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Improvement of Voltage Profile in Distribution Network Using Distributed Generation

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Abstract—This paper presents an efficient methodology for integration of Distributed Generation (DG) power into distribution systems, in order to maximize the voltage limit loadability. The proposed methodology is based on continuation power flow (CPF). The effectiveness of the presented methodology is demonstrated in a test distribution system that consists of 85 nodes with integration of different penetration levels of DG power. The proposed method yields efficiency in obtaining more benefits from the same amount of DG power, decreasing the losses and improving the voltage profile. The simulation of the proposed model was carried out using MATLAB/PSAT and the effective performance was analyzed.

Index Terms—Distributed generation, Distributed network, Continuation Power Flow (CPF) method, Voltage stability, Voltage limits.

I.INTRODUCTION

In general terms, voltage stability is defined as the ability of a power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain equilibrium between load demand and load supply from the power system. Instability that may result appears in the form of a progressive fall or rise of voltages of some buses. Voltage stability problems mainly occur when the system is heavily stressed beyond its capability. While the disturbance leading to voltage collapse may be initiated by a variety of causes, the main problem is the inherent weakness in the power system.

Recently a top priority is given to develop a reliable, sustainable, environment friendly as well as low-cost electrical energy supply. This includes a sensible energy mix and improvements in efficiency of energy generation, transmission and consumption[1]. As a number of events that have been brought to the vulnerability of the current centralized electrical energy supply infrastructure, such as terrorist threats, natural disasters, geopolitical disruptions, ageing of a highly complex infrastructure, climate change and regulatory and economic risks, DG appears to be one of the key answers for different problems[3]. In the distribution system, the electrical power supply will be transferred from a vertical one to a horizontal system. In the traditional systemthe electric power industry has been driven by a paradigm where most of the electricity is generated in large power plants, sent to the consumption areas through HV transmission lines, and delivered to the consumers through a passive distribution infrastructure that involves HV, MV and LV networks. In this paradigm power flows only in one direction from the power station to the network and to the consumer.

The DG term is used to describe small distribution system close to the point of consumption. Such generators may be owned by a utility or more likely by a customer who may use the entire portion or perhaps all of it to the local utility combustion turbine generators, internal combustion engines and generators, photovoltaic panels, and fuel cells. Solar thermal conversion, stirling engines, are considered as DG. When the penetration of DG is high, the generated power of DG units not power flow in the distribution network consequence, the connection of DG to the grid may different technical issues, e.g. voltage profiles quality, stability etc..[8] In spite of the benefits of utilizing DG units within of the system efficiency and the improvements in the technical and operational challenge units into MV distribution networks are needed. Moreover, in more details with respect to the generation types. Optimization of the MV distribution networks with a large penetration of DG is also needed therefore the utilities can get more benefits[9].

Many voltage stability indices are based on the eigen value analysis or singular value decomposition of the system power flow Jacobian matrix. The main difficulty in this method is that Jacobian of NR power flow become singular at voltage stability limit (critical point) .A power flow solution near the critical point prone to divergences and error. Singularity in the

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Jacobian can be avoided by slightly reformulating the power flow equations and applying a locally parameterized continuation technique. During the resulting continuation power flow, the reformulated set of equations remains well conditioned so that divergence and error due to a singular Jacobian are not encountered.

II. CONTINUATION POWER FLOW

The continuation method is a mathematical path-following methodology used to solve systems of nonlinear equations. Using the continuation method, a solution branch can be tracked around the turning point without difficulty. This makes the continuation method quite attractive in approximations of the critical point in a power system. The CPF captures this path-following feature by means of a predictor-corrector scheme [11]. Moreover, CPF can be used to determine generator reactive power limits, voltage limits and flow limits of transmission lines[2]. Bifurcation analysis requires steady state equation of power system models, as follows

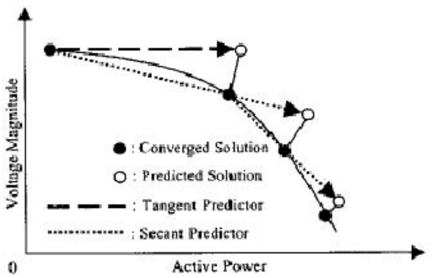

Fig.1. An illustration of the Continuation power flow

A. Power Flow Equations

The power mismatch equations at buses except generator internal buses are given by

$$\Delta P_I^p = -Pd_i^p - V_I^P \sum_{j\in i}\sum_{m=a,b,c} V_j^m (G_{ij}^{pm}\cos\theta_{ij}^{pm} + B_{ij}^{pm}\sin\theta_{ij}^{pm}) = 0 \qquad (1)$$

$$\Delta Q_i^P = -Qd_i^p - V_i^p \sum_{j\in i}\sum_{m=a,b,c} V_j^m \left(G_{ij}^{pm}\sin\theta_{ij}^{pm} - B_{ij}^{pm}\cos\theta_{ij}^{pm}\right) = 0 \qquad (2)$$

Where i = 1, 2, …, N.Pd_i^p andQd_i^p are the active and reactive load powers of phase pat bus i, respectively.$G_{ij}^{pm} + jB_{ij}^{pm}$ $(i, j = 1,2, \dots \dots \dots N)$is the element of the system admittance matrix.

The power mismatch equations at generator internal buses are presented as follows

$$\Delta Pg_i = -Pg_i - \sum_{p=a,b,c}\sum_{m=a,b,c}[V_i^p V_i^m (Gg_i^{pm}\cos\theta_i^{pm} + Bg_i^{pm}\sin\theta_i^{pm})] + \sum_{p=a,b,c}\sum_{m=a,b,c}[V_i^p E_i^p (Gg_i^{pm} \cos(\theta_i^{pm} - \delta_i^m) + Bg_i^{pm}\sin(\theta_i^{pm} - \delta_i^m))] \quad (3)$$

$$\Delta Qg_i = -Qg_i - \sum_{p=a,b,c}\sum_{m=a,b,c}[V_i^p V_i^m (Gg_i^{pm}\sin\theta_i^{pm} - Bg_i^{pm}\cos\theta_i^{pm})] + \sum_{p=a,b,c}\sum_{m=a,b,c}[V_i^p E_i^p (Gg_i^{pm} \sin(\theta_i^p - \delta_i^m) - Bg_i^{pm}\cos(\theta_i^p - \delta_i^m))] \qquad (4)$$

Where i= 1, 2, …,Ng. Ng is the number of generators. In three-phase power flow calculations, P_{gi} and Q_{gi},which are specified, are the active and reactive generation powers of the generator at bus i, respectively. $G_{ij}^{pm} + jB_{ij}^{pm}$ are the elements of the generator admittance matrix. For the case of PV machine, the reactive power constraint equation (4) can be replaced by voltage control constraint[15].

The nonlinear equations (1) – (4) can be combined and expressed in compact form

$$F(x) = 0 \qquad (5)$$

where represents the whole set of power flow mismatch and machine terminal constraint equations. is the state variable vector and given by $X=[\theta^a,V^a,\theta^b,V^b,\theta^c,V^c,\delta^a,E^a]$^t.The Newton equation is given by:

$$J(x)\Delta x = -F(x) \qquad (6)$$

Where

$F(x)=[\mathbf{\Delta P^a}, \mathbf{\Delta Q^a}, \mathbf{\Delta P^b}, \mathbf{\Delta Q^b}, \mathbf{\Delta P^c}, \mathbf{\Delta Q^c}, \mathbf{\Delta Pg^a}, \mathbf{\Delta Qg^a}]^{\mathbf{t}}$

$J(x) = \frac{\mathbf{dF(x)}}{\mathbf{dx}}$ is the system Jacobian matrix.

B. Continuation Power Flow Equations

The three phase continuation three phase power flow can be formulated based on the nonlinear power flow equations given by (5). In principle, a continuation three-phase power flow solution consists of two steps, namely Predictor Step and Corrector Step[16].

B.1. Predictor Step

To simulate three-phase load change,$\boldsymbol{Pd_i^p}$ and$\boldsymbol{Qd_i^p}$ which are shown in (1) and (2), may be represented by

$$Pd_i^p = Pd0_i^p(1+\lambda * KPd_i^p) \qquad (7)$$

$$Qd_i^p = Qd0_i^p(1+\lambda * KQd_i^p) \qquad (8)$$

Where $Pd0_i^p$ and $Q0d_i^p$ are the base case active and reactive load powers of phase p at bus i.λ is the loading factor, which characterize the change of load. The ratio of KPd_i^p / KQd_i^p is constant to maintain constant power factor.

Similarly, to simulate generation changes, P_{gi} and Q_{gi} shown in (3) and (4), are represented by:

$$Pg_i = Pg0_i(1 + \lambda * KPg_i) \qquad (9)$$

$$Qg_i = Qg0_i(1 + \lambda * KQg_i) \qquad (10)$$

Where P_g0_i and Q_g0_i are the total active and reactive powers of the generator of the base case. The ratio of KPd_i^p / KQd_i^p is constant to maintain a constant power factor for a PQ machine.

The nonlinear power flow equations (5) are augmented by an extra variable λ as follows

$$F(x, \lambda)=0 \qquad (11)$$

Where $F(x, \lambda)$ represents the whole set of power flow mismatch equations.

The predictor step is used to provide an approximate point of the next solution. A prediction of the next solution is obtained by taking an appropriately sized step in the direction tangent to the solution path. To solve (11), the continuation algorithm with predictor and corrector steps can be used. Linearizing (11), we have:

$$dF\,(x,\lambda) = F_x\, dx + F_\lambda\, d\lambda = 0 \qquad (12)$$

In order to solve (12), one more equation is needed. With choosing a non-zero magnitude for one of the tangent vector and keep its change as ± 1, one extra equation can be obtained:

$$t_k = \pm 1 \qquad (13)$$

Where t_k is a non-zero element of the tangent vector dx. A set of linearized equations can be obtained by combining (12) and (13) where the tangent vector dx and dλ are unknown variables:

$$\begin{bmatrix} F_x & F_\lambda \\ & e_k \end{bmatrix} \begin{bmatrix} dx \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \qquad (14)$$

Where e_k is a row vector with all elements zero except for k^{th} element, which equals one. In (14), whether +1 or –1 isused depends on how the k^{th} state variable is changing as the solution is being traced. After solving (14), the prediction of the next solution can be determined by:

$$\begin{bmatrix} x^* \\ \lambda^* \end{bmatrix} = \begin{bmatrix} x \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} dx \\ d\lambda \end{bmatrix} \qquad (15)$$

where * denotes the estimated solution of the next step while σis a scalar, which represents the step size.

B.2 Corrector Step

The corrector step is to solve the augmented Newton power flow equation with the predicted solution in (15) as the initial point fig, 1. In the augmented Newton power flow algorithm an extra equation is included and λ is taken as a variable. The augmented Newton power flow equation may be given by:

$$\begin{bmatrix} F(x, \lambda) \\ x_k - \eta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \qquad (16)$$

where η, which is determined by (15), is the predicted value of the continuation parameter x_k. The determination of the continuation parameter is shown in the following solution procedure. The corrector equation (16), which consists a set of augmented nonlinear equations, can be solved iteratively by Newton's approach as follows:

$$\begin{bmatrix} F_x & F_\lambda \\ & e_k \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta\lambda \end{bmatrix} = -\begin{bmatrix} F(x, \lambda) \\ x_k - \eta \end{bmatrix} \qquad (17)$$

III. PLACEMENT ALGORITHM

Different recommended locations for integration of DG forincreasing the amount of loads which can be supplied from the system through enhancing the VLL of the system are the main objective of the suggested methodology. The proposed algorithm is depicted in Fig. 2. The methodology starts with execution of CPF to specify the VLL of the base case of the system and identify the first node which reached the low voltage limit. Then the DG unit with a certain power is 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 resulted nodes according to their loads, then the VLL is checked. This process is continued until no improvement is obtained and as a result the methodology will be ended. Different steps of the proposed algorithm are summarized as follows:

Step 1: Identifying the first node reached the low voltage limit in the network using CPF.
Step 2: Integrating the DG units at that node and examine the VLL of the network.
Step 3: Running the CPF with DG.
Step 4: Identifying another node which reached the low voltage limit using CPF.
Step 5:Dispersing the DG power between the recommended nodes according to their loads.
Step 6: Running the CPF with DG.
Step 7: Examining the VLL with the existence of the different number of DG units.

Step 8: Go to step 4 if an improvement in VLL is achieved otherwise go to step 9.
Step 9: End.

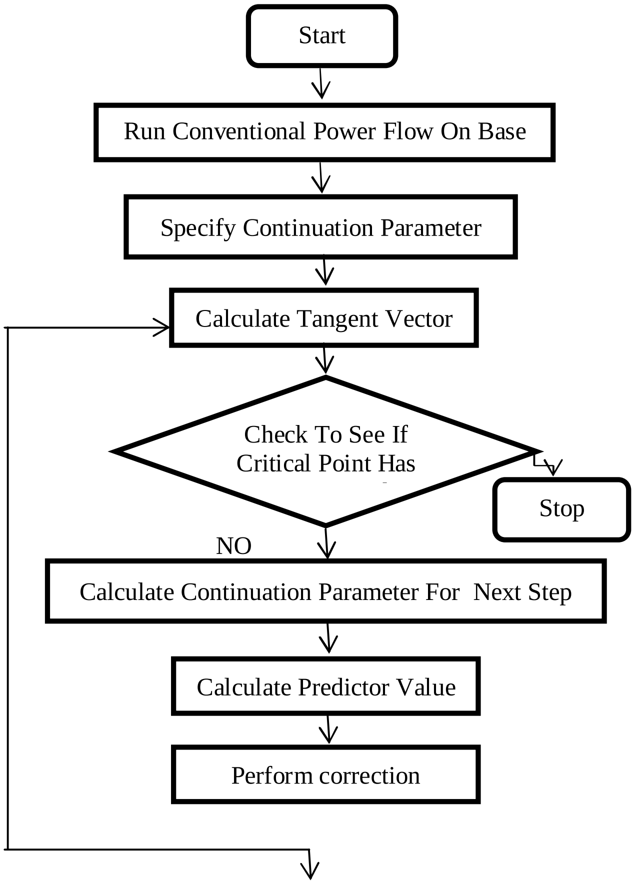

Fig. 2 Flow Chart for Continuation Power Flow

IV. SIMULATION STUDY

The placement methodology is implemented on an 85 node radial distribution network[8](seeFig. 2). The data of thesystem is giveninTable. I. The system was built into PSAT and as a first step the CPF is executed where the limitwas identified to be the low voltage limit. That means theloading parameter (λ) will be increased at all nodes with the same value till the voltage at one node reaches the minimum voltage limit. The VLL can be specified based onthe value of k which has been found in this step to be 1.1515 which means that the load at each node can be increased to be 115.2% of its base case whiles the voltage at all nodes are within the limits. Node no. 54 was found to be the first node reached the low voltage limit. According to the methodology all the DG units (6 X240 kW) are integrated at this node. With integration of the DG units at node no. 54 the CPF is executed for the second time till the voltage at another node reaches the low minimum value.The loading factor (λ) in this step was found to be 1.8229, which means that the VLL is 3.3 MW[15]. Moreover, it has

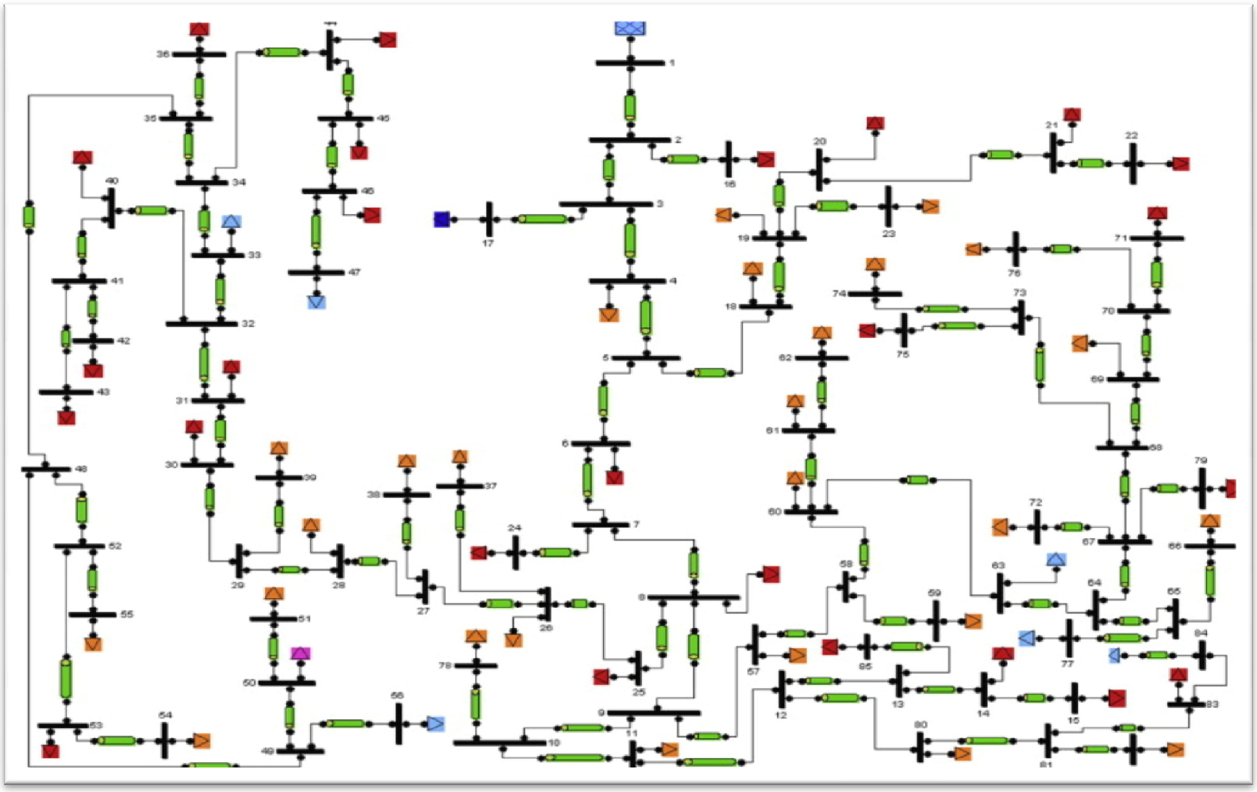

Fig. 3. One line diagram of 85 node distribution network in PSAT Space

Been found that node no. 76 is the node which reaches the minimum voltage limit.Then according to the procedure of the algorithm the DG power were dispersed between nodes No. 54 and 76. That means at each node three DG units were integrated.Then, with the existence of the DG units at nodes No. 54, and 76 the CPF is executed for the third time. In this case the VLL is improved to be 3.68MW with a maximum loading factor of 2.0419. Through this step node No. 47 was the node which first reached the low voltage limit. Therefore, the six DG units were dispersed at the three nodes 54, 76, and 47 with two DG units at each node. The network with presence of the DG units at the three nodes is tested with CPF and in this step the VLL was 3.8MW with a maximum loading factor of 2.1093.

The loading factor (k) in this step was found to be 1.8229, which means that the VLL is 3.3 MW.

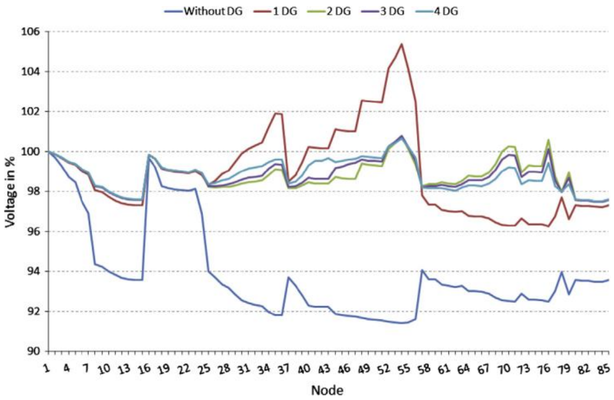

Fig. 4.VoltageProfileswith (0.9 Power Factor)For DifferentDGUnits

Then according to the procedure of the algorithm the DG power were dispersed between nodes No. 54 and 76. (Fig.4)That means at each node three DG units were integrated. Then, with the existence of the DG units at nodes No. 54, and 76 the CPF is executed for the third time. In this case the VLL is improved to be

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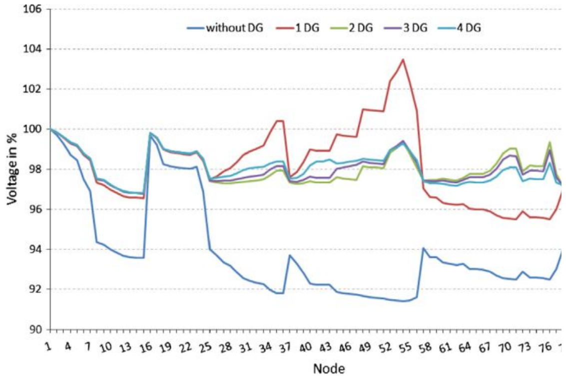

Fig. 5. VoltageProfileswith(UnityPowerFactor)ForDifferentDGUnits'Number.

Moreover, it has been found that node no. 76 is the node which reaches the minimum voltage limit [13] (see fig 3). Therefore, the six DG units were dispersed at the three nodes 54, 76, and 47 with two DG units at each node.The network with presence of the DG units at the three nodes is tested with CPF and in this step the VLL was 3.8MW with a maximum loading factor of 2.1093.The improvement in percentage is calculated relative to the base case. It can be demonstrated that VLL is improved when the DG power is dispersed between the resulted nodes (Fig.5). A 515 kW is the difference in VLL of the system between integrating two units at each node of the three resulted nodes and integrating the six units at one node. This means that the network can be loaded by 15.7% more than the case of concentrated DG units at node No. 54 (Fig.6) while the voltages are kept within the limits.

TABLE I
LINE AND LOAD DATA OF 85 BUS SYSTEM

Line No	Send. Node	Rece. Node	R (Ω)	X (Ω)	P (MVA)
1	1	2	0.108	0.075	0
2	2	3	0.163	0.112	0
3	3	4	0.217	0.149	56
4	4	5	0.108	0.074	0
5	5	6	0.435	0.298	0
6	6	7	0.272	0.186	0
7	7	8	1.197	0.82	35.28
8	8	9	0.108	0.074	0
9	9	10	0.598	0.41	0
10	10	11	0.544	0.373	56
11	11	12	0.544	0.373	0
12	12	13	0.598	0.41	0
13	13	14	0.272	0.186	35.28
14	14	15	0.326	0.223	35.28
15	2	16	0.728	0.302	35.28
16	3	17	0.455	0.189	112
17	5	18	0.82	0.34	56
18	18	19	0.637	0.264	56
19	19	20	0.455	0.189	35.28
20	20	21	0.819	0.34	35.28
21	2	22	1.548	0.642	35.28
22	19	23	0.182	0.075	56
23	7	24	0.91	0.378	35.28
24	8	25	0.455	0.189	35.28
25	25	26	0.364	0.151	56
26	26	27	0.546	0.226	0
27	27	28	0.273	0.113	56
28	28	29	0.546	0.226	0
29	29	30	0.546	0.226	35.28
30	30	31	0.273	0.113	35.28
21	2	22	1.548	0.642	35.28
22	19	23	0.182	0.075	56
23	7	24	0.91	0.378	35.28
24	8	25	0.455	0.189	35.28
25	25	26	0.364	0.151	56
26	26	27	0.546	0.226	0
27	27	28	0.273	0.113	56
28	28	29	0.546	0.226	0
29	29	30	0.546	0.226	35.28
30	30	31	0.273	0.113	35.28
32	32	33	0.182	0.075	14
33	33	34	0.819	0.34	0
34	34	35	0.637	0.264	0
35	35	36	0.182	0.075	35.28
40	40	41	1.002	0.416	0
41	41	42	0.273	0.113	35.28
42	41	43	0.455	0.189	35.28
43	34	44	1.002	0.416	35.28
44	44	45	0.911	0.378	35.28
45	45	46	0.911	0.378	35.28
46	46	47	0.546	0.226	14

47	35	48	0.637	0.264	0
48	48	49	0.182	0.075	0
49	49	50	0.364	0.151	36.28
50	50	51	0.455	0.189	56
51	48	52	1.366	0.567	0
52	52	53	0.455	0.189	35.28
53	53	54	0.546	0.226	56
54	52	55	0.546	0.226	56
55	49	56	0.546	0.226	14
56	9	57	0.273	0.113	56
57	57	58	0.819	0.34	0
58	58	59	0.182	0.075	56
59	58	60	0.546	0.226	56
60	60	61	0.728	0.302	56
61	61	62	1.002	0.415	56
62	60	63	0.182	0.075	14
63	63	64	0.728	0.302	0
64	64	65	0.182	0.075	0
65	65	66	0.182	0.075	56
66	64	67	0.455	0.189	0
67	67	68	0.91	0.378	0
68	68	69	1.092	0.453	56
69	69	70	0.455	0.189	0
70	70	71	0.546	0.226	35.28
71	67	72	0.182	0.075	56
72	68	73	1.184	0.491	0
73	73	74	0.273	0.113	56
74	73	75	1.002	0.416	35.28
75	70	76	0.546	0.226	56
76	65	77	0.091	0.037	14
77	10	78	0.637	0.264	56
78	67	79	0.546	0.226	35.28
79	12	80	0.728	0.302	56
80	80	81	0.364	0.151	0
81	81	82	0.091	0.037	56
82	81	83	1.092	0.453	35.28
83	83	84	1.002	0.34	14
84	13	85	0.819	0.34	35.28

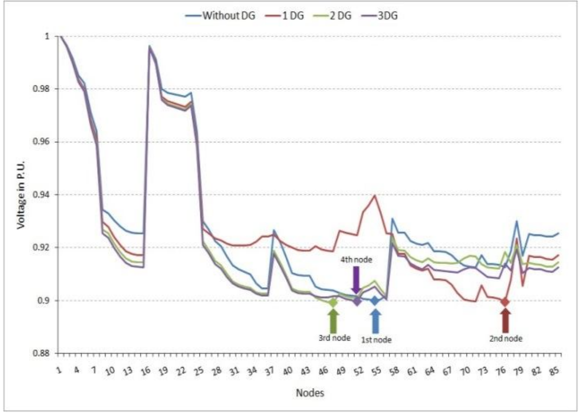

Fig.6.Voltage Profiles of DG Units at the End of Different Iterations

V. CONCLUSION

Aboveallresultsshowsthatvoltagestabilitymargincan befoundeasilybyCPF.The Weakestbus identificationis done bywithoutexcessivecalculation.Placementof distributed generationpowersourceswe get the following conclusions.

Dispersing the same amount of the DG power at different nodes of the network enhances the VLL of the network more than concentrating this power at one node.

More loads can be supplied with lower dispersed power of the DG when it compared with higher concentrated DG power.

Dispersing the same power of the DG does not approximately affect the VSLL of the network when it compared with integration of the same DG power at the weakest node.

Integrating the DGs at the recommended nodes helps to get more decreasing of the active and reactive power losses.

This result is same accurate as to find Bus participation act or using QVmodal analysis.This CPF method is more accurate and simple for Voltage stability analysis.

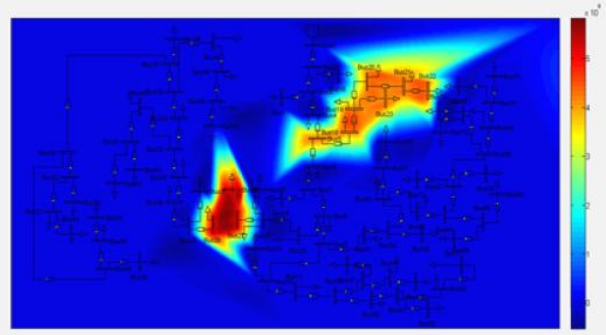

Fig. 7. Voltage Magnitude ofthe 85 Node Distribution Network From PSAT Space

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