves some unique equations formulation to solve DLF problem. A novel DLF technique utilizing Newton-Raphson method with node voltages as state variables is proposed in [5]. In DG modeling, reviewing different works in [6-9] reveals that most of the modeling has been done on the PV and PQ node basis like in [10] where the synchronous and induction types DGs are approximately modeled as PQ nodes in load flow studies.

The theme of this work is to develop an improved DLF technique suitable for handling the DG models for analyzing its effect in voltage sag mitigation. To study the effect of DG integration over voltage sag, the DG power generation limit has to be varied with the load increment. Also, calculation of DG penetration level with maximum DG power generation will help in analyzing the effect of DG modeling over voltage dip conditions. A comparative study of traditional BFS method with proposed DLF technique is studied here. This paper started with an introduction organized in different sections as proposed DLF method. After this a section is dedicated in mathematical explanation of how the DGs mitigate the effect of voltage sag in the system. In the result section, the proposed method is verified over different radial distribution systems and the results are presented with a comparative study. Finally, the discussions are made over the proposed method and conclusion is drawn with a hint of further progress in this regard.

2. PROPOSED DLF METHOD

Proposed method starts with phase impedance matrix (PIM) formation by three phase line modeling. This PIM does not require any lower-upper factorization of matrix. Classical set theoretic approach has been envisaged here in the PIM formulation. Set theory has been applied to branch path set and branch impedance set. Thus, no

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other node and branch identification property is required in this DLF solution. In the beginning three phase line is modeled here because the distribution system taken to analyze is unbalanced one and when has to be analyzed using PIM matrix it requires three phase line model to solve the DLF problem.

The following method of three phase line modeling can be easily applicable for unbalanced distribution system. Assuming a generalized impedance model of a three-phase line with the self and mutual impedances, Carson's equations for three phase four wire grounded system can be constructed as:

$$\left[z_{i,i+1}^{abcn}\right] = \begin{bmatrix} z_{i,i+1}^{aa} & z_{i,i+1}^{ab} & z_{i,i+1}^{ac} & z_{i,i+1}^{an} \\ z_{i,i+1}^{ba} & z_{i,i+1}^{bb} & z_{i,i+1}^{bc} & z_{i,i+1}^{bn} \\ z_{i,i+1}^{ca} & z_{i,i+1}^{cb} & z_{i,i+1}^{cc} & z_{i,i+1}^{cn} \\ z_{i,i+1}^{na} & z_{i,i+1}^{nb} & z_{i,i+1}^{nc} & z_{i,i+1}^{nn} \end{bmatrix} \quad (1)$$

Now applying Kron's reduction technique taking line as a multi grounded neutral point, the above matrix can be reduced to a 3×3 matrix as in (2). Using this reduced impedance matrix, the branch path set will be designed which is required for the formation of PIM matrix.

$$\left[z_{i,i+1}^{abc}\right] = \begin{bmatrix} z_{i,i+1}^{aa\_n} & z_{i,i+1}^{ab\_n} & z_{i,i+1}^{ac\_n} \\ z_{i,i+1}^{ba\_n} & z_{i,i+1}^{bb\_n} & z_{i,i+1}^{bc\_n} \\ z_{i,i+1}^{ca\_n} & z_{i,i+1}^{cb\_n} & z_{i,i+1}^{cc\_n} \end{bmatrix} \quad (2)$$

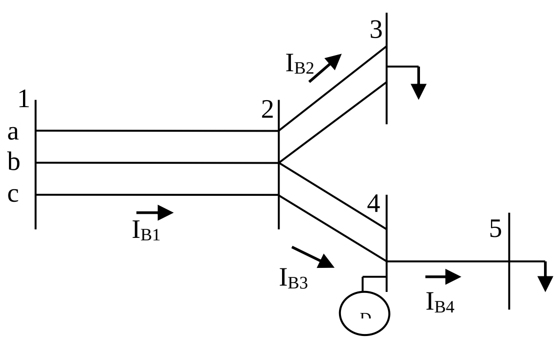


Fig. 1 – Single line diagram of a three-phase unbalanced system with DG

PIM is the only matrix required for DLF solution. A three-phase unbalanced system is taken for derivation purpose as shown in Fig. 1. Phase wise branch impedance (PBI) has been constructed at first as:

$$\left.\begin{aligned} \phi_1 &= \{0\} \\ \phi_2 &= \{[z_{1,2}^{abc}]\} \\ \phi_3 &= \{[z_{1,2}^{abc}], [z_{2,3}^{ab}]\} \\ \phi_4 &= \{[z_{1,2}^{abc}], [z_{2,4}^{bc}]\} \\ \phi_5 &= \{[z_{1,2}^{abc}], [z_{2,4}^{bc}], [z_{4,5}^{c}]\} \end{aligned}\right\} (3)$$

From (3) it is evident that each set of the PBI matrix will contain impedances from slack bus to the i^{th} branch. The first set is a null set as its starting and ending buses are same, i.e., slack bus. Now the voltage drop equation between slack bus to end node through different i^{th} branch path with flow of branch currents I_{Bi} can be formulated as:

$$v_{15} = I_{B1}[z_{1,2}^{abc}] + I_{B3}[z_{2,4}^{bc}] + I_{B4}[z_{4,5}^{c}]. \quad (4)$$

Expressing the branch currents parameters in terms of injected load current to the branch as:

$$I_{B1} = \sum_{k=2}^{5}\left(\frac{S_k}{V_k}\right)^*,\ I_{B2} = \sum_{k=4}^{5}\left(\frac{S_k}{V_k}\right)^*,\ I_{B4} = \left(\frac{S_5}{V_5}\right)^*.$$

Applying the conversions in branch current in (4), we get,

$$v_{15} = \sum_{k=2}^{5}\left(\frac{S_k}{V_k}\right)^*[z_{1,2}^{abc}] + \sum_{k=4}^{5}\left(\frac{S_k}{V_k}\right)^*[z_{2,4}^{bc}] + \left(\frac{S_5}{V_5}\right)^*[z_{4,5}^{c}]. (5)$$

So, on rearranging (10), the new equation will be:

$$v_{15} = \left(\frac{S_2}{V_2}\right)^*[z_{1,2}^{abc}] + \left(\frac{S_4}{V_4}\right)^*\left([z_{1,2}^{abc}] + [z_{2,4}^{bc}]\right) + \left(\frac{S_5}{V_5}\right)^*\left([z_{1,2}^{abc}] + [z_{2,4}^{bc}] + [z_{4,5}^{c}]\right). \quad (6)$$

Next by the application of PBI set which has been formed earlier, equation (6) can be modified with the help of classical set theory as:

$$v_{15} = \left(\frac{S_2}{V_2}\right)^*\sum(\phi_2 \cap \phi_5) + \left(\frac{S_4}{V_4}\right)^*\sum(\phi_4 \cap \phi_5) + + \left(\frac{S_5}{V_5}\right)^*\sum(\phi_5 \cap \phi_5), \quad (7)$$

where

$$\sum(\phi_2 \cap \phi_5) = [z_{1,2}^{abc}]$$
$$\sum(\phi_4 \cap \phi_5) = \left([z_{1,2}^{abc}] + [z_{2,4}^{bc}]\right)$$
$$\sum(\phi_5 \cap \phi_5) = \left([z_{1,2}^{abc}] + [z_{2,4}^{bc}] + [z_{4,5}^{c}]\right)$$

Equation (7) can be rewritten as:

$$v_{15} = \sum_{k=2}^{5}\left(\frac{S_k}{V_k}\right)^*\sum(\phi_k \cap \phi_5).$$

Now the generalized version of derived formulation including the slack bus component as $\sum(\phi_1 \cap \phi_5) = 0$, where φ_1 is a null set. We get,

$$v_{15} = \left(\frac{S_1}{V_1}\right)^*\sum(\phi_1 \cap \phi_5) + \sum_{k=2}^{5}\left(\frac{S_k}{V_k}\right)^*\sum(\phi_k \cap \phi_5)$$
$$\text{or, } v_{1i} = \sum_{k=1}^{i}\left(\frac{S_k}{V_k}\right)^*\sum(\phi_k \cap \phi_i). \quad (8)$$

Therefore, the i^{th} bus voltage can be evaluated as the sum of voltage drop starting from slack bus,

$$V_i = V_1 - v_{1i},$$
$$\text{or, } V_i = V_1 - \sum_{k=1}^{i}\left(\frac{S_k}{V_k}\right)^*\sum(\phi_k \cap \phi_i), \quad (9)$$
$$\text{or } V_i = V_1 - \sum_{k=1}^{i}\left(\frac{1}{V_k}\right)^* S_k \sum(\phi_k \cap \phi_i).$$

Therefore, equation (9) can be written in matrix format as (10). Being ϕ_1 is a null set, every element of first row and column is zero. Generalizing the matrix equation in a reduced form as:

$$[V] = [V_1] - [PIM]\left[\frac{1}{V}\right]^*. \quad (10)$$

So, the desired PIM matrix has been formulated where no singularity of matrix clause will be required to solve it for DLF solution.

3. EXPERIMENTAL RESULTS

The experimental study is performed to demonstrate the proposed algorithm by programming it with the use of MATLAB R2016b software and executed in a computer with Intel core i5, 3.4 GHz processor and 4GB RAM over IEEE 13 bus radial distribution network. The maximum and minimum allowable node voltage limits for IEEE 13 bus system are set as 1.05 and 0.9 pu, respectively. This study helps to demonstrate how the percentage of the distributed generation as well as the loading on the system coupled with the DG model affect the final voltage results thus mitigating voltage sag due to load increment. The DGs connected to the nodes 634 and 652.

The percentage of DG penetration level is determined as

$$\%\, DG\ penetration = \frac{P_{dg}}{(P_{dg}+P_{sub})} * 100, \qquad (11)$$

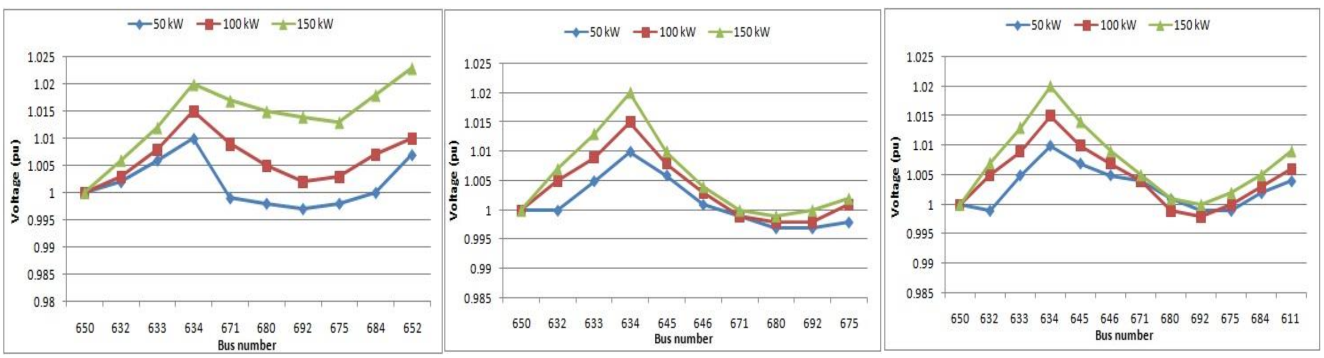
where P_{dg} is the total active power supplied by DGs and P_{sub} is the voltage at the distribution sub-station.

Anticipating the future load growth, DG penetration is increased with increase in the real and reactive power of loads in all the phases of nodes with load. The maximum and minimum reactive power limit changes for different cases with load variation.

3.1 Effect of Change in DG Power Generation Limit

To study the effect of the change in maximum DG power generation limit, the load flow is run by setting the limit of DG power generation as 50, 100 and 150 kW for IEEE 13 bus system.

Also, it is found that the rate of DG penetration level is higher by at least 6 % when both the solar and wind powered DGs generation are varying simultaneously. As with increase in DG power generation limit, the DG penetration level is also getting higher but it also violates the voltage and thermal limits at the nodes. Fig. 2 shows the effect of change in maximum DG power generation limit over the voltage profile of IEEE 13 bus system where the DG power generation limit is varied.



a b c

Fig. 2 – Effect of change in DG power generation limit on voltage profile of IEEE 13 bus system in (a) phase a, (b) phase b and (c) phase c

3.2 Effect of Load Increment

The performances of the solutions obtained with different planning cases are assessed with load growth test to test their capabilities in sustaining future load and also to test the ability of DGs in mitigating the voltage drop due to load growth. For IEEE 13 bus system nodes 634, 646, 611, 675, 652 are subjected to equal percentage load growth rate. This uneven mixed selection of nodes for load increment is done to make the system more real and to check the reliability of proposed method. The performance study based on pu voltage deviation with the load increment in each selected node is shown in Fig. 3. In case of IEEE 13 bus system the highest per unit voltage deviation occurs on a load increment of 30 % of 0.13 at node 634. It is found that on a heavy load increment also the per unit voltage deviation as much less thus mitigating the effect of sudden voltage drop.

3.3 Effect on Voltage Sag Limit

The main causes of the voltage dip are overloads, faults, short circuits, transformer switching, starting of large motors and many others. Here this is based on overloaded condition or gradual increment of load and its effect on voltage sag which is to be mitigated by DG power supply. As mathematically deduced earlier to limit the voltage sag, DGs' maximum power generation limit should be increased. Therefore, to verify the mathematical deductions, both the load and maximum DG power generation has been varied and the voltage sag limit is plotted against these two parameters. Fig. 4 shows the effect of overloading in the system which results in voltage dip at nodes. To mitigate the effect of voltage dip maximum power generation limits of installed DGs are increased slowly corresponds to the load increment.

3.4 Performance Comparison with BFS Method

The results obtained with the proposed three-phase unbalanced distribution load flow method is compared with those obtained with standard distribution load flow techniqueб BFS method [4]. The comparative study of total power loss, execution time and number of iterations is given in Table I and for IEEE 13 bus system. The result shows that the proposed method is much better than BFS method in respect of execution time and number of iterations. Also, the test systems with and without DGs shows a remarkable change in total power loss where system with DGs is having a sharp decrease in power loss of near about 65 %.

Table 1 – Comparison of the solution obtained with different method for IEEE 13 bus system

Distribution load flow method	Total power loss (kW)		Number of iterations		Execution time (s)	
	Without DG	With DG	Without DG	With DG	Without DG	With DG
BFS method [4]	90.68	30.32	6	6	0.103	0.115
Proposed method	88.54	28.93	4	3	0.051	0.58

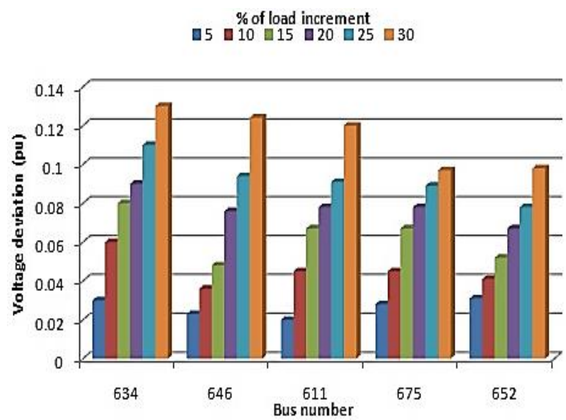


Fig. 3 – Impact of load increment for IEEE 13 bus system

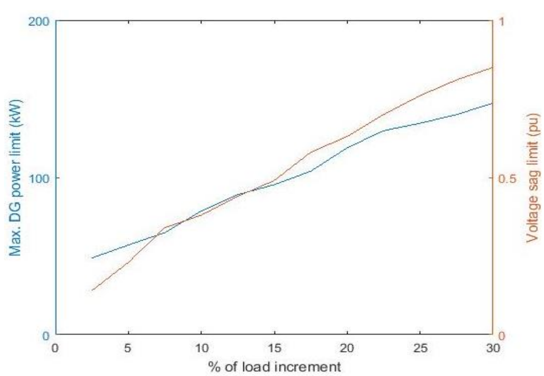


Fig. 4 – Effect on voltage sag limit for IEEE 13 bus system

When comparing the BFS method and the proposed method on the basis of total power loss, both methods show nearly the same results with a negligible change of approximately 2 % in the power loss data. So, on comparing with BFS method it is evident that the proposed method is much faster than BFS method in respect of execution time as the proposed DLF method takes almost half of the time required by the BFS method for both the cases with and without DGs.

4. CONCLUSIONS

In this paper, a new DLF technique has been proposed for radial distribution network where the DGs connected to the network is evaluated on the basis of its impact in voltage sag mitigation. To have voltage sag or dip at the nodes the load increment at selected nodes have been done to test the effect of DGs. on simulation using proposed DLF technique it is found that the DGs, though capable of mitigating the voltage sag in the network but with increase in voltage sag limit the kVA rating of DGs should be increased. In other words, with the rise in load at each node the DG penetration level becomes higher to mitigate the voltage dip at the nodes. Also, the proposed load flow technique is much better in comparison with standard BFS method used for distribution load flow. Using the proposed DLF technique, the analysis of distribution networks coupled with DGs is faster than BFS method irrespective of execution time and number of iterations.

REFERENCES

1. A. Keane, L.F. Ochoa, C.L.T. Borges et al., *IEEE T. Power Syst.* **28** No 2, 1493 (2013).
2. D. Shirmohammadi, W.H. Hong, A. Semlyen, G.X. Luo, *IEEE T. Power Syst.* **3**, 753 (1988).
3. W.C. Wu, B.M. Zhang, *Int. J. Electric Power Energy Syst.* **30** No 1, 8 (2008).
4. A.N. Augugliaro, L.U. Dusonchet, S.A. Favuzza, M.G. Ippolito, E.R. Sanseverino, *Int. J. Electric Power Energy Syst.* **32** No 4, 271 (2010).
5. J.H. Teng, C.Y. Chang, *IEEE T. Power Syst.* **17** No 4, 1238 (2002).
6. S. Khushalani, J.M. Solanki, N.N. Schulz, *IEEE T. Power Syst.* **22** No 3, 1019 (2007).
7. Y. Zhu, K. Tomasovic, *IEEE T. Power Del.* **17** No 3, 822 (2002).
8. C.S. Cheng, D. Shirmohammadi, *IEEE T. Power Syst.* **10** No 2, 671 (1995).
9. S.M. Moghaddas-Tafreshi, E. Mashhour, *Elect. Power Syst. Res.* **79** No 4, 680 (2009).
10. T.-H. Chen, M.-S. Chen, T. Inoue, P. Kotas, E.A. Chebli, *IEEE T. Power Del.* **6** No 4, 1671 (1991).

Дослідження розподілених генерацій для пом'якшення падіння напруги за допомогою незбалансованого потоку навантаження

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У роботі пропонується новий метод трифазного незбалансованого потоку навантаження (DLF) для вивчення впливу розподілених генерацій (DGs), встановлених разом із розподільними мережами для пом'якшення падіння напруги. З метою аналізу DGs моделюються як джерело змінної реактивної потужності та постійного коефіцієнта потужності з використанням як вітрової, так і сонячної енергії. Запропонована методика базується на застосуванні класичної теорії множин, де за її допомогою були сформовані різні матриці імпедансу для тестового випадку. Це дозволяє методу бути більш гнучким і надійним для роботи в будь-якій ситуації. В рамках визначеної матриці PSIM, моделювання DGs включено для дослідження впливу DGs. Вплив DGs на пом'якшення падіння напруги математично пояснюється за допомогою фазової діаграми. Запропонована методика випробувана на стандартних радіальних розподільних мережах IEEE 13 з програмуванням на платформі MATLAB. Для аналітичних цілей можна використовувати інші тестові мережі. Для обґрунтування претензій досліджуються різні випадки, такі як приріст навантаження та збільшення максимальної потужності DGs. Також проведено порівняння між запропонованою DLF технікою і традиційним методом розгортки, де доведено ефективність запропонованої методики над традиційним методом. Щодо загального аналізу запропонованого методу, він показує кращі результати порівняно з традиційним методом розгортки назад вперед за часом виконання та кількістю ітерацій.

Ключові слова: Розподільний потік навантаження (DLF), Розподілені генерації (DGs), Падіння напруги, Радіальна розподільна мережа.