Voltage Index Method for Optimal Allocation of DG Units in a Distribution system to improve the Voltage Stability Margin

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Abstract-***Integration of renewable energy based distributed generation (DG) units provides potential benefits to conventional distribution systems. The power injections from renewable DG units located close to the load center's provide an opportunity for system voltage support, reduction in energy losses, and reliability improvement. Therefore, the location of DG units should be carefully determined with the consideration of different planning incentives. DG units can have their impacts on the voltage stability margins .However voltage stability plays very important role in the planning and operation of power system. Optimization techniques are used to locate and size of the DG units in the system. In this paper a modified voltage index method is proposed to locate and size the DG units so as to improve the voltage stability margin. In this study the probabilistic nature of both load and renewable DG generation are considered. The proposed method starts by selecting the candidate buses which are sensitive to voltage profile for the installation of DG units. Here the constraints are the system voltage limits, Feeders capacity, and the DG penetration level.***

Keywords: Distributed generation, distribution system, Load flow, Optimal locations,Optimal sizes, Voltage index method.

I. INTRODUCTION

Distributed power generation (DG) is electricity production that is on-site and refers to small generating units installed near local loads or load centers to avoid the need of the network expansions in order to cover new load areas or to support the increased energy transfer which would be necessary for satisfying consumers demand. DG can be an alternative for residential, commercial, and industrial applications. However, distributed generation can be defined in a variety of ways as reported in the literature.

The Electric Power Research Institute (EPRI) defines distributed generation as generation from 'a few kilowatts up to 50 MW[1]. International Energy Agency (IEA) defines distributed generation as generating plant serving a customer on-site or providing support to a distribution network, connected to the grid at distributed level voltages. The International Conference on large High Voltage Electric Systems (CIGRE) defines DG as smaller than 50–100 MW [1].

The share of DGs in power system is increasing worldwide and their contribution in the future power system is expected to beeven more [2]. There are many reasons behind the increasingly widespread use of DG deferring the Transmission and Distribution(T&D) costs, good efficiencies especially in cogeneration and in combined cycles, creating opportunities for new utilities in the power generation sector, and provides a flexible way to choose a wide range of combinations of cost and reliability. DG impacts different parameters of a power system, comprising voltage profile, line losses, and short circuit current, amount of injected harmonic, and system reliability and stability. The parameters have to be appropriately investigated prior to installation of DG units.

The problem of allocating DG units to optimal places and also their sizing is of higher priority amongst all issues. However, installation ofDG units in non-optimal places may results in an increase in system losses and a bad effect on voltage profile and other parameters which may lead to a growth of costs, and consequently an opposite effect on what is expected. Therefore, DG should be allocated in anoptimal way to maximize the system efficiency. Many authors have proposed sensitivity based approaches and optimization based methods for optimal location and sizing of DGs in distribution systems.The impact of DG on radial distribution network is explainedi.e., voltage support, loss reduction, and distribution capacity release and power quality issues in [3].

Two new approaches based on sensitivity of real and reactive power losses with respect to size and operating point of DG has been proposed to determine the most suitable DG size and location towards minimizing power losses in the distribution systems. Integrating DG units can have an impact on the practices used in distribution systems, such as the voltage profile, power flow, power quality, stability, reliability, and protection. Since DG units have a small capacity compared to central power plants, the impacts are minor if the penetration level is low (1%–5%). However, if the penetration level of DG units increases to the anticipated level of 20%–30%, the impact of DG units will be profound [4].This paper presents a method for placement of DG units in distribution networks. This method is based on the analysis of power-flow continuation and determination of most sensitive buses to the voltage collapse . After that, the DG units with certain capacity will be installed in these buses via an objective function and an iterative algorithm. In this algorithm, continuation voltage collapse point or maximum loading, however; it is needed to investigate the impact of DG technologies on static voltage stability and analysis tools for studying of voltage stability. This method will be executed on a typical 41-bus test system.The DG units allocation and sizing is based on minimizing the overall cost.

Hemdan and Kurrat [5] recommended considering the voltage stability as an objective function when dealing with optimum location of DG units. Recently, the work in [6] and [7] proposed methods to locate distributed generation units to improve the voltage profile and voltage stability of a distribution system. H.Hedayati et al in [6] placed DG units at the buses most sensitive to voltage profile, and resulted in improvement in voltage stability margin, as well as decrease in the power losses. M.Alonso and H.Amaris in [7] developed the work in [6] to maximize the loadability conditions in normal and contingency situations.The problem of voltage stability is tackled by assuming that all the DG units are dispatchable. However, this paper introduces the probabilistic nature of both the renewable energyresources and the load demand as vital factors to be considered for improving the voltage stability. Therefore, this paper will tackle placing and sizing of the DG units to improve the voltage stability margin and consider the probabilistic nature of therenewable energy resources and the load. In fact, placing and sizing DG units with an objective of improving the voltage stability margin while considering renewable DG generation and load probability might be a complicated problem due tothe complexity of running continuous load flow and at the same time considering the probabilistic nature of the load and the DG unit's resources. Therefore, this paper proposes a modified voltage index method to locate and size the DG units so as to improve the voltage stability margin. With conditions of both not exceeding the buses voltage, and staying within the feeder current limits. The probability of the load and DG units are modeled and included in the formulation of the sizing and placing of the DG units. The remainder of this paper is arranged as follows. Section II represents the DG units impact on voltage stability, Section III carries out selection of the candidate buses for DG units installation, Section IV formulates a method to locate and size the DG units, Section V describesthe system which is under study, and Sections VI and VII demonstrates the results and conclusion, respectively.

II. IMPACT OF DG TECHNOLOGIES ON VOLTAGE STABILITY

Reliable assessment of voltage stability of an electric power system is essential for its operation and control. To accommodate the need for accurate analysis of voltage stabilitya number of analytical and computational tools have been developed. Typically, two voltage stability problems are analysed: 1) determination of the maximum loading problem; 2) computation of the critical loading of the power system. In the former case, a loading scenario is assumed and the maximum power transfer to the load buses is computed. In the latter case, a minimum system loading is sought that would render the power system voltage unstable, i.e., the loading that would cause voltage collapse. Such a loading is referred to as critical loading of the system.

Voltage collapse is an instability of heavily loaded electric power systems which leads to declining voltages and blackout. It is associated with bifurcation and reactive power limitations of the power system. Power systems are expected to become more heavily loaded in the future decade as the demand for electric power rises while economic and environmental concerns limit the construction of new transmission and generation capacity. Heavily loaded power systems are closer to their stability limits and voltage collapse blackouts will occur if suitable monitoring and control measures are not taken. It is important to understand mechanisms of voltage collapse so that voltage collapse blackouts may be effectively prevented. Most of the current approaches to analyzing voltage collapse are presented in [8]. Several types of stability problems in power systems can be explained using bifurcation theory. Bifurcation points can be defined as equilibrium points where changes in the "quantity" and/or "quality" of the equilibria associated with a nonlinear set of dynamic equations occur with respond to slow varying parameters in the system.

Conventional synchronous generators are capable of both generating and absorbing reactive power. Therefore, the use of DGs utilizing overexcited synchronous generators will allow on-site production of reactive power. The local generation of reactive power reduces its import from the feeder, thus reduces the associated losses, and improves the voltage profile. Asa result, the voltage security is also improved. *P-V* curves have been traditionally used as graphical tools for studying voltage stability in electric power systems. Fig. 1 conceptually shows the impact of a synchronous generator on voltage stability of a hypothetical node. As can be seen in the figure, the installation of a DG unit ΔP MW moves the operation point from point A to point B on the associated P-V curve, which results in an increase of the node voltage by the amount $V_{DG} - V_0$ and enhancement in voltage security: the stability margin increases from$m_0 to m_{DG}$. The overall impact of a DG unit on voltage stability is positive. This is due to the improved voltage profiles as well as decreased reactive power losses, as the following equation suggests:

$$Q_{Loss} = \frac{(P_{Load}-P_{DG})^2+(Q_{Load}-Q_{DG})^2}{V^2} X_{line} \quad (1)$$

Where,P_{Load}, P_{DG}, Q_{Load}, Q_{DG} are the active and reactive powers of the load and DG, respectively, andX_{line} is the aggregate reactance of the line connecting the load to the feedingsubstation. Note that for simplicity, the resistance of the line is neglected. Clearly, as the active power injected by distributed generator increases, the reactive power loss decreases. Thus, ithas a positive impact on the voltage stability.

The penetration of the DG units in a distribution system can increase or decrease the voltage stability margindepending on their operation at unity, lead or lag power factors. Currently most of the installed DGs are commonly connected to operate at unity power factor to avoid interference with the voltage regulation devices connected to the system . For this reason, this study assumes that all of the DG units are operating at unity power factor. In addition, some utilities allow the DG units to operate in fixed power fact or mode ranging from 0.95 lagging to 0.95 leading, a case study representing this condition is also considered.

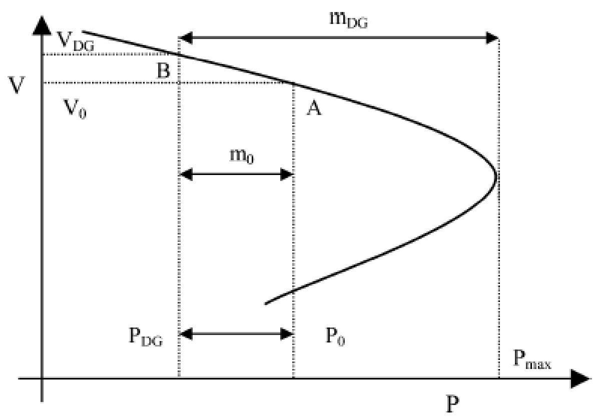

Fig.1. P-V Curve enlargement of voltage stability margin

III. SELECTION OF THE CANDIDATE BUSES

In this literature the proposed method starts by selecting candidate buses into which to install the DG units on the system. For the installation of DG units Candidate buses can be selected by selecting sensitive buses to the voltage profile. Because in this study we are focusing on improving the voltage stability. The buses which are selected for the DG installation should be located on the main feeders of the system. This voltage sensitivity analysis is conducted by observing the voltage changes with respect to the change of the DG injected power, andit can be explained as follows.

Generally Power systems are modeled with the following nonlinear differential algebraic equations.

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{pmatrix} \begin{pmatrix} \Delta\theta \\ \Delta V \end{pmatrix} (2)$$

Here, Q is the reactive load power which is assumed to be constant and ΔQ is the incremental change in bus reactive power.

$$\Delta P = (J_{PV} - J_{P\theta} J_{Q\theta}^{-1} J_{QV})\Delta V (3)$$

$$\Delta V = (J_{RPV})^{-1} \Delta P (4)$$

Here voltage magnitude variations due to DG active power injection variations is given by the reduced Jacobian matrixJ_{RPV}. In this case, (4) can be used to study the DG units impacts on voltage profile. This equation is valid only if the DG units are operating at unity power factor, otherwise consider the sensitivity. Therefore, the system load values at an operating point can be analyzed using (4) to determine the buses most sensitive to the voltage profile. For the DG installation most sensitive buses should be selected as the candidate buses.

IV. FORMULATION OF DG PLACEMENT PROBLEM

After the selection of the candidate buses the next step is the allocation of the DG units within the system. It requires some information about the DG resources and their uncertainties.

It also requires load modeling and their criticality at each bus and allocation of the DG units in the most sensitive buses might violate the feeders capacity and the voltage limits which is depending on the DG units size and the load demand of the system. In this a method is proposed for the location of theDG units with an objective of improving the voltage stability of the system.

In this some, assumptions are considered. Those assumptions are given below.

• At the same candidate bus more than one type of DG can be installed.

• The DG units are assumed to operate at unity power factor.
•All buses in the system are subjected to the same wind speed and solar irradiance.
•Penetration level is considered as 30%.

Modelling of the load and the DG units

A. Objective function

Optimal placement and sizing of DG units with an objective of increasing the voltage stability margin can be formulated by using the modified voltage index method. The following equation is used to improvethe voltage profile of the system.

$$V_n = \frac{V_{P,withDG}}{V_{P,withoutDG}} \quad (5)$$

Where, $V_P = \sum_{i=1}^{m} V_i L_i K_i$
V_i Voltage magnitude at bus i
L_i Load demand at bus i
K_i Weight factor
m Total number of load buses in the distribution system

This equation can be used to improve the voltage stability margin.And it is modified by including the probabilistic nature of the DG as in

$$V_{index} = \frac{(\sum_{n=1}^{N} V_n pr_n)}{96} \quad n=1,2,\ldots N \quad (6)$$

Where, N is the number of load and DG generation combinations.The highest V_{index} gives the suitable location for the DG units installation with objective of improving the voltage profile.

If ,V_{index} is less than 1 then DG units will worsen the Voltage profile. If it is equal to one then DG units will not impact on the voltage profile. Otherwise if it is greater than one then the voltage profile is improved.

B. Constraints

Power flow equations:

$$P_{G_{n,1}} + C(n,1) * P_{DGD_i} + C(n,2) * P_{DGW_i} + C(n,3) * P_{DGS_i} - C(n,4) * P_{D_i} = \sum_{j=1}^{m} V_{n,i} * V_{n,i} * Y_{i,j} * \cos(\theta_{ij} + \delta_{n,j} - \delta_{n,i}) \forall i, n \quad (7)$$

$$Q_{G_{n,1}} - C(n,4) * Q_{D_{n,i}} = -\sum_{j=1}^{m} V_{n,i} * V_{n,i} * Y_{i,j} * \sin(\theta_{ij} + \delta_{n,j} - \delta_{n,i}) \quad \forall i, n \quad (8)$$

Branch current equations:

$$I_{n,ij} = |Y_{i,j}| * [(V_{n,i})^2 + (V_{n,j})^2 - 2 * V_{n,i} * V_{n,j} * \cos(\delta_{n,j} - \delta_{n,i})]^{\frac{1}{2}} \quad \forall n, i, j \quad (9)$$

Where, $I_{n,ij}$ is the current in the feeder which is connecting buses i and j during state n.

Slack bus voltage and angle is

$$V_{n,1} = 1.025$$

$$\delta_{n,1} = 0.0 \quad (10)$$

Voltage limits at other buses :

$0.95 \le V_{n,i} \le 1.05 \; \forall i \in$ substation bus, n.(11)

Feeder capacity limits :

$$0 \le I_{n,ij} \le I_{ij_{max}} \; \forall \; i,j,n \quad (12)$$

Maximum penetration on each bus:

$P_{DGD_i} + P_{DGW_i} + P_{DGS_i} \le$ 10MW.(13)

Maximum penetration of DG units on the system is

$$\sum_{i=1}^{m} P_{DGD_i} + \sum_{i=1}^{m} CF_w P_{DGW_i} + \sum_{i=1}^{m} CF_s P_{DGS_i} \le y * \sum_{i=1}^{m} P_{D_i} \quad (14)$$

V. SYSTEMS UNDER STUDY

(a). 41 Bus system [9]

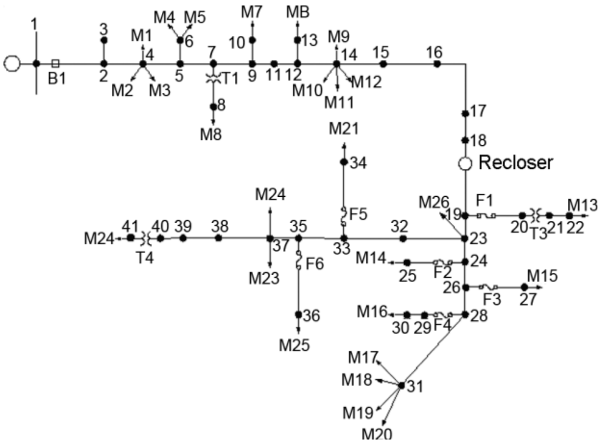

Fig. 2.Distribution test system of 41 buses

Fig.2shows a single line diagram of a 41 buse rural distribution system which is having a peak load of 16.18 MVA and 300A. The system's complete load and line data is taken from [9]. The substation voltage is set to 1.025 p.u.

(b). 39- Bus system[10]

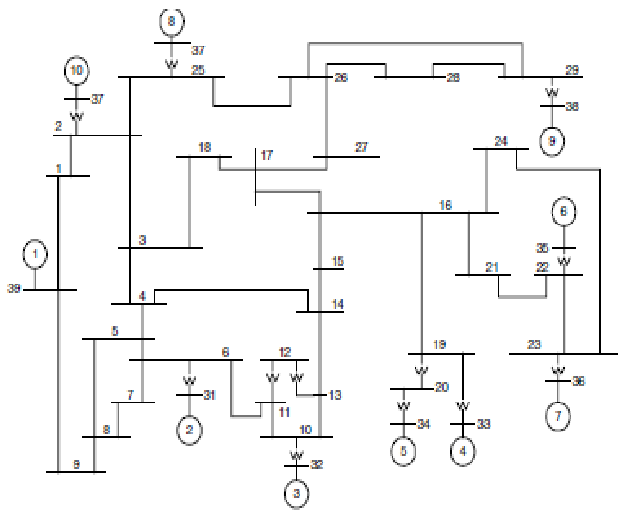

Fig.3.Single line diagram of a 39 bus system

Fig.3. shows the single line diagram of a 39 bus system.The data is at 100 MVA base and 12.66 kV. The load and line data is taken from the ref. [10].

VI. RESULTS

(a). 41- Bus system

Results for the candidate bus selection:

This selection is achieved by developing case studies which are equal to the number of the system buses which are located in the main feeders. In each case, a DG unit is installed at a certain bus, and the changes of the system voltages are observed. The installed DG unit is assumed to generate constant power of 4.5 MW at unity power factor (about 30% of the penetration level), and the system load demand is taken at the peak value.

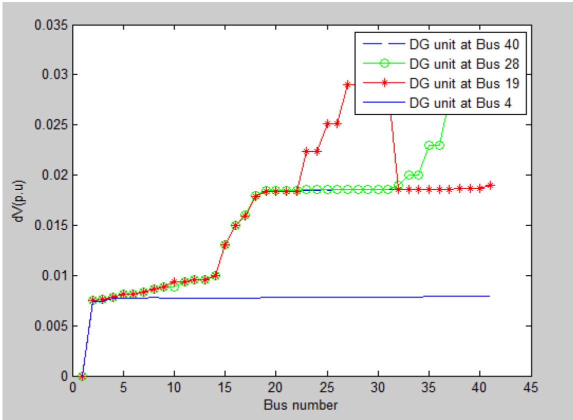

Fig.4. Result of voltage sensitive analysis for 41 bus system with 30% penetration level

Fig.4. shows that the buses from 19 to 41 can improve the voltage profile better than the buses from 1to 18. And it represents the impact of $\Delta V/\Delta P$.The X - axis shows the bus numbers and the Y- axis shows the changes in voltage due to the injection of the DG unit.

Results of the DG Units Impacts on Voltage Stability

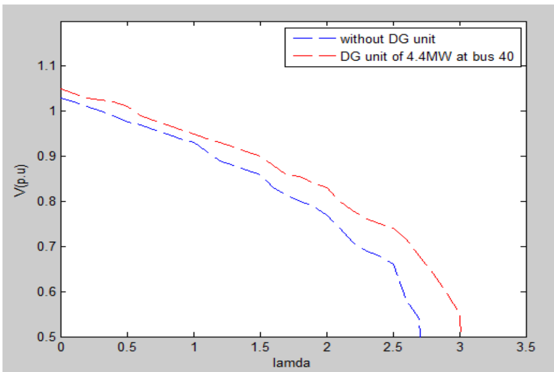

Fig.5. Impact of DG unit on maximum loadability and voltage stability margin

Fig.5. shows the impact of the DG unit on voltage stability margin and maximum loadability.The study of the impact of the DG size is conducted by installing one DG unit in one of the candidate buses, and then finding

the maximum loadability and the voltage of the system by using voltage index method.

Results for impact of size and location of DG units on maximum loading

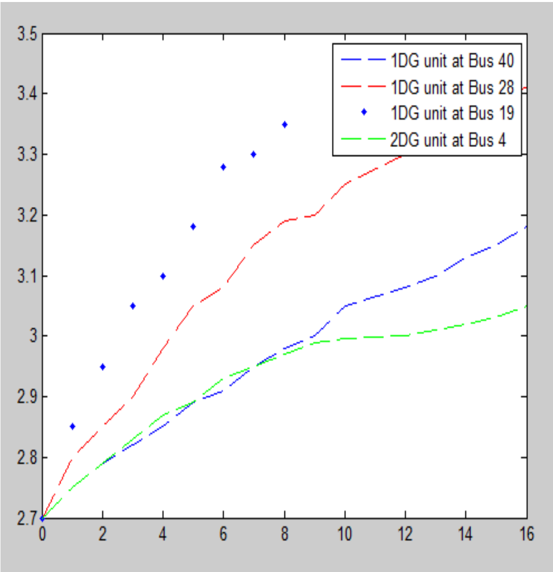

Fig.6. Impact of the size of the DG units on maximum loading.

Fig.6. shows the impact of the size of the DG units on maximum loading

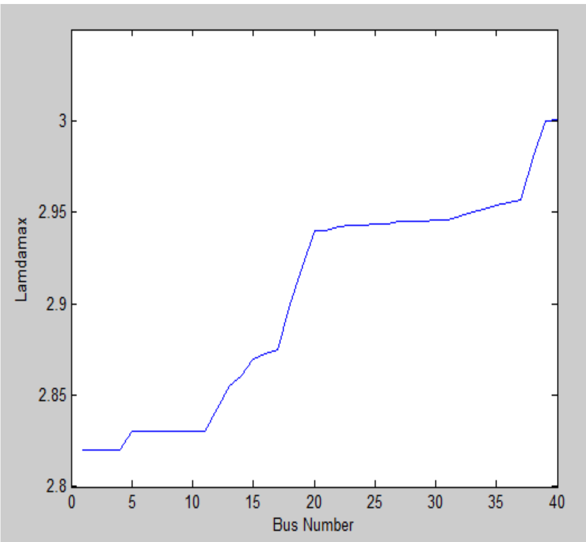

Fig.7. Impact of the location of the DG units on maximum loading

Fig.7. shows the impact of the location of the DG units on maximum loading.

(b). 39-Bus system

Result for voltage sensitivity analysis of 39-bus system

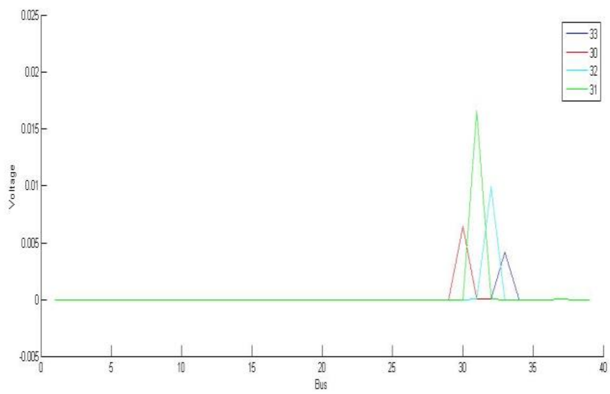

Fig.8. Voltage sensitivity analysis for 39 bus system with 30% penetration level.

Fig.8. shows the buses from 28 to 32 can improve the voltage profile better than the buses from 1 to 27.And it represents the impact of $\frac{\Delta V}{\Delta P}$. The X -axis shows the bus numbers and the Y- axis shows the changes in voltage due to the injection of the DG unit.

VII. CONCLUSION

In this literature, the analysis has been carried out for radial distribution systems and locations of distributed generators have been obtained based on the sensitivity approach and mixed integer nonlinear programming. In this voltage index method is used to locate and size the DG units with an objective of increasing the voltage stability margin. A direct approach for distribution load flow solution is presented. Two matrices are used to solve load flow solution. The BIBC matrix represents the relationship between bus current injections to branch currents, and the BCBV matrix represents the relationship between branch currents to bus voltages. These two matrices are combined to form a direct approach for solving load flow solutions.

APPENDIX

The detailed Load and line data of the systems which are under study are given in [9],[10].

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