Loss Reduction of Power Distribution Network Using Optimum Size and Location of Distributed Generation

Adnan Anwar, Student Member, IEEE, and H. R. Pota, Member, IEEE

Abstract—Distributed generation (DG) units reduce electric power losses and hence improve reliability and voltage profile. Determination of appropriate size and location of DG is important to maximize overall system efficiency. In this paper, an optimization method has been presented to determine the appropriate size and proper allocation of DG in a distribution network. Results obtained from this method have been compared with using the repeated load flow method. A new approach to perform repeated load flow by using simulation engine ‘openDSS’ COM server through Matlab programming is also introduced here. Both optimized method and repeated load flow based method have been compared for three IEEE distribution test systems. This analysis shows that using appropriate size and location of DG, total power loss in primary distribution system can be reduced significantly.

Index Terms—Distributed generation, Optimum size, Optimum location, Power loss, Sensitivity analysis.

I. INTRODUCTION

The growth of electricity demand is increasing rapidly. DG is one of the better alternatives to fulfill this ever growing energy demand. Moreover, it reduces system energy loss, alleviates transmission congestion, improves voltage profile, enhances reliability and provides lower operating cost. Because of small size compared with conventional generation units, DG is more flexible to install in terms of investment and time. As a result, integration of Distributed Energy Resources (DER) with distribution network offers a promising solution; therefore, an intensive level of research is needed to understand the impacts of distributed resources on Distribution System. Before operating distributed and dispersed generation in power system, different technical, environmental, commercial and regulatory issues should be analysed properly. Most significant technical barriers are protection, power quality, stability and islanding operation. However, there are some other issues which should be analysed before to maximize these technical benefits. From previous studies, it has been seen that different penetration level and various placement of DER will impact the distribution system differently [1]. Moreover, improper DG size and inappropriate allocation of DER may lead to higher power loss than when there is no dispersed generation in the system at all [2]. Therefore, detail and exact analysis method is required to determine the proper location and size of DG more accurately and precisely. In distribution system, DG should be allocated in an optimal way such that it will reduce system losses and hence improve voltage profile [3]. In our study, we will try to focus on optimum location and size of DG to decrease total system power loss. In most of the previous researches of DG sizing and allocation, DG has been connected with grid directly. Significant risks are associated in connecting such equipment directly to utility distribution system. The insulation level of the machines may not synchronize with the system. Therefore, direct connection of DG is often discouraged [4]. In our analysis, we have connected DG through a three-phase step down transformer.

The organization of this paper is as follows; Definition of DG is discussed in section II. Section III describes distribution losses with the variation of DG size and location. Previous analysis methodology is discussed in section IV. Objective of our analysis is given in Section V. Our analysis Methodology is shown in Section VI. In Section VII, test system and analytical tools have been discussed. Simulation results and discussion have been presented in section VIII. Evaluation of estimation performances have been analyzed and compared in Section IX. Finally, the paper is concluded by brief remarks in Section X.

II. DEFINITION OF DISTRIBUTED GENERATION AND RATING OF DG (SIZE)

Generally, Distributed generation means the electric power generation within distributed network to fulfill the rapid energy demand of consumers. However, distributed generation can be defined in a variety of ways.

1) The Electric Power Research Institute (EPRI) defines distributed generation as generation from ‘a few kilowatts up to 50 MW’ [5].
2) 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 [6].
3) The International Conference on large High Voltage Electric Systems (CIGRE) defines DG as ‘smaller than 50-100 MW’ [5].

Although there are variations in definitions, however, the concept is almost same. DG can be treated as small scale power generation to mitigate the consumer energy demand. Distributed Generation can come from a variety of sources and technology. To analysis the DER impacts, different types of ‘generator groups’ can be considered [7]. Here, we will
consider induction generator as distributed generation source for our analysis purpose.

As the technical design of each distribution network is unique, therefore, it cannot be answered what should be the optimum generation capacity or rating of DG [5]. The maximum size or rating of DG which can be connected to a distribution network depends on numerous factors, such as voltage level within the distribution system, power loss profile and other technical, environmental, commercial and regulatory issues. In our paper, we will focus on the technical issues only.

As DG offers lots of benefit, the penetration of DG in distribution system is increasing rapidly. Therefore, DG should be allocated in an optimal way to maximize the system efficiency.

III. DISTRIBUTION LOSSES WITH THE VARIATION OF DG SIZE AND LOCATION

In a distribution system, power loss varies with numerous factors. Real power losses of a distribution system depend on the resistance of distribution lines, core losses of transformers and motors. As dielectric and rotational losses are so small compared with line losses, therefore, only line losses are considered in this analysis. The complex power $S_{ij}$ from node i to j and $S_{ji}$ from node j to i are

$$S_{ij} = V_i I_{ij}^*$$  
$$S_{ji} = V_j I_{ji}^*$$

Where, $V_i$ and $V_j$ are the voltages at node i and j respectively. The line current $I_{ij}$ which is measured at bus i in the positive direction of i to j and $I_{ji}$ which is measured at bus j in the positive direction of j to i. Therefore, power loss in any line between node i and j can be written as the algebraic sum of power flows determined from (1) and (2) [8].

$$S_{Lij} = S_{ij} + S_{ji}$$  

After any converged loadflow, power loss in any line can be calculated using (3) and taking the summation of all line losses, total power loss of the network can be calculated using equation (4) where n is the number of lines.

$$LOSS = \sum_{k=1}^{n} S_{L}(k)$$

For any distribution system, placement of any DG unit will change the power loss profile of that system. Actually, in a distribution network, power loss curve with the variation of power generation at a particular location is approximately quadratic function because Line Losses $\propto I^2R$ and I $\propto S$ considering I is the line current, R is the resistance, and S is the apparent power flowing through the line [9]. Therefore, as the DG size is increased in any location of a power distribution network, the total system losses are reduced to a minimum value. With further increasing of DG, losses again start to increase. This trend of losses with DG size variation is given in Fig. 1 for a test case to demonstrate the sizing and location issues of DG. Here, for DG size $P_{DG1}$ we get the minimum power loss which is called optimum DG size for that bus.

Actually, the structure of distribution system is such that power should flow from the substation to the consumer end and conductor sizes are also decreased gradually [3]. When a DG is placed in the network, it is desirable that power should be consumed within the distribution network and thus improves power profile. Any size of DG more than the optimum size will create reverse flow of power towards distribution substation. Therefore, excessive power flow through small sized conductors towards the transmission area will increase the power loss in distribution network.

IV. PREVIOUS METHODOLOGIES

A good number of research work is going on DG integration with grid and its safe and reliable operation [3], [10-17]. However, only a few studies have been done on DG sizing and allocation issue. Different methodologies to determine optimum location and size have been discussed in different literatures. The 2/3 rule is often used in capacitor allocation studies in power distribution network. Similar approach can be performed in DG allocation to reduce system power loss [10]. In the paper [10] authors have used this analytical method and rule of thumb for analysing the distribution system which is radial and has uniformly distributed loads. Rule is simple and easy to use but it cannot provide the proper solution when the load distribution type is changed. Moreover, it can not be applied in meshed network.

In [11], analytical approaches for both radial and networked distribution systems with different types of load configuration are given. Here, separate algorithms have been used for radial and meshed networks. To simplify the analysis, authors have considered only overhead lines for which uniformly distributed parameters like R and L per unit length are same along the feeder. Results obtained from the analysis are very quick; however, one generalized algorithm is expected for both radial and meshed networks. Besides, in practical distribution system, conductor sizes are gradually decreased from substation to load centre, therefore, this analysis procedure would be very complex when line parameters are not uniformly distributed. One major limitation of this approach is, they have only solved the location problem for a fixed size of generator but they have not considered DG sizing issue in their analysis.
Another analytical approach has been proposed based on exact loss formula in [3]. Authors have considered the loss coefficients constant. Here they have considered both sizing and location issues. This process takes only two load flows to determine the location and size of DG. Although the technique is very fast; however, this methodology can be applied only if DG delivers real power [12]. This is one major limitations of this approach. For load flow, authors have considered Newton-Raphson algorithm. Although Newton-Raphson approach has an excellent convergence characteristics but in distribution system because of smaller X/R ratio it can not be decoupled. Moreover, in distribution network, multi-phase, unbalanced operation, unbalanced distributed load and dispersed generation makes the Newton-Raphson approach unattractive [13].

For selection optimum size and location of DG, several genetic algorithms (GA) and fuzzy logic based methods have been discussed in [14], [15], [16], [17]. Although GA provides almost near optimum output but they are computationally very demanding and have a slow convergence [3].

As load flow represents the system states, therefore it can be used for planning the future expansion of power systems. We can calculate the system loss from the load flow result and doing the load flow repeatedly, we can easily tell the location and size of DG for which we get the minimum power loss of the system. This method is known as exhaustive load flow (ELF) method. Although this ELF method gives the exact answer; however, it needs lots of load flow computation. Therefore, ELF method needs to be optimized to get accurate answer and less computational time.

In the previous literatures, researchers have considered radial distribution system but they have not considered three phase unbalanced system. As, distribution system is three phase and unbalanced, therefore, more detailed analysis is needed based on these type of distribution networks.

V. PROBLEM FORMULATION

The main goal of our analysis is to determine optimum size and location of dispersed generation so that it can reduce the real power loss in a distribution system. This analysis is important for efficient power system planning and operation. Distributed generation not only reduces the power loss of a system but also improves the voltage profile. However, inappropriate size and allocation of DG can cause low or over-voltage in the distribution system [18]. Therefore, another goal of our analysis is to check whether the voltage profile remains within permissible limit. So, voltage constraint becomes,

\[ V_{\text{min}} \leq V \leq V_{\text{max}} \]  

Distribution step-type voltage regulators are used to maintain line voltages within predetermined limits; as a result end user can get a constant voltage output [19]. Impact of DG on voltage regulation with the presence of voltage regulator is discussed in [20]. The test systems, which we used for our analysis, comes with voltage regulators which maintain a permissible voltage limit throughout the analysis. During our analysis, we considered \( V_{\text{min}} = 0.94 \text{ pu} \) and \( V_{\text{max}} = 1.06 \text{ pu} \). In section IX-B, we will show how optimum size and location of DG impacts on voltage level of the interconnecting bus.

VI. PROPOSED ANALYSIS METHOD

In our analysis, repeated load flow for loss reduction has been performed in a different approach by integrating openDSS with Matlab which makes the analysis faster, more accurate and efficient. Base on sensitivity, a new methodology has been proposed to calculate optimum size and location of DG. Finally, these two methods have been analysed and compared.

A. Optimized Algorithm using Sensitivity

For any distribution system, if DG size is varied from \( P_{DG1} \) to \( P_{DG2} \) and their corresponding change in power loss is respectively \( P_{L1} \) to \( P_{L2} \), then the sensitivity factor becomes,

\[ \frac{dP_L}{dP_i} = \frac{P_{L1} - P_{L2}}{P_{DG1} - P_{DG2}} \]  

In our analysis, Sensitivity factors are evaluated for each bus using equation (6) and the bus with maximum sensitivity is identified. Only those buses which have sensitivity factors close to the maximum value have been considered in our analysis. Thus solution space is reduced to only a few buses. After that, for each of these buses, power loss has been determined using large step size of DG variation and then a quadratic curve has been formed using these few samples. The minimum value of the curve represents the optimum size for that bus and corresponding generation is the optimum DG size. The bus which is responsible for minimum loss of the system is the appropriate location for DG allocation. The flow chart of our analysis methodology is given in Fig. 2.

VII. TEST SYSTEM AND ANALYTICAL TOOLS

Our analysis method has been implemented on three IEEE distribution test systems. These are IEEE 34 node test feeder, 13 Node test feeder and 123 Node test feeder. The first one, IEEE 34 Node test feeder is an actual feeder located in Arizona and its nominal voltage is 24.9 kV [21]. The second one, IEEE 13 Node test feeder is small but good for test cases. The third one, IEEE 123 Node test feeder operates at a nominal voltage of 4.16 kV and contains overhead, underground line segments with various phasing, unbalanced loading with all configuration of loads [21]. Single line diagrams of the test feeders are shown in the appendix. The basic data for these three test feeders can be obtained from [22]. For analysis purpose, we have developed several Matlab programs to perform the tasks 3 to 12 shown in flow chart. Only for three phase unbalanced load flow we have used Open Distribution System Simulator (OpenDSS). OpenDSS has an in-process COM server DLL through which the user can design and execute custom solution modes and features externally [23]. We have interfaced openDSS COM server with our Matlab program and load flow results have been imported from openDSS. Then Matlab programs have been used to find out optimum size and location of DG.
**VIII. SIMULATION RESULTS AND DISCUSSION**

Fig. 3 shows the trend of power loss with the variation of DG size for each bus of 34 Node test system. This figure has been obtained using repeated load flow method. In that analysis procedure, DG which is responsible for minimum loss at each bus has been identified first and that is optimum DG size for that bus; therefore, the bus which has minimum loss among the whole network is considered as the optimum location for that network. Although repeated load flow is inefficient due to its large number of load flow computations and thus called ‘exhaustive’ approach but it gives us accurate results. Using this methodology, optimum location of DG for 123 Node test system is bus 76 and optimum DG size is 1.32 MW. Now, using our methodology, for same test system, we have found the optimum size of DG is 1.32 MW and optimum location is bus 76 which is similar with the generated result obtained from repeated load flow. For the other two test systems, IEEE 13 Node test system and IEEE 34 Node test system, we have obtained optimum DG size and location using exhaustive search and proposed method. Results obtained from simulation are shown in table I. For all of the three test systems, results from our proposed method are quite similar with repeated load flow approach but our method is quite faster.

![Fig. 3. Power loss profile with the variation of DG size (for 34 Node test system)](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Test System</th>
<th>Repeated load flow</th>
<th>Proposed Method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Optimum Size (MW)</td>
<td>Optimum Location</td>
</tr>
<tr>
<td>13 Bus</td>
<td>1.28</td>
<td>Bus 675</td>
</tr>
<tr>
<td>34 Bus</td>
<td>1.10</td>
<td>Bus 844</td>
</tr>
<tr>
<td>123 Bus</td>
<td>1.32</td>
<td>Bus 76</td>
</tr>
</tbody>
</table>

**IX. EVALUATION OF ESTIMATION PERFORMANCES**

For 123 Node test system, at bus number 76, power loss curves using both methods have been shown in Fig. 4. We considered the output of repeated load flow as the actual case and output using our method is the approximate one. From the figure we can say, our methodology has a very good match with the actual case; moreover, it takes less no of solution space and time.
A. Active power loss reduction by DG

Active power loss reduction (PLR) by DG may be defined as below:

\[ PLR = \frac{P_{\text{Loss}} - P_{\text{DG Loss}}}{P_{\text{Loss}}} \times 100\% \]  

(7)

where,

- \( P_{\text{Loss}} \) = Power loss of the system before introducing DG
- \( P_{\text{DG Loss}} \) = Power loss of the system after adding DG

For 123 bus test system, before adding any DG, total system power loss was 95.3 kW. Adding an additional DG of optimum size on the optimum location, this loss becomes 65.3 kW. Therefore, active power loss is reduced by 31.5%. Therefore, overall system efficiency improves. Using optimum size and location, active power loss reduction for the three systems are summarized in Table II.

<table>
<thead>
<tr>
<th>Test System</th>
<th>Power Loss (kW) Before adding DG</th>
<th>Power Loss (kW) After adding DG</th>
<th>PLR</th>
</tr>
</thead>
<tbody>
<tr>
<td>13 Bus</td>
<td>110.4</td>
<td>85.4</td>
<td>22.6%</td>
</tr>
<tr>
<td>34 Bus</td>
<td>272.8</td>
<td>125.3</td>
<td>53.9%</td>
</tr>
<tr>
<td>123 Bus</td>
<td>95.3</td>
<td>65.3</td>
<td>31.5%</td>
</tr>
</tbody>
</table>

B. Impact on Voltage profile

Voltage range for static voltage stability varies from country to country and utility to utility. However, ANSI standard should be maintained to supply a steady-state voltage on consumer side of a distribution network [19]. The acceptable steady state voltage range of systems between 1kV and 132 kV is considered within \( \pm 6\% \) of the nominal voltage [24]. For 123 bus test system, nominal voltage is 4.16 kV and voltage base is 4.16 kV, therefore, acceptable voltage should be within 0.94 pu to 1.06 pu. For the other two test systems, we get the same voltage range for steady state voltage stability. In our analysis, using voltage regulator and allocating optimum size of DG in optimum location voltages remain within acceptable limit which is shown in Fig. 5.

X. CONCLUSION

The impact of proper allocation and sizing of DG is very significant. Power Loss of distribution system increases overall system cost and has a major impact in power system management. From our analysis, we can come to know that, improper DG size and inappropriate DG allocation may cause a greater system loss than the loss without DG. DG should be allocated in those locations where they provide higher reduction of losses. Although DG is usually consumer’s property, nevertheless, it is the interest of utilities and engineers to determine the appropriate size and location for safe, reliable and stable operation of the distribution system. Our analysis method identifies this sizing and location issues accurately and precisely in a faster manner. To understand the impact of proper allocation and size of DG properly, more detail dynamic analysis is needed which will be our future work.

APPENDIX

Fig. 6. IEEE 13 Node Test Feeder
REFERENCES


Adnan Anwar was born in Bangladesh in 1987. He received B.Sc in Electrical and Electronic Engineering from Islamic University of Technology (IUT), Bangladesh in 2008. In 2009, he joined at the University of Asia Pacific (UAP) as a lecturer. He is currently pursuing his Masters by Research at the University of New South Wales, Australian Defence Forces Academy, Canberra, Australia. His research interests include computer aided analysis of power distribution network, optimization of distribution system, power system dynamics and control, integration of renewable energy sources in distribution system and smart grids.

Hemanshu R. Pota received the B.E. degree from SVRCET, Surat, India, in 1979, the M.E. degree from the IITC, Bangalore, India, in 1981, and the Ph.D. degree from the University of Newcastle, NSW, Australia, in 1985, all in electrical engineering. He is currently an Associate Professor at the University of New South Wales, Australian Defence Force Academy, Canberra, Australia. He has held visiting appointments at the University of Delaware; Iowa State University; Kansas State University; Old Dominion University; the University of California, San Diego; and the Centre for AI and Robotics, Bangalore. He has a continuing interest in the area of power system dynamics and control, flexible structures, and UAVs.