# Impact of Distributed Generation on the Voltage Profiles of the Unbalanced Distribution System

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*Abstract*—**With the advent of deregulation, distributed generation (DG) will play an increasing role in electric distribution systems. This paper addresses the issue of voltage profiles when DG is integrated into the electric power system in a way that assures power quality in the grid and at end-use customer facilities. It also provides a technical assessment of the impact of distributed generation technologies on the voltage distribution of the unbalanced distribution system using the developed fast three phase load flow.**

***Index Terms*—Distributed Generation, Voltage Profile, Three-Phase Load Flow.**

## I. Introduction

VARIOUS new types of distributed resources (DR) for generation and storage such as micro turbines and fuel cells are now being developed to augment more traditional distributed generation (DG) sources such as solar and wind power[1,2,3,4]. A common belief among developers is that DG will improve the local power quality, a potential that is sited as one of the value attributes of installing distributed generators[5]. In some cases, distributed generation is being promoted as fulfilling the requirements for premium-quality power of high technology or sensitive end-use customers. Whether this assertion is valid depends on the specific technologies, site conditions, and potential interaction with the existing electric power system.

This paper includes unbalanced, steady state analysis on the voltage profiles in the distribution system with DG. The fast three-phase load flow algorithm is developed and evaluated to assess DG impact on the distribution system. Based on this assessment, calculation procedures are developed for evaluating these impacts of distributed generation.

In the case of voltage control (steady-state analysis), each administratively separated region regulates its own voltage, with interconnections to the neighboring regions neglected. However, due to distributed generation, the need for a systematic, on-line coordination is emerging to insure the global security of the unbalanced distribution system.

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In response to evaluate the potential distribution system impacts of the DG concept, this paper starts from the review of three-phase distribution system in section II part A. The updated studies in three-phase load flow is then developed in part B. In part C, the IEEE 13 bus testing system is used to verify the accuracy of the proposed methods. The simulation section is followed by more detailed discussion of how the DG model affects distribution system voltage profiles. The case studies are used to show the different effects of different penetration level. In the end, section VI summarizes the paper and provides future work.

## II. Distribution System Three Phase Load Flow

### A. Distribution System Feeder Review

The primary feeders of the distribution system consist of three-phase overhead or underground lines, and double-phase or single-phase lines, which is near the end users. The series impedance of a line between bus i and j, is represented by a $3\times3$ matrix[6]:

$$Z_{ij} = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} \\ z_{ba} & z_{bb} & z_{bc} \\ z_{ca} & z_{cb} & z_{cc} \end{bmatrix}_{ij} \quad (1)$$

If any phase of the line does not exist, the corresponding row and column in the matrix should contain all zero entries.

### B. Fast Three Phase Load Flow

Some methods about three phase load flow were proposed in previous research[7,8]. In reference [7], a topology based load flow was proposed. Newton-Raphson method was applied in the reference [8]. Since the DG is system dependent and the topology of the distribution system generally is simple, the method in reference [7] is applied and revised for the new scenario in this paper. First of all, it is applied in single-phase diagram to show the algorithm, then the details for three-phase system. At each bus i, the complex power $S_i$ is specified by

$$S_i = P_i + jQ_i \quad \text{i=1,2,…,N} \quad (2)$$

and the corresponding equivalent current injection at the k-th iteration is

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \quad (3)$$

where

$V_i^k$ is the node voltage at the k-th iteration
$I_i^k$ is the equivalent current injection at the k-th iteration

Note this is also valid to represent each phase in the each bus.

The single-phase line diagram in next figure will be used as an example. A set of equations based on KCL is gotten.

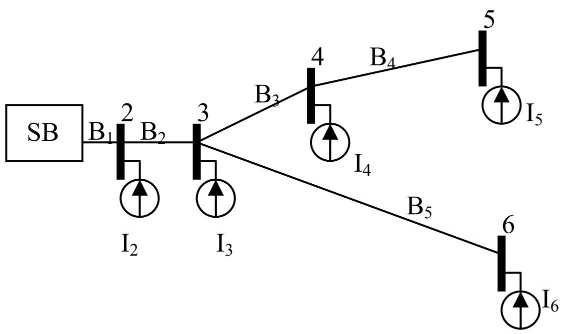



Fig 1. A Simple Distribution System

The branch current $B_5$, $B_4$, $B_3$, $B_2$, $B_1$ can be represented as
$B_5=I_6$,
$B_4=I_5$,
$B_3=I_4+I_5$,
$B_2=I_3+I_4+I_5+I_6$,
$B_1=I_2+I_3+I_4+I_5+I_6$,

The matrix relationship between the injection current and branch current is

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (4)$$

that is [B]=[BI][I]. (5)

Then, the relations between the branch currents and bus voltages can be obtained. For example,

$V_2=V_1-B_1Z_{12}$, (6)
$V_3=V_2-B_2Z_{23}$, (7)
$V_4=V_3-B_3Z_{34}$, (8)
Substitute (6), (7) to (8),
$V_4=V_1-B_1Z_{12}-B_2Z_{23}-B_3Z_{34}$, (9)
Generalize it as matrix,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (10)$$

[dV]=[VB][B] (11)

Then $[\Delta V^{k+1}] = [VI][I^k]$ (12)

where [VI]=[VB][BI] (13)

For three-phase distribution system, all the algorithms are still the same. But the voltage, current, and power now are all in a,b,c phases. The dimension is three times as single-phase system. Each element in Z matrix and VB matrix is 3×3 full elements such as (1). While in BI matrix, each element also becomes 3×3. But it is different from the VB matrix and it only has diagonal elements. If any phase of the line does not exist, the corresponding row and column in the matrix should contain all zero entries.

The proposed algorithm is summarized as follows:

(1) Input system data.
(2) Build the current matrix like (4).
(3) Build the matrix like (9).
(4) Use (4) and (9) to get $[\Delta V] = [VI][I]$
(5) Start iteration k=0
(6) k=k+1, solve for three-phase load flow, use (3) and (10) update the current and voltage
(7) if $\left| I_i^{k+1} - I_i^k \right| > \varepsilon$, then go to (6)
(8) else get the report and end the procedure

### C. *Testing Case and Results*

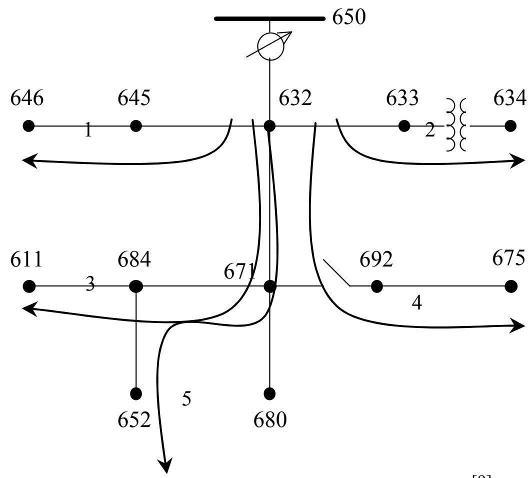
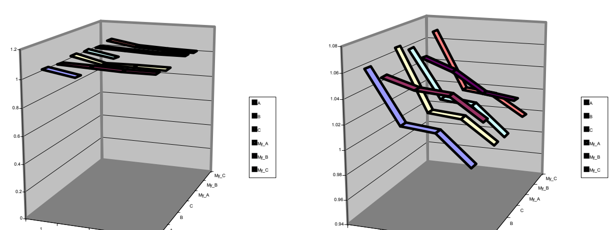
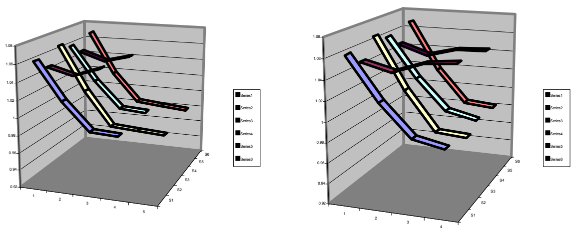



Fig 2. IEEE 13 Node Test Feeder[9]

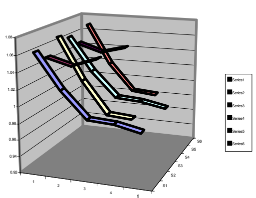
Use the IEEE 13 bus distribution system as an example to prove the above analysis.



Voltage profiles through Path 1and Path 2



Voltage profiles through Path 3 and Path 4



Voltage profiles through Path 5

Fig 3. Comparison of the proposed method and standard one

It takes only 3 iteration steps to get the $10^{-4}$ accuracy. The maximum deviation from the solution is less than 2% which is accurate enough for the algorithm.

## III. Simulation

Compared with the IEEE 13 bus distribution system, the results are with 2% error. It is used for three-phase unbalanced load flow analysis in the distribution system with DG. Investigations/Parameter variations are made on the distribution system with DG.

In the IEEE 13-bus testing system, the load and system are all unbalanced. It is used as test bench for the system with DG. The load is shown as following

TABLE I.
LOAD DATA OF THE SYSTEM

| Node | Load | Ph-1 | Ph-1 | Ph-2 | Ph-2 | Ph-3 | Ph-3 |
|---|---|---|---|---|---|---|---|
| | Model | kW | kVAr | kW | KVAr | kW | kVAr |
| 634 | Y-PQ | 160 | 110 | 120 | 90 | 120 | 90 |
| 645 | Y-PQ | 0 | 0 | 170 | 125 | 0 | 0 |
| 646 | D-Z | 0 | 0 | 230 | 132 | 0 | 0 |
| 652 | Y-Z | 128 | 86 | 0 | 0 | 0 | 0 |
| 671 | D-PQ | 385 | 220 | 385 | 220 | 385 | 220 |
| 675 | Y-PQ | 485 | 190 | 68 | 60 | 290 | 212 |
| 692 | D-I | 0 | 0 | 0 | 0 | 170 | 151 |
| 611 | Y-I | 0 | 0 | 0 | 0 | 170 | 80 |
| | TOTAL | 1158 | 606 | 973 | 627 | 1135 | 753 |

Assume DG is installed at the end of each radial feeder, penetration level is from 0, 10%, 25%, to 50%.

Y-axis in all the following figures represents voltage (p.u.) profiles along the specific path. X-axis is the bus along the linb.

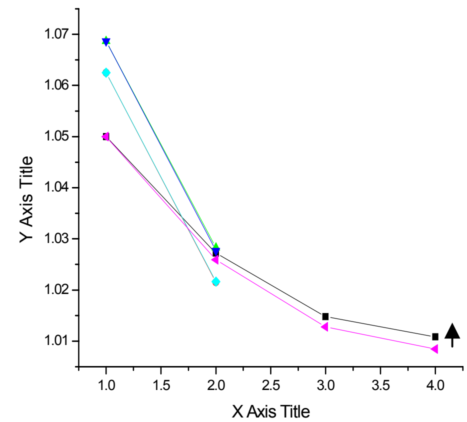



Fig 4. 10% DG penetration on bus 646 compared with 0% DG

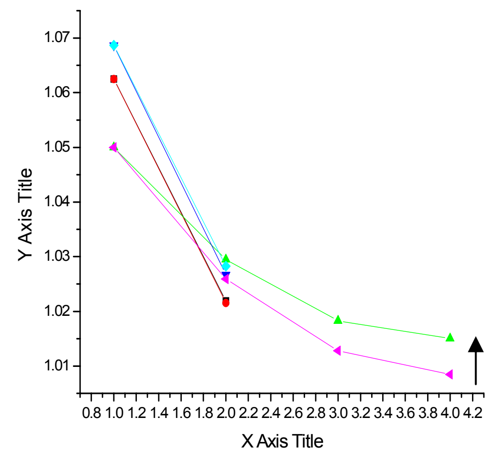



Fig 5. 25% DG penetration on bus 646 compared with 0% DG

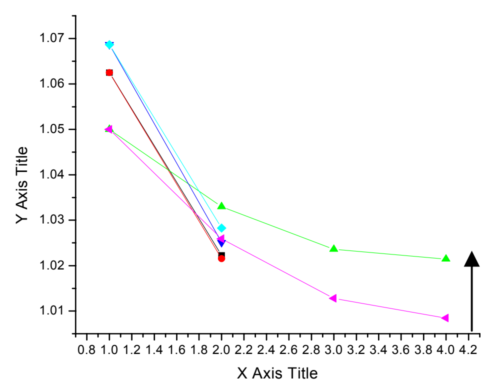



Fig 6. 50% DG penetration on bus 646 compared with 0% DG

The above three figures show the voltage distributed along the path 1. As the penetration increasing, the voltage profiles are also increasing because of the DG at the user end helping the voltage increasing along the downstream of the line 1. So do the rest of the lines in the system. Almost all the voltage profiles are improved except voltage along phase C at the far end of the user at path 2 shown in figure 7.

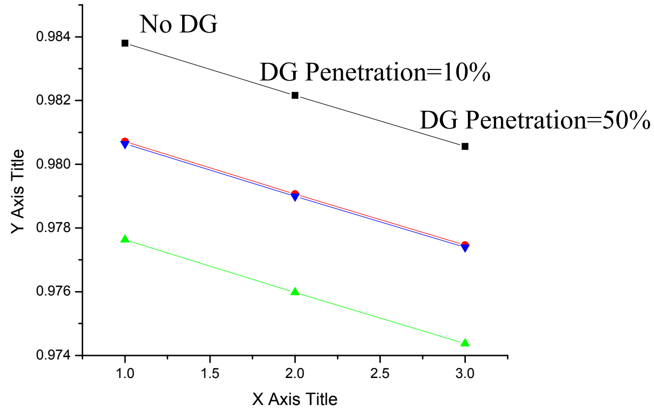



Fig 7. The voltage profiles along the path 2 with DG increasing in path 1

In the unbalanced distribution system, installation of DG would generally help the voltage profiles, but there are some exceptions and may worse the voltage profiles. The unbalanced system and load are the main reasons.

Then one DG is installed at Bus 652.

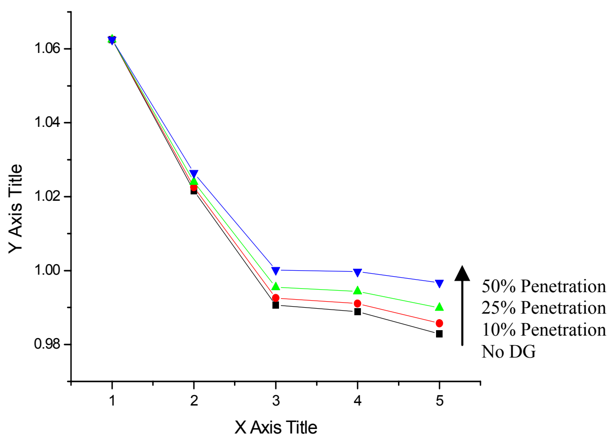



Fig 8. The voltage profiles (phase a) along path 5

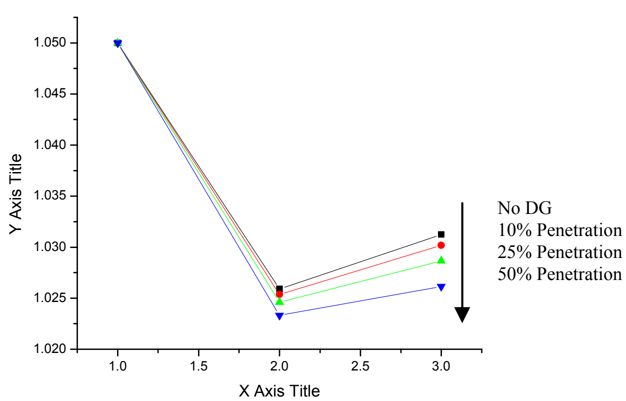



Fig 9. The voltage profiles (phase b) along path 5

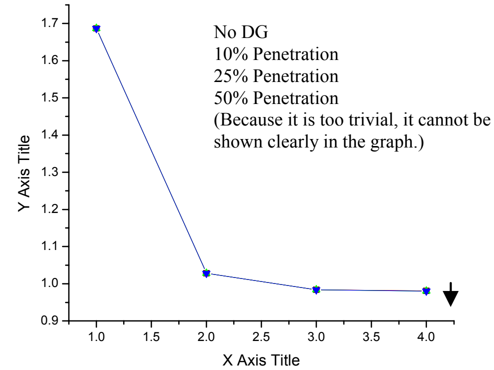



Fig 10. The voltage profiles (phase c) along path 5

From the figure 8-10, the voltage profiles are improved in phase A that is the phase DG installed. It hints that the voltage profiles can be surely flattened only in the phase that DG is installed. While on the other phases, it is hard to determine and usually it is based on the system configuration and load distribution.

In the case of one three-phase DG is installed at bus 671, the voltage profiles are shown in figure 11-14. Because the loads are balanced, the 3-phase balanced DG should be connected to that bus.

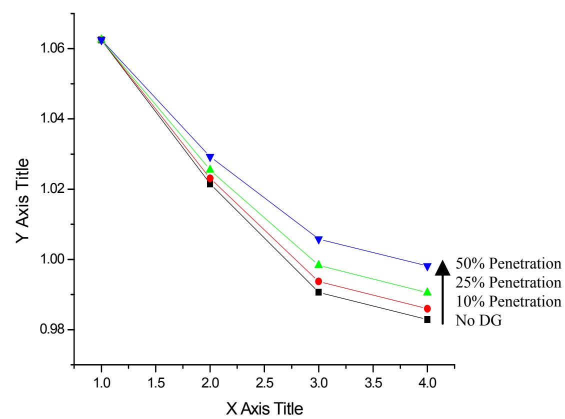



Fig 11. The voltage profiles (phase a) along path 5

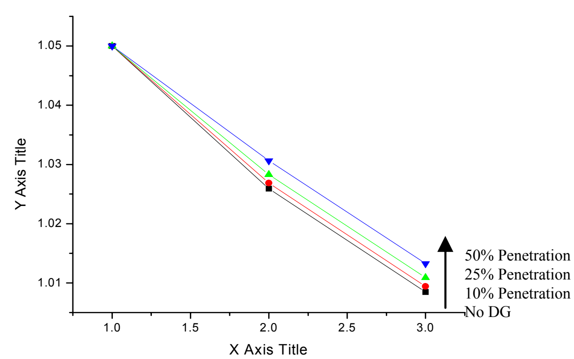



Fig 12. The voltage profiles (phase a) along path 1

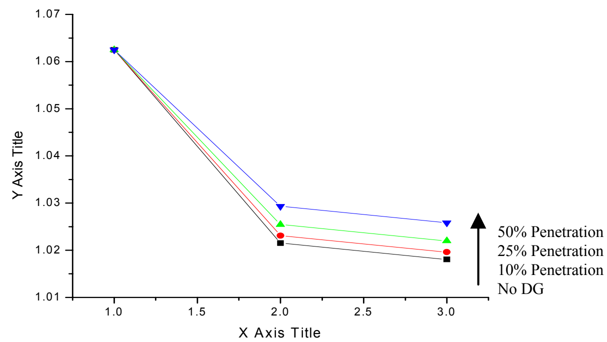



Fig 13. The voltage profiles (phase a) along path 2

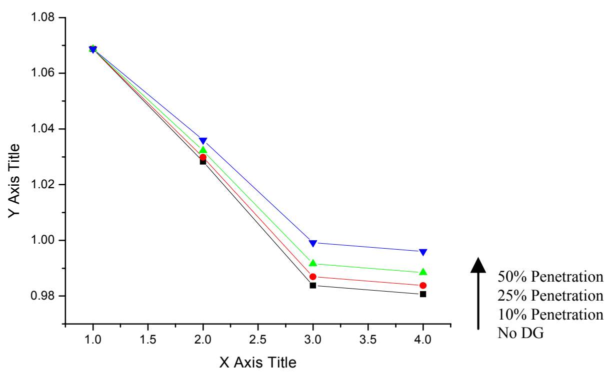



Fig 14. The voltage profiles (phase a) along path 4

Based on the above comparisons, when the DG is sited at the 3-phase balanced load center, the overall voltage profiles can be flattened. This gives the one possible way to optimize the location of the DG.

Single-phase loads on long radial lines often result in unbalanced conditions in three-phase power systems. Also, during peak loading times, these lines require switched shunt capacitors for voltage stabilization. In the testing system, there are a couple of buses that is highly unbalanced loaded.

Based on the result from DG installed on bus 675 and 671, in both cases, since the load is three phases, the voltage profiles are flatten in all buses throughout the system if the output of DG is three-phase balanced.

In the heavily loaded feeder, obviously, it helps the voltage profiles. While in the lightly loaded feeder, DG would cause unacceptable voltage violations.

In table II, the execution time and number of iterations with the change of DG in each path are listed. The time and iteration steps increase with DG installed deeper in the down stream of the network.

TABLE II
EXECUTION TIME AND NUMBER OF ITERATIONS

| Path No. | Execution Time (sec.) | Number of Iterations[a] |
|---|---|---|
| 1 | 0.0056 | 2 |
| *2* | 0.012 | 3 |
| *3* | 0.0123 | 3 |
| *4* | 0.025 | 4 |
| *5* | 0.0275 | 4 |

## IV. CONCLUSIONS

In all, for three phase balanced DG, the overall system voltage profile can be flattened by installation of them. In unbalanced system and single phase or double phase DG, the voltage profiles can be improved in the phase that DG is installed, but it might sharpen the profiles. It is hard to determine and for future work to explore.

By providing utilities with a clear understanding of the impact of distributed generation on power quality, the paper can help utilities to better advise end-users who are considering or already using distributed generation. The calculation worksheets provided in this paper helps utility to evaluate the impact of distributed generation on grid power voltage quality. The paper also helps all those concerned with the interconnection of distributed resources to the electrical distribution system to clearly understand the impact of DG technologies on voltage profiles and to amend some of the misconceptions about the inherent power quality benefits of these technologies. It is important for utilities and end-users to understand the limitations as well as the benefits of distributed generation so that all parties involved can make an informed decision regarding the application of these valuable resources.

Widespread addition of distributed generation in electric power distribution systems will affect voltage profiles both through its impact on the grid and through its potential to provide quality power when separated from the grid. Given the current technology, interconnection standards, and utility distribution system practices, it is possible that the impact of DG on power quality will be neutral at best; and, as DG becomes a significant portion of the distribution feeder load, it could have a negative impact. Long-duration voltage variations may also be possible due to the interaction of upstream voltage regulators with distributed generators. Voltage unbalance on existing distribution networks will also be a factor limiting DG penetration. From the end-user's point of view, the most critical impact will be on voltage harmonic distortion and the potential of temporary over voltage when separated from the grid in the future.

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