Integration of distributed generation for reduction of line losses into a radial distribution feeder

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Abstract- Due to the increasing interest on renewable sources in recent times, the studies on integration of distributed generation to the power grid have rapidly increased. In order to minimize line losses of power systems, it is crucially important to define the location of local generation to be placed. Proper location of DGs in power systems is important for obtaining their maximum potential benefits. This paper presents analytical approaches to determine the optimal location to place a DG on radial systems to minimize the power loss of the system. Simulation results are given to verify the proposed analytical approaches.

Key words: — Analytical approach, distributed generation, radial systems, optimal placement, power loss.

I. INTRODUCTION

In recent times, due to the increasing interest on renewable sources such as hydro, wind, solar, geothermal, biomass and ocean energy etc., the number of studies on integration of distributed resources to the grid have rapidly increased. Distributed generation (DG), which consists of distributed resources, can be defined as electric power generation within distribution networks or on the customer side of the network [1]. Distributed generation (DG) devices can be strategically placed in a power system for grid reinforcement, reducing power losses and on-peak operating costs, improving voltage profiles and load factors, deferring or eliminating for system upgrades, and improving system integrity, reliability, and efficiency [3]. These DG sources are normally placed close to consumption centers and are added mostly at the distribution level. They are relatively small in size (relative to the power capacity of the system in which they are placed) and modular in structure. A common strategy to find the site of DG is to minimize the power loss of the system [5]. There are methods of loss reduction techniques used like feeder reconfiguration, capacitor placement, high voltage distribution system, conductor grading, and DG unit placement. All these methods except DG unit placement are involved with passive element. Both DG units and capacitors reduce power loss and improve voltage regulation; but with DGs, loss reduction is almost double that of Capacitors [4]. A simple method for placing DG is to apply rules that are often used in deciding location of shunt capacitors in distribution systems. A “2/3 rule” is presented in [6] to place DG on a radial feeder with uniformly distributed load, where it is suggested to install DG of approximately 2/3 capacity of the incoming generation at approximately 2/3 of the length of line from the sending end. This rule is simple and easy to use, but it cannot be applied directly to a feeder with other types of load distribution, or to a networked system. Celli and Pilo propose a method to establish an optimal distributed generation allocation on distribution network based on a Genetic Algorithm considering all the technical constraints, like feeder capacity limits, feeder voltage profile and three-phase short circuit current in the network nodes [7]. Griffin and Tomsovic present an algorithm to determine the near optimal, with respect to system losses, placement of these units on the power grid. Further, the impacts of dispersed generation at the distribution level are performed with an emphasis on resistive losses, and capacity savings [8]. This paper presents analytical approaches for optimal placement of DG with unity...
power factor in power systems using loss reduction criterion. First, placement of DG on a radial feeder is analyzed and the theoretical optimal site (bus location) for adding DG is obtained for different types of loads such as uniformly, centrally and increasingly distributed loads with DG sources. The proposed method is tested by a series of simulations on subset of it, to show the effectiveness of the proposed methods in determining the optimal bus for placing DG. In practice, there are more constraints on the availability of DG sources, and we may only have one or a few DGs with limited output available to add. Therefore, in this study the DG size is not considered to be optimized. The procedure to determine the optimal bus for placing DG may also need to take into account other factors, such as economic and geographic considerations.

DISTRIBUTION SYSTEMS

Two types of distribution system

1. Radial Distribution system

2. Ring Main distribution system

Figure 1.—Loop (or ring) distribution system. Connected directly to distribution centers. These laminate the need for substations because the generator generates a usable voltage. Primary Feeders Primary feeders are those conductors in a distribution system that is connected from the distribution sub-stations and that transfer power to the distribution centers (fig. 2-2). They may be arranged as radial, loop, or network systems and may be overhead or underground.

RADIAL DISTRIBUTION SYSTEM.— A schematic example of a radial distribution system is shown in figure 2-3. In this system, primary feeders take power from the distribution substation to the load areas by way of sub feeders and lateral-branch circuits. This is the most common system used because it is the simple stand least expensive to build. It is not the most reliable system, however, because a fault or short circuit in a main feeder may result in a power outage to all the users served by the system. Service on this type of system can be improved by installing automatic circuit breakers that will reclose the service at predetermined intervals. If the fault continues after a predetermined number of closures, the breaker will be locked out until the fault is cleared and service is restored.

PRIMARY LOOP (OR RING) DISTRIBUTION SYSTEM.— The loop (or ring) distribution system is one that starts at a distribution substation, runs through or around an area serving one or more distribution transformers or load centers, and returns to the same substation. The loop system (fig. 2-4) is more expensive to build than the radial type, but it is more reliable and may be justified in areas where continuity of service is required—at a medical center, for example. In the loop system, circuit breakers sectionalize the loop on both sides of each distribution transformer connected to the loop. A fault in the primary loop is cleared by the breakers in the loop nearest the fault, and power is supplied the other way around the loop without interruption to most of the connected loads. If a fault occurs in a section adjacent to the distribution substation, the entire load can be fed from one direction over one side of the loop until repairs are made.

NETWORK SYSTEM. — The network system (fig. 2) is the most flexible type of primary feeder
Sample Benefits of Distributed Generation Systems

1. Shorter construction times
2. Reduced financial risk of over- or under-building
3. Reduced project cost-of-capital over time due to better alignment of incremental demand and supply
4. Lower local impacts of smaller units may qualify for streamlined permitting or exempted permitting processes, reducing fixed costs per kW
5. Significantly reduced exposure to technology obsolescence
6. Local job creation for manufacturing, technician installers/operators
7. Higher local, small-business development and taxes vs. overseas manufacturing
8. Lower unit-cost, automated manufacturing processes shared with other mass-production enterprises (i.e., automotive industry)
9. Shorter lead times reduce risk of exposure to changes in regulatory climate
10. Significant reduction in fuel disruption risk (portfolio of locally produced fuels and “fuel-less” technologies—solar, wind)
11. Reduced fuel-forward price risk
12. Reduced trapped equity
13. Reduced exposure to interest-rate fluctuations
14. Potential for more modular, routine analysis for capital expansions
15. Multiple off ramps for discontinued projects, without same level of risk
16. Ability to redeploy portable resources as demand profiles change
17. Portability = Higher capacity utilization
18. Reduced site remediation costs after decommissioning
19. Higher system efficiency reduces ratio of fixed-to-variable costs (fuel)
20. Potential for lower unit costs for replacement parts when mass produced
21. Displaces that portion of customer load with highest line losses
22. Displaces that portion of customer load with greatest reactive power requirements
23. Displaces that portion of customer load with highest marginal energy costs
24. Weather-related (solar, wind) interruptions more easily predicted and of shorter duration than equipment failures at central plants
25. “Hot swap” capability – when one DG module (panel, tracker, inverter, turbine) is unavailable, all other modules continue operating
26. Load siting reduces or eliminates line losses on electric transmission and distribution lines
27. Inherently improved system stability due to multiplicity of inputs
28. Reduced regional consequences of system failure
29. Improved transmission and distribution reliability due to reduced peak loading, conductor and transformer cooling.
30. Fast ramping within the distribution system, ability to reduce harmonic distortions at customer’s site.

Possible Negative Impacts of Distributed Generation on Reliability

In light of the many potential benefits associated with DG, there has been a large body of work devoted to addressing a number of concerns with regard to the impact of DG on system stability and safety. Standards agencies, such as the IEEE, have promulgated interconnection standards to protect both the grid and the DG equipment. Some states have instituted interconnection rules that serve the same purpose. However, some of the equipment required to meet these standards or other utility-imposed rules can be costly, especially if used for smaller scale DG projects. Research is on-going to find better solutions and to optimize the use of DG in the grid.

Some researchers are also examining possible common cause failure modes that could become important if the use of DG grows. One DG failure mode, the loss of local natural gas supply, is also important for central generation as more central station power plants use that relatively clean fuel.

II. THEORETICAL ANALYSIS FOR OPTIMAL PLACEMENT OF DG ON A RADIAL FEEDER

To simplify the analysis, only overhead lines with uniformly distributed parameters are considered,
i.e., R and L per unit length are the same along the feeder while C and G per unit length are neglected. The loads along the feeder are assumed to be time-invariant.

A. Theoretical Analysis

(i). A Radial feeder without DG

First consider a radial feeder without DG. The loads are distributed along the radial feeder with the phasor load current density as shown in Fig.1. Hence, the phasor current flowing through the feeder at point x (the distance x being measured from the receiving end) is

\[ I(x) = \int_{0}^{x} I(x) \, dx \] .................. (1)

Assuming the impedance per unit length of line is, the incremental power loss in x is

\[ dP(x) = \left( \left| \int_{0}^{x} I(x) \, dx \right| \right)^{2} R \, dx \] .................. (2)

The total power loss along the feeder is

\[ P_{loss} = \int_{0}^{1} dP(x) = \int_{0}^{1} \left( \left| \int_{0}^{x} I(x) \, dx \right| \right)^{2} R \, dx \] ........ (3)

(ii.) A Radial feeder with addition of DG at location \( x_0 \)

Consider a DG is added into the feeder at the location \( x_0 \), as injected current source as shown in Fig.1. The feeder current between the source (at \( x=1 \)) and the location of DG (at \( x=x_0 \)) will also change as result of injected current source. The feeder current after adding DG can be written as follows:

\[ I(x) = \begin{cases} \int_{0}^{x_0} I(x) \, dx & 0 \leq X \leq X_D \\ \int_{x_0}^{X} I(x) \, dx - I_{DG} & X_0 \leq X \leq L \end{cases} \] .......... (4)

The corresponding power loss in feeder is

\[ P_{loss} = \int_{0}^{x_0} \left( \left| \int_{0}^{x} I(x) \, dx \right| \right)^{2} R \, dx + \left( \left| \int_{x_0}^{X} I(x) \, dx - I_{DG} \right| \right)^{2} \, R \, dx \] ........ (5)

(iii).Procedure to find the optimal placement of DG on a Radial Feeder

The goal is to add DG at location to minimize the power loss in the feeder. Differentiating the equation (5) with respect to and setting the result to zero, i.e.

\[ \frac{dP_{loss}}{dx} = 0 \] ........................................ (6)

The solution of the above equation will give the optimal site for minimizing the power loss.

III. ANALYTICAL APPROACH FOR OPTIMAL PLACEMENT OF DG UNIT ON A RADIAL FEEDER WITH SOME TYPICAL LOAD DISTRIBUTIONS

We will illustrate the procedure to find the optimal placement of DG on radial feeder with the following three different load distributions: (a) uniformly distributed loads, (b) Centrally distributed loads and (c) Increasingly distributed loads. These types of load profiles are shown in the Fig.2 through Fig. 4 (a) Uniformly distributed loads: For uniformly distributed load profile, the phasor load current density is constant and can be used to calculate the total feeder without DG is

\[ P_{loss} = \int_{a}^{2} I_{a}^{2}(x) \, R \, dx \] ......... (7)

After adding DG, using equation (5), it can be shown that total power loss along the feeder with DG is

\[ P_{loss} = I_{a}^{2}(x) \, R \, I_{DG}^{2} - I_{a}(x) \, I_{DG}(l^{2}-x_{0}^{2}) \] \\
\[ + I_{DG}^{2}(l^{2}-x_{0}^{2}) \] ....................................... (8)

From optimal location of DG, different equation with respect to \( x_0 \) and equating it to be zero, we can evaluate the optimal location of DG unit to be at equation

\[ x_0 = \frac{I_{DG}}{2 \, I_{a}(x) \, R} \] ........................................ (9)

If the DG units supply all the loads then substituting value in the equation (9), the optimal location of a DG on the feeder is
\[ X_0 = \frac{l}{2} \] ................................. (10)

Hence, substituting the values of \( x_0 \) in equation (8), the total power loss after adding the DG on feeder is

\[ P_{\text{loss}} = \frac{I_{\text{d}2}(x) \cdot R_1 \cdot I_1^2}{12} \] ................................. (11)

Hence from equation (7) and (11), the power loss reduction after adding the DG on a feeder is,

\[ \frac{P_{\text{loss}}}{I_{\text{d}2}(x) \cdot R_1 \cdot I_1^2} \times \frac{1}{4} = \frac{P_{\text{loss}}}{I_{\text{d}2}(x) \cdot R_1 \cdot I_1^2} \times \frac{1}{3} \times 100 \]

\[ = \% \] ................................. (12)

Thus power loss reduction is

\[ = \frac{I_{\text{d}2}(x) \cdot R_1 \cdot I_1^2}{12} / \frac{I_{\text{d}2}(x) \cdot R_1 \cdot I_1^2}{3} \times 100 \]

\[ = 75 \] ................................. (13)

Fig. (2A) uniformly distributed loads

(b) Centrally distributed loads:

Consider centrally distributed load profile, the phasor current density can be taken as shown in fig.

\[ I(x) = \int_0^x I(x) \cdot dx \] ................................. (14)

\[ I(x) = \begin{cases} \int_0^x I(x) \cdot dx & ; 0 \leq X \leq \frac{l}{2} \\ \int_0^{\frac{l}{2}} I(x) \cdot dx - \int_0^x (1-x) \cdot dx & ; \frac{l}{2} \leq X \leq l \end{cases} \]

\[ = \begin{cases} \int_0^x I(x) \cdot dx - \int_0^{\frac{l}{2}} (1-x) \cdot dx & ; \frac{l}{2} \leq X \leq l \end{cases} \]

Using equation (3), the total power loss along the feeder before adding the DG

\[ P_{\text{loss}} = \int_0^x dP_{\text{loss}} = (0.00312) \cdot I_{\text{id}}^2 \cdot R_1 \cdot I_1^2 \] ................................. (16)

\[ I(x) = \begin{cases} \int_0^x I(x) \cdot dx & ; 0 \leq X \leq \frac{l}{2} \\ \int_0^{\frac{l}{2}} I(x) \cdot dx - I_{DG} \cdot G & ; \frac{l}{2} \leq X \leq l \end{cases} \]

Using a similar procedure given above, it can be shown that the power loss along the feeder after adding DG is

\[ P_{\text{loss}} = \int_0^x dP_{\text{loss}} = (0.00312) \cdot I_{\text{id}}^2 \cdot R_1 \cdot I_1^2 \] ................................. (17)

(c) Increasingly distributed loads:

Total power loss along the feeder after adding the DG is

\[ P_{\text{loss}} = \int_0^x dP_{\text{loss}} = (0.0155) \cdot I_{\text{id}}^2 \cdot R_1 \cdot I_1^2 \] ................................. (18)

\[ \int_0^x I(x) \cdot dx \] ................................. (15)
Fig. (4A) increasingly distributed loads:

IV. ANALYTICAL AND SIMULATION RESULTS AND DISCUSSIONS

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Power loss Before adding DG</th>
<th>Power loss After adding DG</th>
<th>Percentage of power loss reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniformly Distributed</td>
<td>((I_1^2(x)R_{1}^2)/3)</td>
<td>((I_2^2(x)R_{1}^2)/12)</td>
<td>75</td>
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<tr>
<td>Centrally Distributed</td>
<td>((0.0239)I_{id}.R_{1}^2)</td>
<td>((0.0031).I_{id}^2.R_{1}^2)</td>
<td>86.9</td>
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<tr>
<td>Increasingly Distributed</td>
<td>((0.133).I_{id}.R_{1}^2)</td>
<td>((0.155).I_{id}.R_{1}^2)</td>
<td>88.3</td>
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</table>

Table 1

Table I shows the results of analysis, using the foregoing procedure, to find the optimal location for placing DG on a radial feeder with three different load distributions; uniformly distributed load, centrally distributed load and increasingly distributed load and the results shown in Table I, it is assumed that the DG supplies all the loads on the feeder in each case, and the distribution system supplies the system power losses significantly when it is located properly. Several simulation studies with different load distributions were carried out to verify the results obtained analytically for radial systems. A radial feeder with a DG was simulated under uniformly distributed, centrally distributed and increasingly distributed loads. The simulated system for uniformly distributed loads is shown in Fig. 5. The system architecture is the same when the loads are centrally distributed or increasingly distributed. The line parameters, DG and load sizes are listed in Table II. For each type of load configuration, the rating of DG is chosen to be equal to the load on the feeder. The total system power loss is calculated by adding DG at each bus location one-by-one: (i), the proposed analytical method and (ii) simulation method. The simulations studies were carried out using SIMULINK tool box in MATLAB. The figures 6.A, 7.A and 8.A show the analytical results for the total system power loss of the radial feeder with three different load distributions (uniformly, centrally and increasingly distributed loads) and different sizes of DG are located at each bus locations. The results obtained using simulation studies are shown in figures 6.B, 7.B and 8.B. The figures show the results of power losses after adding DG on a radial feeder having different types of concentrated loads like uniformly, centrally and increasingly distributed loads respectively. The magnitude of power losses decreases to minimum value and again increases with the location of DG source from sending end bus to receiving end bus on feeder. In uniformly distributed radial feeder, 3.5 MW size of DG gives minimum amount of loss at bus no.8 and loss as optimal loss. It is concluding that the bus no.8 is called optimal location or place of DG and 3.50 MW DG is the optimal size. From these figures, it is noted that (i). The values of the system power losses obtained by all these methods are nearly equal. (ii). The system power losses are dependent upon the location of DG. (iii). The optimal location of DG is obtained by selecting a bus at which the system power loss is minimum. (iv). At optimal location of DG, the system power losses are reduced significantly. (v). The optimal location of DG obtained in each method is in agreement with the other methods. In Table III, the optimal bus for placing DG to minimize the total system power loss is given for each load distribution. The total system power losses are given both with and without DG. It is noted that the simulation results agree well with the theoretical results.

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Load at each buses (MW)</th>
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</thead>
<tbody>
<tr>
<td>Uniformly Distributed</td>
<td>0.5  0.5  0.5  0.5  0.5  0.5</td>
</tr>
<tr>
<td>Centrally Distributed</td>
<td>0.05 0.1 0.2 0.3 0.4 0.5 0.4</td>
</tr>
<tr>
<td>Increasingly Distributed</td>
<td>0.05 0.15 0.2 0.25 0.3 0.35 0.4</td>
</tr>
<tr>
<td>DG size (MW)</td>
<td>U  C  I</td>
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<td></td>
<td>5.5  2.6  3.3</td>
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Table 2

<table>
<thead>
<tr>
<th>Line Loading</th>
<th>DG (MW)</th>
<th>Analytical Simulated</th>
<th>(T_1) with DG</th>
<th>(T_1) without DG</th>
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<tbody>
<tr>
<td>Uniformly Distributed</td>
<td>5.5  6  6  356  102</td>
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<tr>
<td>Centrally Distributed</td>
<td>2.6  6  6  95  13</td>
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<td></td>
<td></td>
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<tr>
<td>Increasingly Distributed</td>
<td>3.3  9  9  208  29</td>
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Table 3
V. CONCLUSION

This paper presents analytical approaches to determine the optimal location for placing DG on a radial feeder to minimize power losses. The proposed approaches are not iterative algorithms, like power flow programs. Therefore, there is no convergence problems involved, and results could be obtained very quickly. A series of simulation studies have been conducted to verify the validity of the proposed approaches, and results show that the proposed methods work well. In practice, there are other constraints which may affect the DG placement. Nevertheless, methodologies presented in this paper can be effective, instructive, and helpful to system designers in selecting proper sites to place DGs.

REFERENCES