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Allocation of Decentralized Generators in Distribution Networks for Enhancing Normal Operation Loadability

Nasser G. A. Hemdan, *Student Member, IEEE* and Michael Kurrat, *Member, IEEE*

***Abstract*—This work presents a new approach for placement and dispersing of Decentralized Generation (DG) power in medium voltage distribution networks based on Continuation Power Flow (CPF) method. The main objectives of the proposed method are to maximize the Normal Operation Loadability (NOL) (i.e. the maximum loading which can be supplied by the power system while the voltages at all nodes are kept within the limits) and to obtain more benefits from the same amount of DG power. The results obtained with the proposed methodology for a 85 node distribution network demonstrate its applicability.**

***Index Terms*-- Continuation power flow, Decentralized generation, Distribution networks, Voltage limits**

I. INTRODUCTION

TRENDS in energy consumption requirements, and in the evolution of electricity generation and storage technologies, will ultimately fuel a boom DG, a solution that offers the best long-term answer to questions of reliability, price, and pollution. DG is generally defined as generation, storage, or devices that are connected to, or injected into, the distribution lines of the electricity grid. They may be located at a customer's premises on either side of the meter or may be located at other points on the distribution line, such as a utility substation [1]. DG is integrated with different sizes and different technologies at distribution levels, therefore the structure of the future energy supply will be as seen in Fig. 1 [2]. The planning of electric systems with the presence of DG requires the definition of several factors, such as: the best technology to be used, the number and capacity of the units, the best location, the network connection way, etc. [3].

The installation of DGs in certain locations to meet the increasing demand can reduce or avoid the need for building new Transmission and Distribution (T&D) lines and upgrade the existing power systems [4]-[7]. Different technical issues have to be considered before integration of DG to obtain maximum benefits. Therefore, DG can be allocated in the distribution networks for minimizing the losses [8]-[13], enhancing the voltage stability limit loadability [14]-[16], and improving the voltage profile of the system [17], [18].

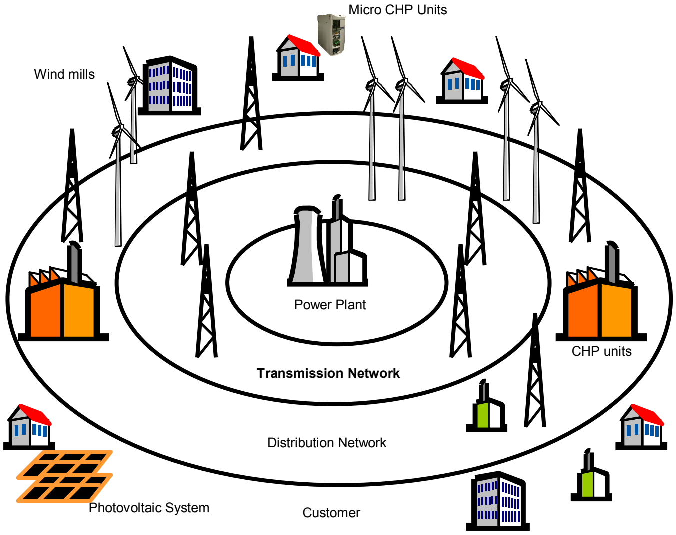

Fig. 1. Structure of the future energy supply [2]

From the review of the previous work of the allocation algorithms and objectives, it can be observed that, very little literatures deal with the optimal allocation of DG to maximize the loadability of the system. Nevertheless, the loadability which has been introduced in the previous work is the maximum loading according to the steady state voltage stability limit.

This paper introduces a new methodology to maximize the NOL of a distribution system through dispersing a certain DG power based on CPF. The NOL is the maximum loading which can be supplied by the power system while the voltages at all nodes are kept within the limits. The importance of NOL comes from the practical point of view, where the loadability of a distribution system is limited by voltage drop, as most of the distribution feeders are long and operating at low and medium voltage levels [14]. Other technical issues like the system losses, voltage profile, and voltage stability margins are investigated for the resulted locations. All the results presented in this paper are produced with the help of Power System Analysis Toolbox (PSAT) [19] which is based on MATLAB.

This paper is organized as follows: section 2 describes DG in general. Section 3, presents a brief introduction of CPF method. The allocation algorithm is discussed in details in

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section 4. Details of the distribution test system are given in section 5. A presentation and discussion of the simulation results are given in section 6. Finally the conclusions of this work are highlighted in section 7.

II. DECENTRALIZED GENERATION

Decentralized generation is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular (and sometimes renewable-energy) generators, and they offer a number of potential benefits. In many cases, distributed generators can provide lower-cost electricity and higher power reliability and security with fewer environmental consequences than can traditional power generators. In contrast to the use of a few large-scale generating stations located far from load centers (the approach used in the traditional electric power paradigm), DG systems employ numerous, but small plants and can provide power onsite with little reliance on the distribution and transmission grid. DG technologies yield power in capacities that range from a fraction of a kW to about 100 MW [20]. The primary drivers behind the growth of DG and the current focus on its integration into electric power system operation and planning can be classified into three main categories, namely environmental, commercial and national/regulatory. The environmental drivers contain limiting green house gas (GHG) emissions, and avoidance of the construction of new transmission circuits and generation plants. While the commercial drivers are, general uncertainty in electricity markets favours small generation schemes and DG is a cost effective route to improved power quality and reliability. The national/regulatory drivers are diversification of energy sources to enhance energy security, and support for competition policy [21]. DG can be classified according to their electrical applications to standby, stand alone, peak load shaving, rural and remote application, providing combined heat and power (CHP), and base load application [4].

III. CONTINUATION POWER FLOW

The general principle behind the CPF is rather simple. It employs a predictor-corrector scheme to find a solution path of a set of power flow equations that have been reformulated to include a load parameter [22]. CPF can be used for determining generator reactive power limits, flow limits of transmission lines and *voltage limits*. CPF will be used in this paper to evaluate the maximum loading with respect to the voltage limit. Bifurcation analysis requires steady-state equation of power system models, as follows:

$$\dot{x} = 0 = f(x,y,\lambda) \qquad (1)$$

$$0 = g(x,y,\ \lambda)$$

Where *x* are the state variables, *y* are the algebraic variables (voltage amplitudes and phases) and *λ* is the loading parameter, i.e. a scalar variable which multiplies generator and load directions as follows:

$$P_G = (\lambda + \gamma k_G)P_{G0} \qquad (2)$$

$$P_L = \lambda P_{L0} \qquad (3)$$

$$Q_L = \lambda Q_{L0} \qquad (4)$$

In (2), (3) and (4) P_{G0}, P_{L0}, and Q_{L0} are the base case generator and load powers. K_G is the distributed slack bus variable, and γ is the generator participation coefficients. The CPF method implemented in PSAT consists of a predictor step realized by the computation of the tangent vector and a corrector step that can be obtained either by means of a local parameterization or perpendicular intersection [23].

A. Predictor step [23]

At generic equilibrium point, the following relation applies:

$$g(y_p,\lambda_p) = 0 \Longrightarrow \left.\frac{dg}{d\lambda}\right|_p = 0 = \nabla_y g\big|_p \left.\frac{dy}{d\lambda}\right|_p + \left.\frac{\partial g}{\partial \lambda}\right|_p \qquad (5)$$

And the tangent vector can be approximated by:

$$\tau_p = \left.\frac{dy}{d\lambda}\right|_p \approx \frac{\Delta y_p}{\Delta \lambda_p} \qquad (6)$$

From (5) and (6) one has:

$$\tau_p = -\nabla_y g\big|_p^{-1} \left.\frac{\partial g}{\partial \lambda}\right|_p \qquad (7)$$

$$\Delta y_p = \tau_p \Delta\lambda_p \qquad (8)$$

A step size control k has to be chosen for determining the increment Δy_p and $\Delta\lambda_p$, along with a normalization to avoid large step when $|\tau_p|$ is large:

$$\Delta\lambda_p = \frac{k}{|\tau_p|} \qquad (9)$$

$$\Delta y_p = \frac{k\tau_p}{|\tau_p|} \qquad (10)$$

Where $k = \pm 1$, and its sign determines the increase or the decrease of *λ*. Fig. 1 presents a pictorial representation of the predictor step.

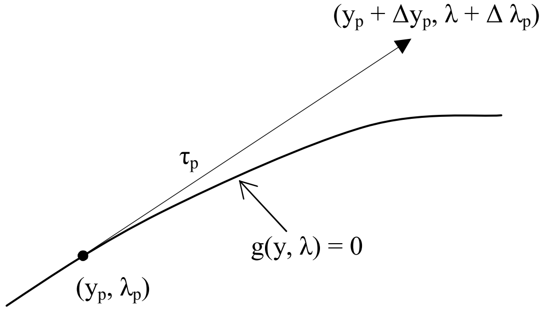

Fig.2. Predictor step by means of tangent vector.

B. Corrector Step [23]

In the corrector step, a set of n+1 equation is solved, as follows:

$$g(y,\lambda) = 0 \qquad (11)$$

$$\rho(y,\lambda) = 0 \qquad (12)$$

Where the solution of g must be in the bifurcation manifold and ρ is an additional equation to guarantee a non-singular set at the bifurcation point. As for the choice of ρ, there are two options: the perpendicular intersection and the local parameterization. In case of perpendicular intersection, whose pictorial representation is presented in Fig. 2, the expression of ρ becomes:

$$\rho(y,\lambda)=\begin{bmatrix}\Delta y_p\\ \Delta\lambda_p\end{bmatrix}^T\begin{bmatrix}y_c-(y_p+\Delta y_p)\\ \lambda_c-(\lambda_p+\Delta\lambda_p)\end{bmatrix}=0 \qquad (13)$$

While for local parameterization, either the parameter λ or a variable y_i is forced to be a fixed value.

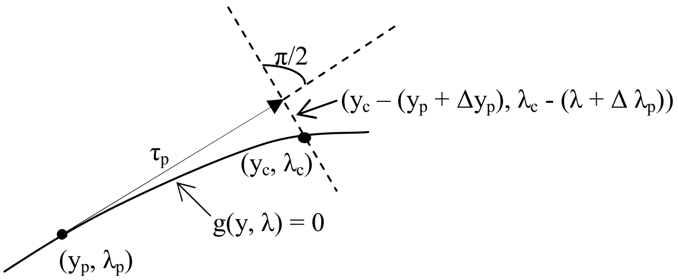

Fig.3. Corrector step obtained by means of perpendicular intersection.

IV. ALLOCATION ALGORITHM

The main objective of this work is to allocate and disperse the DG power to maximize the NOL of the network. As seen in Fig. 4, the proposed methodology starts with execution of CPF to identify the first node reached the low voltage limit. Then the DG units are integrated at that node and after that the CPF is executed. Therefore, another node can be obtained and then the DG units' power is dispersed between the two nodes. Then the objective function is checked. This process is continued until no improvement is obtained, and then the process will stop.

V. TEST SYSTEM

The 85 node distribution network [24] used in this paper is depicted in Fig. 5. It is a balanced three phase radial distribution system that consists of 85 nodes, operating at 11 kV voltage level. It is assumed that all the loads are fed from the substation located at node 1. The system has 75 loads totaling 1.8 MW and 1.84 Mvar, real and reactive power loads respectively. The NOL of the system without integration of DG is found to be 2073 kW.

6 × 240 kW, 0.4 kV DG units are used in the simulation. Each DG unit is integrated through 0.4/11 kV transformer, which has R = 0.0 p.u., and X = 0.13 p.u. The DG is modeled as a PQ synchronous generator operates at 0.9 capacitive power factor. Decentralized synchronous generators are normally not set up to maintain a constant voltage. They are controlled to maintain a constant active power output with a constant reactive power. As a result, the synchronous generators can be represented approximately as constant complex power devices, i.e. they can be represented as a PQ specified devices in a steady state power flow study [25].

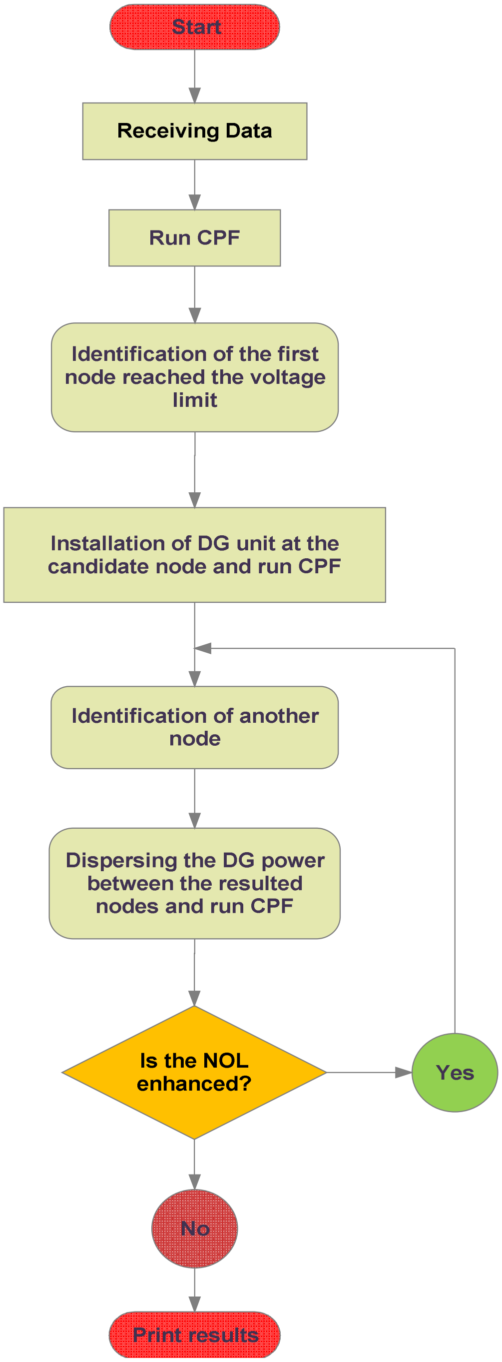

Fig. 4. Flowchart of the proposed algorithm

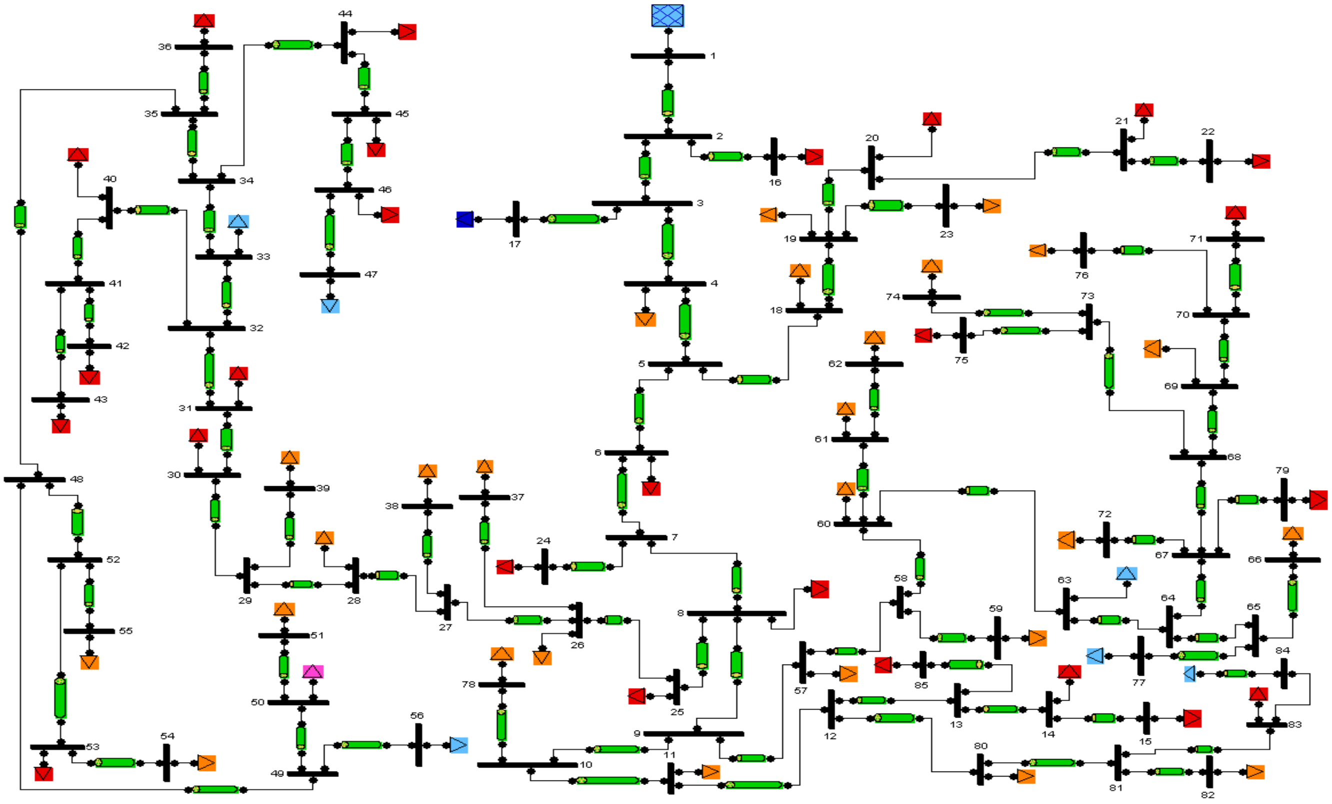

Fig. 5. One line diagram of 85 node distribution system in PSAT space.

VI. SIMULATION RESULTS

The placement methodology is applied to the test system. It was found that node 54 is the first node reached the low voltage limit after running the CPF. According to the methodology all the DG units are integrated at this node as can be seen in Fig. 6. Then the process will be completed until no improvement in NOL is achieved. The resulted nodes priority and DG power at each node are given in Table I. The results of integrating the DG units at the candidate nodes will be introduced as follows: normal operation loadability, distribution system losses, voltage profile and steady state voltage stability limit.

TABLE I
RESULTED NODES PRIORITY AND DG UNITS INTEGRATED AT EACH NODE

Iteration No.	Nodes Priority	No. of DG Units Integrated
1	Node 54	6 units
2	Nodes 54 and 76	3 units at each node
3	Nodes 54, 76 and 47	2 units at each node

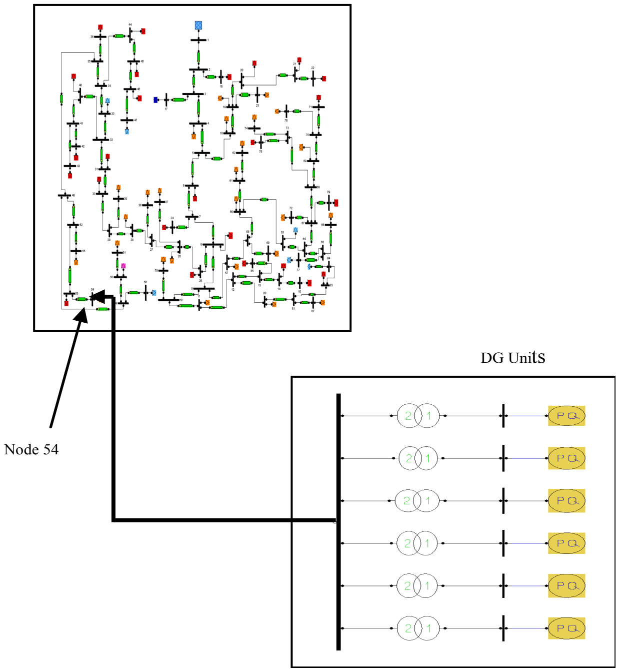

Fig. 6. DGs (6 units) integrated via 6 transformers into distribution network at node 54.

A. Normal Operation Loadability

Generally, it can be seen in Fig. 7 that integrating DG enhances the NOL of the distribution system compared with the case without DG. Also it can be demonstrated that NOL is improved when the DG power is dispersed between the resulted nodes. A 515 kW is the difference in NOL of the system between integrating 2 units at each node of the three resulted nodes and integrating the 6 units at one node. This means that the system can be loaded by 15.7% more than the case of concentrated DG units at node 54 while the voltages are kept within the limits. When DG is owned by the electrical utility, then dispersing the DG power at more than one location will be helpful in supplying more loads and postponing the reinforcement of the existing system to meet the increasing demand.

B. Distribution System Losses

Power losses can be divided into two categories: real power loss and reactive power loss. The resistance of the lines causes the real power loss, while reactive power loss is produced due to the reactive element. Normally, the real power loss draws more attention for the utilities as it reduces the efficiency of transmitting energy to customers [26]. The real power loss was calculated by using the following equation [27]:

$$P_{losses} = P_{substation} + P_{DG} - \sum P_{loads} \qquad (14)$$

The real power loss of the system with integration of DG units is illustrated in Fig. 8. It can be concluded that allocating of the DG units according to the proposed algorithm decreases the real power loss. Also, it can be noticed that the loss is decreased from 119.4 kW with integration of 6 units at one node to 50 kW with integration of 6 units at three nodes. That means the losses is reduced by 58%.

C. Voltage Profile

Fig. 9 shows the voltage profile of the system with integration of the DG units at one node (node 54) and at two nodes (nodes 54 and 76) and at three nodes (nodes 54, 76 and 47) representing the three iterations respectively. It can be demonstrated that dispersing the DG power makes the voltage more uniform. While integrating all DG power at one node increases the voltage at some nodes and leave the voltage at other nodes low. It can be concluded also that using the voltage profile to judge the NOL is not a good indicator so that the NOL has to be evaluated via different methods.

D. Steady State Voltage Stability Limit

A comparison between the steady state voltage stability limit with integration of DG at different number of locations is given in Table II. It can be seen that the voltage stability limit will be approximately the same regardless the DG power is dispersed or concentrated.

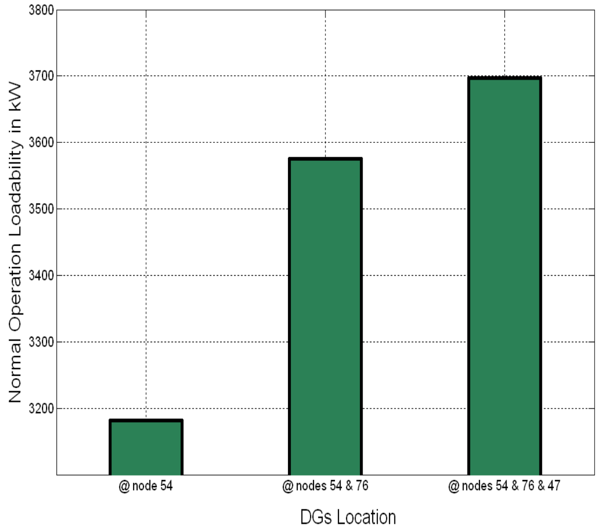

Fig. 7. Normal operation loadability of the system with integration of DG (different iterations)

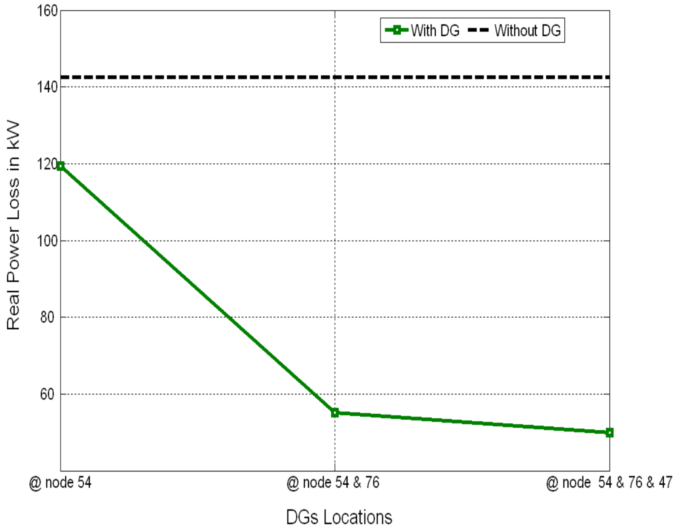

Fig. 8. Real power losses of the system with integration of DG (different iterations)

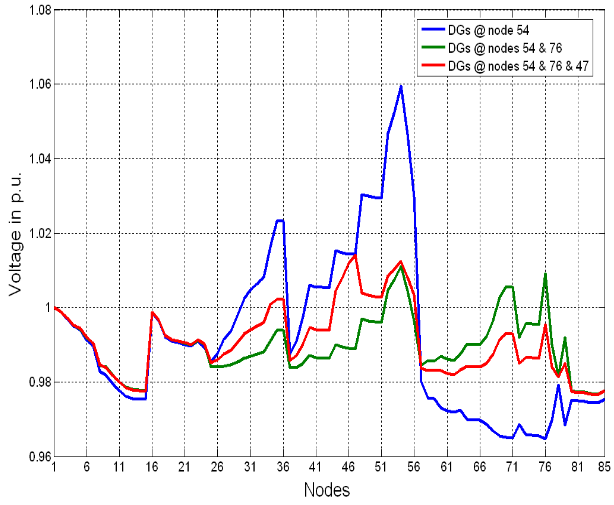

Fig. 9. Voltage profile of the system with integration of DG (different iterations)

TABLE II
VOLTAGE STABILITY RESULTS WITH INTEGRATION OF DG (DIFFERENT ITERATIONS)

DG units location	Maximum loading parameter (λ)	VSL loadability in kW
Node 54	4.4466	8003
Nodes 54 & 76	4.4051	7929
Nodes 54 & 76 & 47	4.4423	7996

VII. CONCLUSIONS

A new methodology for placement and dispersing of DG units in medium voltage distribution networks is presented in this work. This methodology is based on continuation power flow method. The main objective of the proposed approach is to maximize the normal operation loadability with the existence of a certain a mount of DG power. The following conclusions can be drawn form the results:

- Integration of DG into distribution networks enhances the normal operation loadability.

- Dispersing the same amount of DG power enhances the normal operation loadability of the system more than concentrating this power at one node.

- More loads can be supplied with the same power of DG, if DG units are allocated probably.

- Dispersing the same power of DG doesn’t approximately affect the voltage stability limit when it compared with integration of the same DG power at the weakest node.

- The proposed allocation method yields efficiency in decreasing the real power loss and obtaining a more uniform voltage profile of the system.

- The results obtained by applying the proposed methodology demonstrate its applicability.

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IX. BIOGRAPHIES

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