Optimal Placement of Distributed Generation with Sensitivity Factors Considering Voltage Stability and Losses Indices

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Abstract— Loss minimization in distribution networks has considered as great significance recently since the trend to the distribution generation will require the most efficient operating scenario for economic viability variations. Furthermore, voltage instability phenomena can occur in distribution systems and caused a major blackout in the network. The decline of voltage stability level will restrict the increase of load served by distribution companies. To control distribution networks, it can be used from Distributed Generation (DG). DG is increasingly drawing great attention and development of DGs will bring new chances to traditional distribution systems. However, Installation of DG in non-optimal places can result in an increasing in system losses, voltage problems, etc.

This paper presents two scenarios for distributed generation placement in a distributions system. In the first scenario only minimizing the total real power losses in the system is considered. Both the optimal size and location are obtained as outputs from the exact loss formula. The next scenario considered the voltage stability index (SI) to find optimum placement. In these scenarios different DG placements are compared in terms of power loss, loadability and voltage stability index. To improve power transfer capacity, two line stability indices have been introduced. Distribution power flow solution algorithm is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices. These scenarios are executed on typical 33 and 30 bus test system and yields efficiency in improvement of voltage profile and reduction of power losses; it also may permit an increase in power transfer capacity, maximum loading, and voltage stability margin.

Keywords—Distributed generation; radial systems; Distribution load flow; power losses; stability index; Optimal placement.

I. INTRODUCTION

Distributed generation (DG) is associated with the use of small generation units located close to or in the load centers. DG can be implemented either by end user, by project developer, or by distribution utilities. Final consumers get an alternative supply for peak consumption or a back up option. Project developers have a business opportunity in the energy market. Distribution utilities see it as an interesting option to reduce losses, to deal with the high cost of not supplied energy, or to avoid or delay network expansion. The problem of DG allocation and sizing is of great importance. Studies have indicated that inappropriate selection of location and size of DG, may lead to greater system losses than the losses without DG. For that reason, the use of an optimization method capable of indicating the best solution for a given distribution network can be very useful for the system planning engineer. Optimum allocation cause to utilities takes advantage of reduction in system losses; improve voltage regulation and improvement in reliability of supply. DG could be considered as one of the viable options to ease some of the problems (e.g. high loss, low reliability, poor power quality, congestion in transmission system) faced by the power systems, apart from meeting the energy demand of ever growing loads[1]-[3].

The optimum DG allocation can be modeled as optimum active power compensation. DG allocation studies are relatively new, unlike capacitor allocation that has been studied for many years. In [4],[5], power flow algorithm is presented to find the optimum DG size at each load bus assuming every load bus can have a DG source. Such methods are, however, inefficient due to a large number of load flow computations. The genetic algorithm (GA) based method to determine size and location is used in [6]–[8]. GA is suitable for multi objective problems like DG allocation and can give near optimal results, but they are being computationally demanding and slow in convergence. In [9], analytical method to place DG in radial as well as meshed systems to minimize power loss of the system is presented. In this method separate expressions for radial and network system are derived and a complex procedure based on phasor current is proposed to solve the location problem. However, this method only optimizes location and considers size of DG as fixed.

In this paper, exact loss formula is used to find optimum sizing for DG in each buses. The DG is considered to be located in the primary distribution system and two scenarios have been implemented.
In the first scenario only minimizing of total real power losses in the system is considered. The next scenario considered the voltage stability index (SI) to find optimum placement. In these scenarios different DG placements are compared in terms of power loss, loadability and voltage stability index. To improve power transfer capacity, two line stability indices, the Fast Voltage Stability Index (FVSI) and Line Stability Factor (LSFQ) for voltage stability contingency analysis are compared. The sizing and placement of DG is based on single instantaneous demand at peak, where the losses are maximum values. The rest of the paper is organized as follows: Section II gives an introduction to load flow in distributed generation, using BCBV and BIBC matrices. Section III describes voltage stability, DGs impact on the voltage stability, and line stability indices. Loss sensitivity factor method is presented in Section IV. Section V presents the importance of selection of proper location and size of DG for minimizing distribution losses. Section VI portrays the 33 and 30 bus distribution systems used in the paper. It must be mentioned that 30-bus test has three meshes and it must be considered in load flow program. Finally, the major contributions and conclusions of the papers are summarized.

II. POWER FLOW IN DISTRIBUTION NETWORK

A. Review

Load flow is a very important and fundamental tool for the analysis of any power system and is used in the operational as well as planning stages. Even though the Fast decoupled Newton method [10] works well for transmission system, its convergence performance is poor for most radial distribution systems due to their high R/X ratios which deteriorate the diagonal dominance of the Jacobian matrix. For these reasons, several non-Newton types of methods [11]-[14], that consist of forward/backward sweeps on a ladder system have been proposed.

A new algorithm used in this section for calculations of load flow. The only input data of this algorithm is the conventional bus-branch oriented data used by most utilities.

B. Proposed Method

The presented method is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices which were developed based on the topological structure of the distribution systems and is widely implemented for the load flow analysis of the distribution systems. The details of both matrices can be found in [15].

The method proposed here requires only one base case load flow to determine the optimum size and location of DG. The equivalent-current-injection based model is more practical. For bus Si, the complex load is expressed by:

\[ S_i = (P_i + jQ_i) \quad i = 1, \ldots, N. \]  

(1)

At each bus i, the corresponding equivalent current injection is specified by:

\[ I_i = \left( \frac{P_i + jQ_i}{V_i} \right), \quad i = 1, 2, 3, \ldots, n \]

(2)

Where \( V_i \) is the node voltage, \( P_i + jQ_i \) is the complex power at each bus i, n is the total number of buses. The equivalent current injection of bus i can be separated into real and imaginary parts.

The branch current B is calculated with the help of BIBC matrix. The BIBC matrix is the result of the relationship between the bus current injections and branch currents. The elements of BIBC matrix consist of '0's or '1's:

\[ [B]_{subd} = [BIBC]_{subd(n-1)}\cdot[I]_{(n-1)x1}. \]

(3)

Where \( nb \) is the number of the branches, [I] is the vector of the equivalent current injection for each bus except the reference bus. It can be seen that the bus voltage can be expressed as a function of branch currents, line parameters, and the substation voltage. Similar procedures can be performed on other buses; therefore, the relationship between branch currents and bus voltages can be expressed as:

\[ \Delta V = [Z]_{subd(n-1)}\cdot[B]_{(n-1)x1}. \]

(4)

The voltage drop from each bus to the reference bus is obtained with BCBV and BIBC matrices as:

\[ [\Delta V]_{(n-1)x1} = [BCBV][BIBC][I]. \]

(5)

Where BCBV matrix is responsible for the relations between branch currents and bus voltages. The elements of BCBV matrix consist of the branch impedances. A building algorithm for BIBC and BCBV matrix can be found in [15].

With the help of this approach, the total power losses can be expressed as a function of the bus current injection:

\[ P_{loss} = \sum_{i=1}^{nb} |I|^2, \quad R = |R|^2[BIBC][I]^2. \]

(6)

III. VOLTAGE STABILITY

A. Definition

Voltage stability is the ability of a system to maintain voltage so that when system nominal load is increased, the active power delivered to the load by the system will increase and both power and voltage are controllable. If the ability to maintain power transfer and voltage is lost, the system is voltage unstable. Voltage collapse is the process by which voltage instability leads to a loss of voltage in a significant part of the system. A power system will enter a period of voltage instability prior to a voltage collapse. During voltage instability, the power system is in grave danger and the system operators have lost control of system voltage and power flow. System reactive power reserve supplies will be exhausted and motors may begin to stall. If voltages decline any further, a voltage collapse may occur.
B. Impact of DG in Voltage Stability

In Fig. 1 the installation of a DG unit $\Delta P_{MW}$ 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 and $V_{DG} - V_0$ 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:

$$Q_{loss} = \frac{(P_{\text{load}} - P_{DG})^2 + (Q_{\text{load}} - Q_{DG})}{V^2} X_{\text{line}}$$

(7)

Where, $P_{\text{load}}$, $Q_{\text{load}}$, $P_{DG}$ and $Q_{DG}$ are the active and reactive power of the load and DG, respectively, $X_{\text{line}}$ and is the reactance of the line connecting the load to the feeding substation. Furthermore, an asynchronous generator possesses a number of features that make it very suitable for DG. Some of these features are: relatively inexpensive prices, insignificant maintenance requirements, in addition these motors are robust.

C. Review of Conventional Voltage Stability Indices

Reliable assessment of voltage stability of an electric power system is essential for its operation and control. Many voltage stability indices were proposed to measure a margin to the limitation of the power flow solution. Reference [16] presents a criterion that made use of the sensitivity of reactive power with respect to voltage. Determinant of the Jacobian matrix of the power flow equation has been presented by Afterwards in [17]. Tamura, et al. proposed an index that employed an angle between a pair of multiple power flow solutions [18]. That is based on the fact that a pair of multiple power flow solutions becomes closer and merges at the saddle bifurcation point as power system conditions get heavy-loaded gradually. Carpentier, et al. presented an index with the optimal power flow calculation [19]. The index shows that a power system lacks a large amount of reactive power if it is approaches voltage instability. Kessel and Glavitsch developed an index called $L$ with the power flow calculation [20]. The index evaluates the power system conditions with the hybrid matrix. The advantage of the index is to require only one power flow calculation. Thomas and Tiranuchit presented a method that used the minimum singular value of the singular value decomposition technique [21]. Afterwards, LoF, et al. speeded up the method of Thomas and Tiranuchit with the sparse matrix technique [22], [23].

$P-V$ 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. In this paper, index $L$ is used due to the computational efficiency.

D. Mathematical Model for The Developed Stability Index for Distribution Network

D.1 Voltage Stability Index

Using Fig.2, the equation that is mostly used for the calculation of the line sending end voltages in distribution line model [24], [25].

In load flow analysis can be written in general form as:

$$V^2_1 + 2V^2_2 (PR + QX) - V^2_1 V^2_2 + (P^2 + Q^2) |Z|^2 = 0$$

(8)

From this equation and line receiving end active and reactive power equations, after some calculations we have:

$$2V^2_1 V^2_2 - V^2_1 - 2V^2_2 (PR + QX) - |Z|^2 (P^2 + Q^2) \geq 0$$

(9)

From the last equation, it is clearly seen that the value of the (16) is decrease with the increase of the transferred power and impedance of the line, and it can be used as a bus stability index for a distribution networks as:

$$SI(r) = 2V^2_1 V^2_2 - V^2_1 - 2V^2_2 (PR + QX) - |Z|^2 (P^2 + Q^2)$$

(10)

In this study the above simple stability criterion, given in (10), is used to find the stability index for each line receiving end bus in radial distribution networks. After the load flow study, the voltages of all nodes and the branch currents are known, therefore P and Q at the receiving end of each line can easily be calculated and hence using (10) the voltage stability index of each node can easily be calculated. The node, at which the value of the stability index is at minimum, is the most sensitive to the voltage collapse.

Fig 2. One line diagram of a two-bus distribution system
D.2 Line Stability Index

Voltage stability contingency analysis refers to voltage stability study of the failure of one or more system. The time consumed to consider all possible situations is too large and a short contingency list, where only the most serious situations are included, is always applied to reduce the calculation time. A Fast Voltage Stability Index is proposed in [26]. The line stability index is derived from a 2 bus system as shown in Figure 3. The current flow from bus 1 to bus 2 is could be calculated as:

\[ I = \frac{V_i \delta - V_j \delta}{R + jX} \]  \hspace{1cm} (11)

After some calculations, the fast voltage stability index is defined as:

\[ FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2X} \leq 1 \]  \hspace{1cm} (12)

Where \( Z \) is the magnitude of the line impedance. The line stability factor is also derived from the 2 bus model presented in Figure 3.

After some calculations, since the line is lossless, we have:

\[ 4 \left( \frac{X}{V_i^2} \right) (1 - \frac{X}{V_i^2} P_i + Q_i) \leq 1 \]  \hspace{1cm} (13)

The line stability index is therefore defined as:

\[ LQP_{ij} = 4 \left( \frac{X}{V_i^2} \right) (1 - \frac{X}{V_i^2} P_i + Q_i) \]  \hspace{1cm} (14)

The values of LQP or FVSij must be less than 1 for the system to be stable. The line that exhibits FVS or LQP close to 1 implies that the system is approaching its load limit and is nearly unstable. Comparisons between FVS and LQP show that FVS reflects the system stability well in terms of reactive load but not well in terms of active load. Therefore the line stability factor LQP is used as the stability index in this paper.

In each case, one of the lines is eliminated from the system to voltage controlled buses (PV buses). The representation of PV buses in radial systems, for forward-backward sweep power flow method, implies in the creation of network breakpoints, where the voltages of the two buses (terminal and fictitious) should be maintained at the same specified module through reactive power injection at the buses [30],[31].

IV. LOSS SENSITIVITY FACTOR

Sensitivity factor method is based on the principle of linearization of original nonlinear equation around the initial operating point, which helps to reduce the number of solution space. Loss sensitivity factor method has been widely used to solve the capacitor allocation problem [27]. Its application in DG allocation is new in the field and has been reported in [28]. The real power loss in a system is given by (1). This is popularly referred to as “exact loss” formula [29].

\[ P_L = \sum_{i=1}^{N} \sum_{j=1}^{N} \left[ \alpha_i (P_{ij} + Q_{ij}) + \beta_j (Q_{ij} - P_{ij}) \right] \]  \hspace{1cm} (16)

Where:

\[ \alpha_i = \frac{r_{ij}}{V_i V_j} \cos(\delta_i - \delta_j) \]  \hspace{1cm} (17)

\[ \beta_j = \frac{r_{ij}}{V_i V_j} \sin(\delta_i - \delta_j) \]  \hspace{1cm} (18)

The sensitivity factor of real power loss with respect to real power injection from DG is given by:

\[ \alpha_i = \frac{\partial P_i}{\partial P_{ij}} = 2 \sum_{j=1}^{N} (\alpha_i P_j - \beta_j Q_j) \]  \hspace{1cm} (19)

Sensitivity factors are evaluated at each bus, firstly using the values obtained from the base case power flow. The buses are ranked in descending order of the values of their sensitivity factors to form a priority list. The top-ranked buses in the priority list are the first to be studied alternatives location.

V. DG SIZING AND SITTING FORMULATION

A. Sitting and Sizing

It is important to have an accurate look to the problem of allocation and sizing of DG. The installation of DG units at non optimal places can result in an increasing in system losses, increase in costs and, therefore, having an effect opposite to the desired. Therefore, the use of a methodology capable of analyzing the influence on some system characteristics of DG allocation and sizing can be very effective for the system planning engineer. Given a set of possible expansion alternatives, the evaluation of a as mentioned before, DG allocation and sizing strategy should be made through a power flow program for distribution networks. A way of modeling the DG units is by constant power injection sources connected to voltage controlled buses (PV buses). The representation of PV buses in radial systems, for forward-backward sweep power flow method, implies in the creation of network breakpoints, where the voltages of the two buses (terminal and fictitious) should be maintained at the same specified module through reactive power injection at the buses [30],[31].
B. Placement Due to Losses Minimization

According to section III, at minimum losses the rate of change of losses with respect to injected power becomes zero [32].

\[
\sum_{j=1}^{N} (\alpha_j P_j - \beta_j Q_j) = 0
\]

(20)

\[
P_{DG} = P_{Di} + \frac{1}{\alpha_i} \left[ \beta_i Q_i - \sum_{j=1, j \neq i}^{N} (\alpha_j P_j - \beta_j Q_j) \right]
\]

(21)

\(P_{DG}\): real power injection from DG placed at node i.

\(P_{Di}\): load demand at node i.

Optimum size of DG for each bus i can be gained from (21), for the loss to be minimized. Any size of DG other than \(P_{DG}\) placed at bus i, will lead to higher loss. This loss, however, is a function of loss coefficient \(\alpha\) and \(\beta\).

VI. SIMULATION RESULTS

Two scenarios have been considered and in each scenarios losses minimization and stability index have been implemented separately for finding optimal placement and best rate values for DGs. Simulations have been implemented on the 33 and 30 bus distribution systems (Fig.3).

A. 33 Bus Radial System

The total real and reactive power loads on this system are 3715Kw and 2300 KVar. The initial power loss in this system is 209.87 kW. The lowest bus bar voltage limit is 0.9075 which occurs in node 18. Fig. 4 Shows Voltage profile when no DG is installed.

Case 1: DG allocation and sizing considering minimization of losses

In this case, allocation of DGs has been performed using exact loss formula (32). Optimal DG size and related losses in each bus have been compared and presented in Table I for two case systems. For 33 bus radial test system, as shown in the Table I, bus 6 is the best location for minimization of the losses. In this condition optimal DG size is 2.4818 Mw and losses is 110.6318 kW.

The initial power loss in this system is 383.40 kW. Fig. 5 Shows Voltage profile when no DG is installed.

B. 30 Bus Meshed System

It is a balanced three-phase loop system that consists of 30 nodes and 32 segments. It is assumed that all the loads are fed from the substation located at node 1.

The loads belonging to one segment are placed at the end of each segment. The system has 30 loads totaling 4.43 MW and 2.12 Mvar, real and reactive power loads respectively [32].
TABLE I.
OPTIMAL DG SIZE AND RELATED LOSSES IN TWO STUDY CASE

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Optimum DG size (MW)</th>
<th>Losses (kW)</th>
<th>Optimum DG size (MW)</th>
<th>Losses (kW)</th>
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<td>4.71304</td>
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</table>

In 30-bus meshed test system, bus 12 is the best location for minimization of the losses. In this condition optimal DG size is 3.2956 MW and losses is 77.8754 kW.

Fig.6 depicts losses versus bus numbers that optimum DG size has been installed separately and load flow has been implemented.

Case 2: DG allocation and sizing considering voltage and line stability indices

In this case, allocation and sizing of DGs have been performed using voltage and line stability indices that described in section III.

For 33 bus radial test system, voltage profile is portrayed in Fig 7. Fig 8 compares SI after installation DG two best candidate buses. Comparison between SI indices for all buses when optimum DG sizes has been installed in each bus shown in Fig 9. Table II shows SLPQ and FVSI Indices. As it mentioned in section II the line that exhibits FVSI or SLQP close to 1 implies that the system is approaching its load limit and is nearly unstable. It is observed that after DG allocation in buses there is no overload in system.

Fig 9, Tables II show that the SI stability index is improved when DG is installed in bus 27. It must be mention that although losses will increase up to 115.01 kW; however stability in network is increased considerably.
Similarly for 30 bus test system, voltage profile is portrayed in Fig 10. Also, Comparison between SI indices has been shown in Fig 11. Table III shows SLPQ and FVSI Indices. It is observed that after DG allocation in buses there is no overload in system.

Figs 11 and Tables III show that the SI stability index is improved when DG is installed in bus 26. It must be mention that although losses will increase up to 86.21 kW; however stability in network is increased considerably.

In order to verify the optimal size at the above location, a number of load flow simulations were carried out with different sizes of DG, starting from 0 to 5 MW. The results show that optimization through this approach is true. Moreover, it shows that, beyond a value of 4.2MW of DG size, the total system losses have increased more than the system losses without DG units. The correct size of DG is playing an important role in minimizing the losses by decreasing the current drawn from the substation from a long distance.

**VII. CONCLUSION**

This paper presents a method for optimal allocation of Distributed Generation in two study case distribution systems. In this paper, our aim was optimal distributed generation allocation for loss reduction in distribution network in the first scenario. Minimizing the losses in the system would bring two types of saving, in real life, one is capacity saving and the other one is energy saving. The second scenarios considered the voltage stability index (SI) to find optimum placement. In these scenarios Different DG placements are compared in terms of power loss, loadability and voltage stability index. To improve power transfer capacity, two line stability indices,
The Fast Voltage Stability Index (FVSI) and Line Stability Factor (LQP) for voltage stability contingency analysis are compared. The sizing and placement of DG is based on single instantaneous demand at peak, where the losses are maximum values. The results of execution of these scenarios on two typical 33 and 30-bus test system were clarified robustness of this method in optimal and fast placement of DG. The results showed efficiency of this method for improvement of voltage profile, reduction of power losses and also an increase in power transfer capacity, maximum loading and voltage stability margin. Other benefits of DG such as higher reliability and better power quality against voltage sags and swells can be easily understood.

8. REFERENCES