Optimal Placement based on Distributed Generation to Improvement of Voltage Stability in Multi-Phase Distribution Systems

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Abstract–Improving voltage stability is one of the most critical issues in evaluating the performance of power systems. Whereas the use of distributed generation resources in distribution networks plays an important role, the optimal sitting and sizing of these units are vital for improving voltage stability and reducing losses. Distribution systems are known to be substantially unbalanced, so a three-phase power flow is required as an efficient tool for unbalanced network analysis. This paper presents a new voltage stability index with simple updating that can update just by active and reactive power demand in each iteration of power flow. Also, in order to find the optimal siting and sizing of distributed generation units (DGs), the voltage stability is analyzed by considering the Imperialist Competition Algorithm (ICA). The obtained results show the improvement of voltage profile and voltage stability as well as the reduction of total losses in the IEEE 34 bus multi-phase distribution system.

Keywords: Voltage stability, Backward/forward load flow, Imperialist competition algorithm, Distributed generation, Multi-phase distribution systems.

1. Introduction

The electrical distribution system (EDS) will soon face the penetration level of distributed generation units. This can be assessed due to several important factors such as environmental issues, the development of new technologies such as fuel cells and photovoltaic (PV) systems, and other alternative energy sources. The advantages of DG installation include reducing losses, improving voltage profile, increasing total energy efficiency, improving power quality, improving reliability and security in the network. In order to achieve the mentioned advantages, the sizing and siting of DGs are investigated by various methods such as analytical analysis [1-2], heuristic [3-5], artificial intelligence and genetic algorithm (GA) methods [6-7]. These resources at high penetration levels may have many adverse effects on the power system, especially in distribution networks [8].Over-Voltage [9], reverse power flow [10], and voltage unbalance [11] can be listed as some of the important effects mentioned.

Recently, most electrical power systems operate in conditions very close to their stability limits, and as a result, this has led to greater sensitivity to maintaining power quality and security at related levels [12].The ultimate goal in the operation of an electrical system is to supply energy with a voltage and frequency acceptable to customers at the lowest cost. Therefore, it is vital to know an accurate knowledge of how the operating points of the current system work for voltage instability constraints as an important issue in the performance of the whole system in the face of a disturbance.

The concept of voltage stability in a power system is maintaining a stable voltage in all buses, which depends on the ability to maintain a balance between consumer demand and generation and its transmission losses through the power system. Among the very important factors in the phenomenon of voltage instability, can be the sudden loss and absorption of load in an area, the departure of lines and some instruments of the system by protection relays, and the lack of synchronism of some generators due to their excitation current limit [13].

Many methods and techniques have been reported for

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voltage stability analysis and voltage collapse prediction. Some of these methods include analysis based on P-V and P-Q curves, modal analysis, eigenvalue analysis, sensitivity analysis method, energy function, and continuous power flow [14]. In addition, some methods of static voltage stability analysis have been extended to identify the weakest buses in the network by determining the indicators such as L-index, voltage collapse prediction index, voltage stability index (VSI), and improved VSI. Moreover, some researchers have republished line indices such as fast VSI (FVSI), line stability index (L_{mn}), voltage collapse proximity index (VCPI), and line voltage factor (LQP) to identify critical lines in power systems [14].

Load flow analysis is the most important issue in power system design, control and operational studies [15]. New algorithms have been developed based on many optimization methods for evaluating engineers and operators in all aspects related to the performance of planning in distribution systems. These algorithms include methods such as Newton-Raphson [16-17], the fast decuple method [17], the hybrid method [18], methods based on bus admittance [19] and methods based on analysis in networks with a radial structure such as sweep backward/forward methods [12]. It is well known that most DSs are significantly unbalanced. Hence, three-phase load flow is generally used as a suitable tool for load unbalance analysis in distribution networks. The backward/forward sweeping (FBS) method with high convergence speed in conventional distribution systems has been considered by many researchers due to its very convenient implementation and very simple application of its equations.

In this paper, the application of voltage stability constraint is investigated by presenting a new formula for finding critical lines leading to critical buses against voltage collapse, in the algorithm for finding the optimal sizing and location of DGs in a distribution network.The method of optimization of the ICA using backward/forward load flow in radial distribution systems by identifying the most critical lines leading to buses that are subject to voltage collapse is stated. This algorithm is tested on a standard multi-phase 34-bus IEEE system and the results are satisfactory. The term multi-phase is referred to here as the asymmetric distribution network with three single-phase, two-phase, and three-phase arrangement branches.

2. Backward/Forward Sweep Power Flow Analysis

In radial distribution systems, the use of conventional load flow methods such as Newton-Raphson and Gauss-Seidel cannot be effectively accurate due to the nature of the radial structure of the networks and the high R/X ratio of the lines [20]. Therefore, a proposed method with a backward/forward sweep load flow technique in order to analyze quickly is presented in this paper.

2.1 Backward Sweep Propagation

During the backward sweep, the current of each branch in each section is calculated assuming the initial nominal values of the voltage in each node (according to the known power consumption in each node). In this case, the voltage values are kept constant and the current of each line leading to each bus is calculated using (1) during the backward process until the beginning of the feeder in the *k* iteration.

$$\begin{bmatrix} I_i^a \\ I_i^b \\ I_i^c \end{bmatrix}^k = \begin{bmatrix} \left(S_i^a / V_i^a\right)^* \\ \left(S_i^b / V_i^b\right)^* \\ \left(S_i^c / V_i^c\right)^* \end{bmatrix}^{(k-1)} \tag{1}$$

Where I_i^a, I_i^b, I_i^c are the injection currents to phases *a*, *b* and *c* at node *i*. S_i^a, S_i^b, S_i^c are the sum of the powers of the loads connected to the bus *i* and all loads plus line losses thereafter, and V_i^a, V_i^b, V_i^c are the phase voltages at node *i*.

2.2 Forward Sweep Propagation

In this stage, the goal is to find the voltage of each node from the beginning of the feeder, which is kept constant at a certain value until the end of the network. The calculated current values are kept constant from the previous state and the bus voltages according to (2) are obtained during the forward sweep.

$$\begin{bmatrix} V_i^a \\ V_i^b \\ V_i^c \end{bmatrix}^k = \begin{bmatrix} V_j^a \\ V_j^b \\ V_j^c \end{bmatrix}^{(k-1)} - \begin{bmatrix} z^{aa} & z^{ab} & z^{ac} \\ z^{ba} & z^{bb} & z^{bc} \\ z^{ca} & z^{cb} & z^{cc} \end{bmatrix} \begin{bmatrix} I_i^a \\ I_i^b \\ I_i^c \end{bmatrix}^k \tag{2}$$

Where V_j^a, V_j^b, V_j^c are the voltage values of node *j*.

2.3 Convergence Criteria

This proposed method will be continued until the power deviation in each node reach to acceptable values. When the load flow is converged, the values of voltage in each node and consequently the amount of active and reactive power consumption and losses in each part of the network will be calculated.

$$\begin{bmatrix} \Delta S_i^a \\ \Delta S_i^b \\ \Delta S_i^c \end{bmatrix}^k = \begin{bmatrix} V_i^a \left(I_i^a\right)^* - S_i^a \\ V_i^b \left(I_i^b\right)^* - S_i^b \\ V_i^c \left(I_i^c\right)^* - S_i^c \end{bmatrix}^k \quad (3)$$

3. Formulation of Voltage Stability Index Considering DG

Although voltage instability analysis is a dynamic problem in power systems, in order to estimate the stability limit from the nose point of the P-V curve, the use of static analysis is also acceptable in the system [21]. Using the simplified load flow equation in (4) and converting it into two real and imaginary parts in the presence of DG, those are arranged according to the angle difference between the power sending bus and power receiver bus ($\delta = \delta_j - \delta_i$).

$$\vec{V}_i = \vec{V}_j - \vec{Z}_s * \vec{I}_i \quad (4)$$

$$V_i V_j \cos(\delta) = |V_i|^2 + \left[R_s\left(P_i - P_{DG}\right) + X_s Q_i\right] \quad (5)$$

$$V_i V_j \sin(\delta) = \left[X_s\left(P_i - P_{DG}\right) - R_s Q_i\right] \quad (6)$$

Next, the angle of δ is eliminated from the two relations.

$$\begin{aligned} &|V_i|^4 + \left\{2\left[R(P_i - P_{DG}) + XQ_i\right] - |V_j|^2\right\}|V_i|^2 \\ &+ \left\{(R^2 + X^2)\left[(P_i - P_{DG})^2 + Q_i^2\right]\right\} = 0 \end{aligned} \quad (7)$$

So,

$$|V_i|^2 = \frac{\left\{|V_j|^2 - 2\left[R(P_i - P_{DG}) + XQ_i\right]\right\} \pm \sqrt{\Delta}}{2} \quad (8)$$

$$\begin{aligned} \Delta = &\left\{2\left[R(P_i - P_{DG}) + XQ_i\right] - |V_j|^2\right\}^2 \\ &- 4\left\{(R^2 + X^2)\left[(P_i - P_{DG})^2 + Q_i^2\right]\right\} \end{aligned} \quad (9)$$

To have the desired response for voltages in the receiver bus, must have $\Delta \geq 0$.

$$\left\{|V_j|^2 - 2\left[R(P_i - P_{DG}) + XQ_i\right]\right\}^2 \geq 4\left\{(R^2 + X^2)\left[(P_i - P_{DG})^2 + Q_i^2\right]\right\} \quad (10)$$

It can be seen by doing some mathematical relations and displacements,

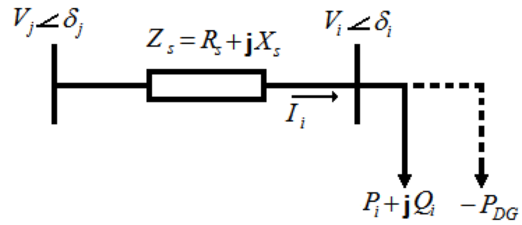


Fig. 1. The Schematic of two-bus system considering DG

$$L_k = \frac{2\sqrt{\left\{(R^2 + X^2)\left[(P_i - P_{DG})^2 + Q_i^2\right]\right\}}}{\left||V_j|^2 - 2\left\{R(P_i - P_{DG}) + XQ_i\right\}\right|} \leq 1 \quad (11)$$

Where L_k is defined as the voltage stability index to determine the weakest lines leading to the critical buses. The voltage collapse will occur in each bus when the value of this indicator reaches one. The lower value of this index represents that the bus is far from the voltage instability. This index is easily updated by changing the power demands which are calculated by power flow algorithm. Also, it can be used for online estimation of closeness to voltage collapse.

4. DG Siting and Sizing Algorithm

In order to achieve the maximum benefits of using distributed generation units, the optimal sizing and the best location of DGs in a distribution network will be vital. The proposed algorithm below is programmed in the MATLAB environment.

4.1Optimal SitingMethod for DGs

In order to appropriate the location of the distributed generation units, an iterative computational method is presented. First, the voltage stability index (L_k) is calculated to find the most critical buses to the voltage collapse and then the optimum size of DG using the proposed algorithm in the next section will be estimated. In each iteration, the voltage stability index is updated based on located DG. The bus connected to the DG with the lowest L_k obtained in iterations will be the optimal installation location for the DGs.

4.2 Optimal Sizing Method for DGs

The proposed objective function in this research is to optimize the DG size by simultaneously minimizing the total power loss (TPL) and the minimum size of the L_k index per repetition (improvement in voltage stability) using the ICA.

$$f = Min\left\{\left(TPL = \sum_{i=1}^{b} |I_i|^2 \cdot R_i\right) + Max \quad of(L_k)\right\} \tag{12}$$

It is subjected to,

$$\begin{cases} 0 \le P_{DG} \le \sum_{i=1}^{n} P_{load,\ i} \\ V_{i,\ \min} \le V_i \le V_{i,\ \max},\quad i = 1,2,...,n \end{cases} \tag{13}$$

Where b is the number of lines in each section, n is the number of buses, P_{DG} is the power injected by the distributed generation unit, P_{load} is a load of each node and the acceptable voltage range in each node is between $0.9pu$ and $1.05pu$.

5. Imperial Competition Algorithm [22]

The imperial competition algorithm is one of the optimization methods that is inspired by political competition. Like other evolutionary algorithms, this algorithm starts with a number of random primary populations, each of which is called a country. Some of the best countries are chosen as imperialists and the rest of the population is considered as colonies. The colonizers, depending on their power, which is inversely proportional to their cost, draw these colonies in a certain process. This move models the policy of absorption [22].

5.1 Formation of Early Empires

In optimization problems, an array of problem variables to be optimized, called a country, is used to find an optimal solution in terms of problem variables. In an $N\text{var}$ -dimensional optimization problem, a country has an array of lengths $N\text{var}*1$.

$$Country = [p_1, \quad p_2, \quad ..., \quad p_{N\text{var}}] \tag{14}$$

To start the algorithm, N number of countries will create as the initial, and $Nimp$ number from the best members of this population (countries with the least amount of cost function) will be selected as imperialists. The rest of the countries are colonies, each belonging to an empire.

5.2Movement of the Colonies towards the Imperialist (Assimilation)

The policy of assimilation or absorption is aimed at analyzing the culture and social structure of the colonies in the culture of the central government. Figure (1) shows the movement of a colony toward the emperor. In line with this policy, the colony is moved by x units in the direction of the line connecting the colony to the imperialist and is moved to a new position. In this motion, x and θ are arbitrary numbers with a uniform distribution, and d is the distance between the emperor and the colony.

$$x \approx U(0, \beta \times d) \tag{15}$$

Where β is a number greater than one and close to 2.

As the colonies move toward the colonial state, some of these colonies may find themselves in a better position than the imperialists. In this case, the colonial country and the colonial country have changed places with each other and the algorithm has continued with the colonial country in a new position. So, it is the new imperialist country that begins to apply the policy of assimilation to its colonies [22-23].

5.3 Revolution Strategy

The revolution is modeled by the random movement of a colonial country to a new random position in the imperialistic competition algorithm. The revolution is the factor that saves the whole evolutionary movement from getting stuck or stopping in optimal local valleys.

5.4 Fall of Weak Empires

The power of an empire is defined as the power of the colonial country plus a percentage of the total power of its colonies. Over time, weak empires lose their colonies, and stronger empires take over these colonies and increase their power. Then, the condition of stopping the algorithm is checked and if this condition is not met, the algorithm goes to the next iteration. Thus, in repeating the algorithm for the capture of these colonies, competition is created between all empires [22-23].

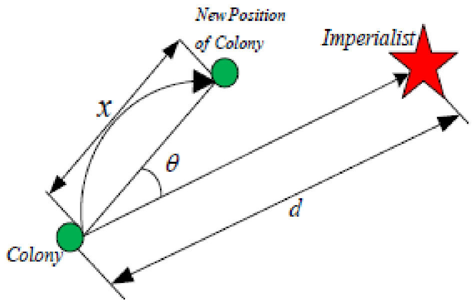


Fig. 2. The movement of the colony towards the Imperialist

6. Simulation and Results

The proposed method test on multi-phase IEEE 34 bus to improve the voltage stability and also find the size and optimal location of the distributed generation unit using the MATLAB programming environment. This case study is 16.9 kV with a total concentrated load of 1047 kW, 677 kVAr and distributed loads of 722 kW, 367 kVAr, and 2 voltage regulators and a capacitor bank that are shown in Figure 3 [24]. Figure 4 shows the total active and reactive power losses in the system for different optimized states for three-phase DG sizing at more critical nodes. Table 1 also shows the optimal DG size. Although the installation of DG in node 16 will have the lowest capacity, the installation of DG at node 13 results in lower power losses and improved voltage stability,

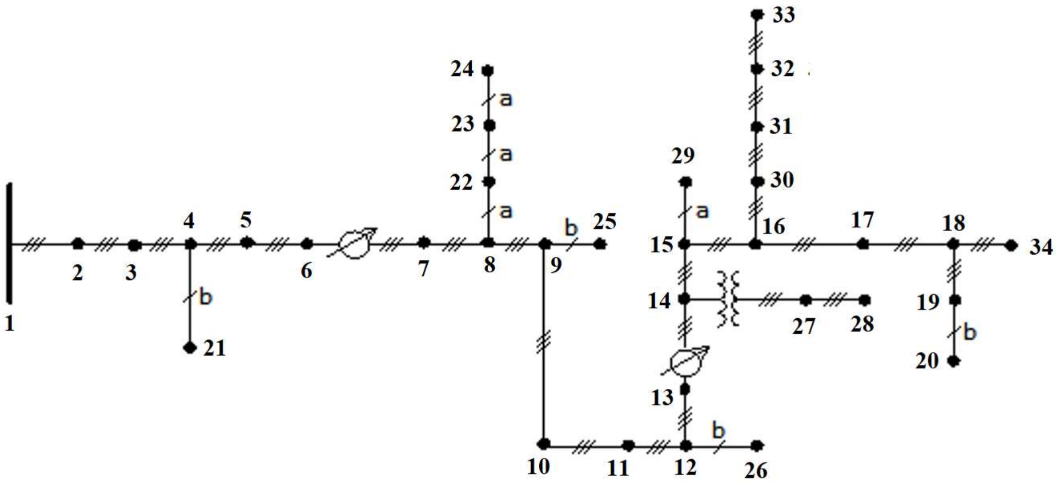


Fig. 3. The schematic diagram of IEEE-34 bus multi-phase distribution system

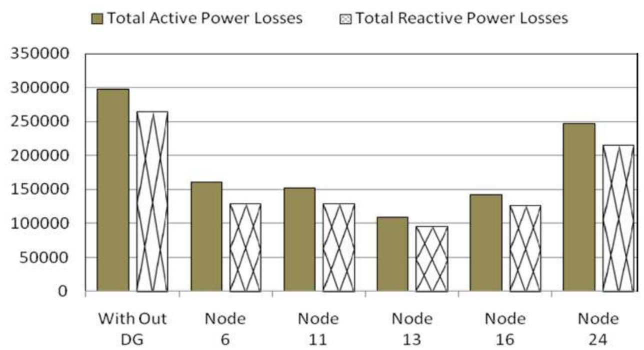
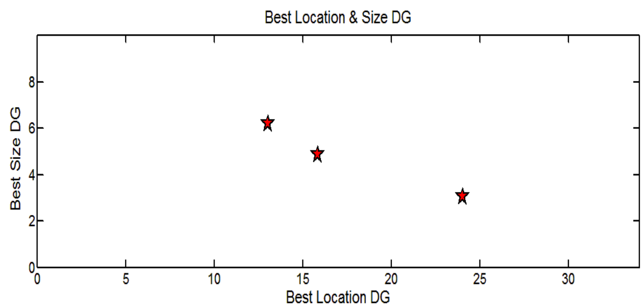


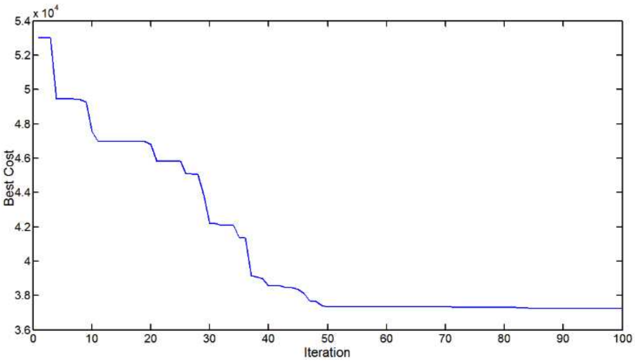
Fig. 4. Total active and reactive power losses with optimum sizing of DG for five critical buses

Table 1. The optimal DG siting and sizing for five cases

DG Size (W)	DG location (bus)	Total active power loss (KW)	Total reactive power loss (KW)
--	Without DG	298.272	246.605
912604	6	160.683	129.384
622888	11	152.906	130.020
622087	13	109.568	96.636
449060	16	142.190	126.517
307288	24	247.396	215.708



(a)

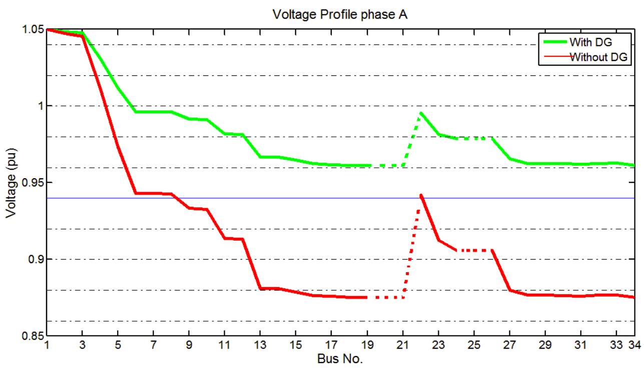


(b)

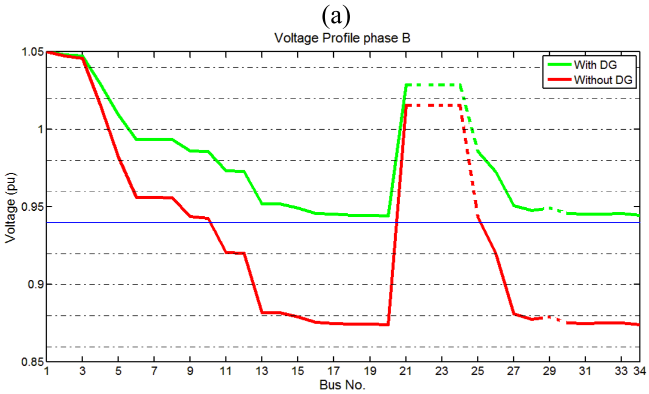
Fig. 5. Optimal results obtained by ICA

The optimization results for three critical buses calculated by the ICA method and the convergence of the algorithm after 100 iterations are illustrated in Fig.5.

Figure 6 shows the voltage profile of all 3 phases without installing DG and with optimum DG calculated at the critical bus 13. As can be seen, the optimal placement of the DG with a size of 622,888 kW has improved the voltage profile. It can also be seen that the voltagelevel range in all phases has improved from approximately 0.86 p.u. to approximately 0.93 p.u. to 0.96 p.u. The dotted lines indicate the non-connection of the corresponding phase in those nodes.



(a)



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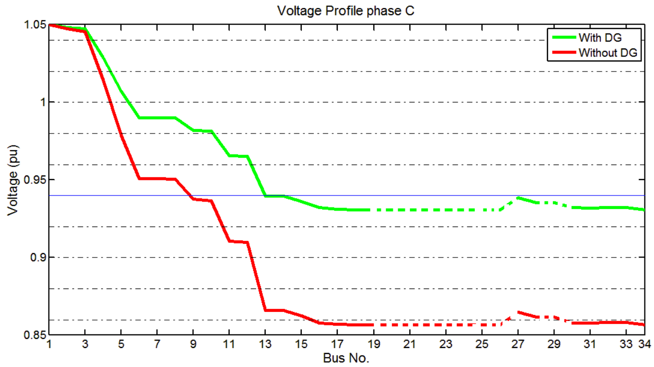

(c)

Fig. 6. The voltage profiles with and without optimal DG, (a) Phase A, (b) Phase B, and (c) Phase C

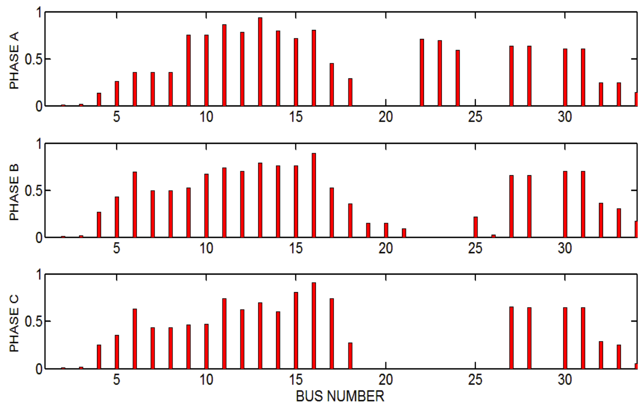

Fig. 7. The voltage stability index values without DG installation

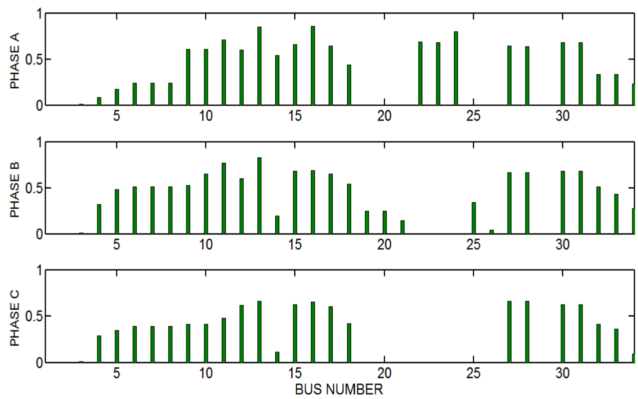

Fig. 8. The voltage stability index values with optimal DG installation (bus 13).

Figures 7 and 8 show the values of the voltage stability index without DG installation and with its optimal installation in critical node 13. It is observed that some buses do have not any branch connected to which the value of indicators is zero. It illustrates that no need to calculate for voltage stability index for these buses. It is shown that boss of the voltage stability index and the total power loss are improved. Although the choice of other DG capacities may lead to a further reduction in power losses, it will require a larger size and consequently a higher cost, and especially a lack of proper improvement in the voltage stability index.

5. Conclusion

In this paper, an acceptable method for improving the voltage stability index and power loss reduction is presented by determining the optimal sizing and location of the DG. In this study, using the Imperial competition algorithm (ICA), due to the high speed and low repetition in the power flow program, it is shown that this approach is practical for online analysis of real distribution systems. Results provided by simulation on the standard multi-phase 34-bus IEEE network show that it is vital to consider the voltage stability analysis in order to achieve the desired responses to reduce power losses in the distribution systems with the presence of distributed generation units.

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