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Distributed Generation Allocation For Power Loss Minimization And Voltage Improvement Of Radial Distribution Systems Using Different Techniques

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Abstract
Numerous advantages attained by integrating **Distributed Generation (DG)** in distribution systems. These advantages include decreasing power losses and improving voltage profiles. Such benefits can be achieved and enhanced if DGs are optimally sized and located in the systems. This paper presents a distribution generation (DG) allocation strategy to improve node voltage and power loss of radial distribution systems using different techniques. The objective is to minimize active power losses while keep the voltage profiles in the network within specified limit. The optimal DG placement and sizing problem is investigated using following approaches. Here, the optimization problem is treated as single-objective optimization problem, where the system's active power losses are considered as the objective to be minimized. Firstly, BIBC, BCBV matrices are formed on a 34 bus test system using data's of a reference paper. Also, examples of BIBC and BCBV matrices of IEEE 5 Bus system are discussed. Then, different methods of loss minimization are considered for fulfilling the purpose.The DG's impacts on the existing power system are also investigated in this dissertation. Analytical methods for finding optimal sites to deploy DG sources in power systems are presented and verified with simulation studies.

Keywords: *Distributed Generation, Optimal Placement, BIBC Matrix, BCBV Matrix.*

1. Introduction

Electrical energy is continuously lost due to resistance in power system networks, and distribution system loss accounts for more compared to transmission system [1]. Moreover, distribution systems are well known for a higher ***R*/X ratio** compared to transmission systems and significant voltage drops can result in substantial power and energy losses along distribution feeders. As a result, loss reduction in distribution systems is one of the greatest challenges to many utilities around the world. Reconfiguration and capacitors placement is two major methods for loss reduction in distribution systems. In recent years, penetration of DG into distribution systems has been increasing around the world. Major reasons for this trend are liberalization of electricity markets, constraints on building new transmission and distribution lines and environmental concerns [2], [3]. For instance, a research by the **Electric Power Research Institute (EPRI)** estimates that DG will be about 25% of the new generation by 2010, while a similar study by the **National Gas Foundation** shows that this figure could be even higher, account for nearly 30% [3]. Given this trend, if DGs are placed properly and appropriately sized, they could also be considered as an effective way to reduce losses, improve voltage profiles and increase reliability. There is a wide range of terminologies used for **"distributed generation,"** such as **"embedded generation," "dispersed generation,"** or **"decentralized generation"** [3]. DG essentially means a small-scale power station different from a traditional or large central power plant. At present, there are several technologies ranging from traditional to non-traditional used in DG application. The former is non-renewable technologies such as internal combustion engines, combined cycles, combustion turbines, and micro-turbines. The latter technologies include fuel cells, storage devices, and a number of renewable energy-based technologies such as photovoltaic, biomass, wind, geothermal, ocean, etc. When renewable energy-based DG units are placed for loss reduction, both aspects of sustainable energy, i.e., renewable energy and energy efficiency are addressed. The challenges in DG applications for loss reduction are proper location, appropriate sizes, and operating strategies. Even if the location is fixed due to some other reasons, improper size would increase the losses in the system beyond the losses for case without DG. Optimal sizing and location depend on the type of DG as well. Hence, in this report, an attempt is made to develop simple analytical expressions for sizing, which can be easily calculated.

2. Definition

It refers to power generation at the point of consumption. Generating power on- site, rather than centrally, eliminates the cost, complex, interdependencies, and inefficiencies associated with transmission and distribution. Historically, DG means combustion generators (e.g. diesel equipment's). They were affordable and in some cases reliable, but they are not clean and continuous. Recently, solar energy has become one popular DG, due to its clean and continuous properties.

Distributed energy is generated or stored by a variety of small, grid- connected devices referred to as – **Distributed Energy Resources (DER)**.They are – mass- produced, small and less site- specific.

A brief summary of each definition is given below:

1. Standardized and modular generation source using RES in a range of up to MW (Austria)
2. Co-generation connected to the distribution network (Belgium)
3. Source less than 10 MW, not centrally planned and connected to the Distribution Network (Bulgaria)
4. Source not operated by utility (Czech Republic)
5. Source without agreement between the owner and the TSO (Denmark)
6. Source less than 50 MW for local consumption and/or for selling to the utility (Estonia)
7. Source less than 20 MW, not centrally planned and not centrally dispatched, and connected to the Distribution Network (Finland)
8. Electricity generation plant owned by a third party, connected to the grid (France)
9. Integrated or stand-alone modular source close to the point of consumption (Germany)
10. Small scale power generation connected to distribution grid (Greece)
11. Source less than 10 MW using RES or cogeneration used mainly for Heat (Hungary)
12. Co-generation less than 1 MW rating and close to the end user (Italy)
13. Generation not active in system balancing (The Netherlands)
14. Source connected to the Distribution Network (Norway)
15. Electricity or Heat source connected to the user (Poland)
16. Decentralized source less than 50 MW rating (Romania)
17. Source less than 100 MW, not centrally planned and dispatched, and connected to the Distribution Network (Slovakia)
18. Modular generation less than 50 MW located at the customer site (Spain)
19. Source connected to the Distribution Network or to the customer site (Sweden)
20. Source not connected to the Transmission system (UK)
21. For the Republic of Ireland, the definition deals with 'small generators' or 'embedded generators' but not directly to distribution generation.

After studying and analyzing several papers, proposed a general definition for DG, suggesting that the most apt definition would be **"an electric power source connected directly to the distribution network or on the customer side of the meter"**.

2.1 LITERATURE REVIEW

Classically, most distribution systems (DS's) are radial in nature, contain only one power source, and serve residential, commercial and industrial loads. DSs are also operated at the lowest voltage levels in the overall power networks [1]. Power is delivered in bulk to substations. The substation is usually where the transmission and distribution networks meet. The backbone of the distribution networks typically is comprised of 3-phase mains. Laterals are tapped off these mains and are usually single-phase (unless 3-phase service is required by a customer) [1-2]. In addition, the lines used for DSs tend to have a higher resistance to impedance ratio (R/X) than the lines in transmission networks [2]. The modern power distribution network is constantly being faced with a very rapid growing load demand, this increasing load is resulting into increased burden and reduced voltage also effect on the operation, planning, technical and safety issues of distribution networks [8-10]. This power loss in distribution networks have become the most concerned issue in power losses analysis in any power networks. In the effort of reducing power losses within distribution networks, reactive power compensation has become increasingly important as it affects the operational, economical and quality of service for electric power networks [9-10]. The planning should be such that the designed system should economically and reliably take care of spatial and temporal load growth, and service area expansion in the planning horizon [11-12]. In [11], various distribution networks planning models presented. The proposed models are grouped in a three-level classification structure starting with two broad categories, i.e., planning without and with reliability considerations. Planning of a distribution system relies on upon the load flow study. The load flow will be imperative for the investigation of distribution networks, to research the issues identified with planning, outline and the operation and control. Thusly, the load flow result of distribution networks ought to have efficiency and time proficient qualities. The load flow for distribution system is not alike transmission system due to some in born characteristics of its own. There are few techniques are available in literature. Ghosh and Das [14] proposed a method for the load flow of radial distribution network using the evaluation based on algebraic expression of receiving end voltage. Dharmasa et al. [15] presented non-iterative load flow solution for voltage improvement by Tap changer Transformer in the distribution networks. Teng et al. [16] has proposed the load flow of radial distribution networks employing node-injection to branch-current (BIBC) and branch-current to node-voltage (BCBV) matrices. With the deregulation of energy markets, escalating costs of fossil fuels, and socio-environmental pressures, power networks planners are starting to turn away from the centralized power networks topology by installing smaller, renewable-powered generators at the distribution level [3-5] which is known as distributed generation. Renewable energy source (RES) based DGs are wind turbines, photovoltaic, biomass, geothermal, small hydro, etc. Fossil fuel based DGs are the internal combustion engines (IC), combustion turbines and fuel cells [3] [6-7] [13].

2.2 BIBC and BCBV Matrix formation

BIBC and BCBV matrices investigate the topological structure of distribution networks. Basically the BIBC matrix is making an easy relation between the node current injections and branch currents. These relations give a simple solution for branch currents variation, which is occurs due to the variation at the current injection nodes, these can be obtained directly by using BIBC matrix. The BCBV matrix builds an effective relation between the branch currents and node voltages. The concern variation of the node voltages is produced by the variant of the branch currents.

$$[IB] = [BIBC][I]$$
$$[\Delta V] = [BCBV][IB]$$

Joining the above two equations, the relations between the node current injections and node voltages could be communicated as:

$$[BCBV] = [BIBC]^T.[ZD]$$
$$[\Delta V] = [BIBC]^T.[ZD][BIBC][I]$$
$$[DLF] = [BCBV][BIBC]$$
$$[DLF] = [BIBC]^T.[ZD][BIBC]$$
$$[\Delta V] = [DLF][I]$$
$$[\Delta V] = [BCBV][BIBC][I]$$

The iterative solution for the distribution system load flow can be obtained by solving various equations which are specified below:

$$I_i^k = I_i^r(V_i^k) + j.I_i^i(V_i^k) = \left(\frac{P_i + j.Q_i}{V_i^k}\right)^*$$
$$[\Delta V^{k+1}] = [DLF].[I^k]$$
$$[V^{k+1}] = [V^0] + [\Delta V^{k+1}]$$

The new definition as given uses just the DLF Matrix to take care of Load Flow Problem. Subsequently, this strategy is extremely time-efficient, which is suitable for on-line operation and Optimization Problem of distribution networks.

2.3 Algorithm for distribution networks load flow

The algorithm steps for load flow solution of distribution networks are given below:

Step 1: Read the distribution networks line data and bus data.

Step 2: Calculate the each node current or node current injection matrix. The relationship can be expressed as –

$$[I] = [\frac{S}{V}]^* = [\frac{P - j.Q}{V^*}]$$

Step 3: Calculate the BIBC matrix.

Step 4: Evaluate the branch current by using BIBC matrix and Current Injection Matrix (ECI).

Step 5: Form the BCBV matrix.

Step 6: Calculate the DLF matrix.

Step 7: Set Iteration $k = 0$

Step 8: Iteration $k = k + 1$

Step 9: Update voltages by using previous equations, as –

$$I_i^k = I_i^r(V_i^k) + j.I_i^i(V_i^k) = \left(\frac{P_i + j.Q_i}{V_i^k}\right)^*$$
$$[\Delta V^{k+1}] = [DLF].[I^k]$$
$$[V^{k+1}] = [V^0] + [\Delta V^{k+1}]$$

Step 10: If $max((|V(k+1)| - |V(k)|) > tolerance)$ go to step 6.

Step 11: Calculate branch currents, and losses from final node voltages.

Step 12: Display the node voltage magnitudes and angle, branch currents and losses.

Step 13: Stop.

2.4 Algorithm for distribution networks load flow with DG

The algorithm steps for load flow solution of distribution networks are given below:

Step 2: Calculate DG power and capacitor bank power for each nodes and update the system bus data.

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Step 3: Calculate the total power demand with DG or capacitor bank or with both by the help of previous equations. The relationship can be expressed as –

$[S] = [S_{Di}] - [S_{DGi}] - [S_{CBi}]$

Step 5: Calculate the modified impedance matrix and modified current injection matrix for tap changer by the help of previous equations.

Other steps are same as before.

2.5 Optimal Placement of DG on a Radial Feeder

For the purpose of simplifying the analysis, only overhead transmission lines with uniformly distributed parameters are considered, i.e., R and L (series resistance and inductance) per unit length are the same along the feeder while the shunt capacitance and susceptance of lines are neglected. The loads along the feeder are assumed to vary in discrete time duration; for example, the feeder load distributions along the line for time durations T_i and T_{i+1} are shown in figure below-

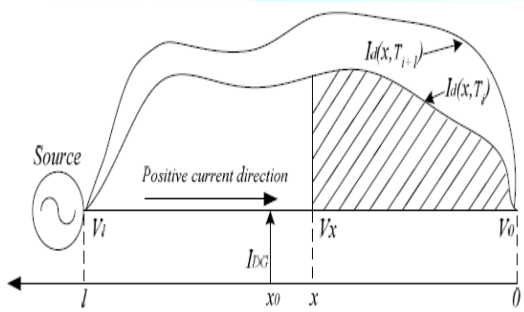

Fig. 1 Optimal Placement of DG on a Radial Feeder

At first, we will consider a radial feeder without DG. During the time duration T_i, the loads are distributed along the line with the phasor current density $I_d(x, T_i)$ as in above diagram.

The phasor feeder current at point x is:

$$I(x, T_i) = \int_0^x I_d(x, T_i)dx \quad (1)$$

Assuming the impedance per unit length of the line is $Z = R + jX \left(\frac{Ohm}{Km}\right)$, then the incremental power loss and phasor voltage drop at point x are:

$$dP(x, T_i) = \left(\left|\int_0^x I_d(x, T_i)dx\right|\right)^2.Rdx \quad (2)$$

$$dV(x, T_i) = \left(\int_0^x I_d(x, T_i)dx\right).Zdx \quad (3)$$

Now, total power loss along the feeder within the time duration T_i:

$$P_{loss}(T_i) = \int_0^l dP(x, T_i) = \int_0^l \left(\left|\int_0^x I_d(x, T_i)dx\right|\right)^2.Rdx \quad (4)$$

Voltage drop between point x and the receiving end:

$$V_{drop}(x, T_i) = [V_x(T_i) - V_0(T_i)] = \int_0^x dV(x, T_i) = \int_0^x \int_0^x I_d(x, T_i)dx.Zdx$$

(5)

Here, voltage at point x:

$$V_x(T_i) = [V_0(T_i) + V_{drop}(x, T_i)] = [V_l(T_i) - V_{drop}(l, T_i) + V_{drop}(x, T_i)]$$

(6)

Now, total voltage drop across the feeder:

$$V_{drop}(l, T_i) = [V_l(T_i) - V_0(T_i)] = \int_0^l dV(x, T_i) = \int_0^l \left(\int_0^x I_d(x, T_i)dx\right).Zdx$$

(7)

Now, consider a DG is added into the feeder at location x_0 as in diagram.

In general, load current density $I_d(x, T_i)$ changes (normally, decreases) as a result of adding DG due to improvements in voltage profile along the line.

This change in the load current density will cause the feeder current to decrease.

Feeder current between source (at $x = l$) and DG location (at $x = x_0$) is also changes as a result of injected current source $I_{DG}(T_i)$.

However, the change in feeder current due to the change in the load current density is generally much smaller than the change in the feeder current due to the injected current $I_{DG}(T_i)$.

So, here, changes due to load current density are neglected.

So, after adding DG $I_d(x, T_i)$ is used as in equation (1).

Here, feeder current:

$$I(x, T_i) = \begin{cases} \int_0^x I_d(x, T_i)dx & ; (0 \le x \le x_0) \\ \int_0^x I_d(x, T_i)dx - I_{DG}(T_i) & ; (x_0 \le x \le l) \end{cases} \quad (8)$$

Corresponding power loss and voltage drop in the feeder are:

$$P_{loss}(x_0, T_i) = \int_0^{x_0} \left(\left|\int_0^{x_0} I_d(x, T_i)dx\right|\right)^2.Rdx + \int_{x_0}^l \left(\left|\int_0^x I_d(x, T_i)dx - I_{DG}(T_i)\right|\right)^2.Rdx$$

(9)

$$V_{drop}(x, T_i) = \begin{cases} \int_0^x \int_0^x I_d(x, T_i)dx.Zdx & ; (0 \le x \le x_0) \quad \ldots\ldots\ldots\ldots (10) \\ \int_0^{x_0} \int_0^x I_d(x, T_i)dx.Zdx + \int_{x_0}^0 \left(\int_0^x I_d(x, T_i)dx - I_{DG}(T_i)\right).Zdx & ; (x_0 \le x \le l) \end{cases}$$

The average power loss in a given time period T is:

$$\overline{P_{loss}}(x_0) = \frac{1}{T}.\sum_{i=1}^{N_t} P_{loss}(x_0, T_i).T_i \quad (11)$$

Where, $N_t \rightarrow$ number of time durations in the time period T

$$T = \sum_{i=1}^{N_t} T_i \quad (12)$$

Equation (6) can still be used under this situation to calculate voltage at point x obtained from equation (10).

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2.6 Procedure to find the Optimal Location of DG on a Radial Feeder

The goal is to add DG in a location to minimize the total average power loss and assure that the voltages V_x along the feeder are in the acceptable range, 1 ± 0.05 p.u. that is:

$$\frac{d\overline{P_{loss}}(x_0)}{dx_0} = 0 \qquad (13)$$

The solution x_0 of the above equation will give the optimal site for minimizing the power loss, but it cannot guarantee that all the voltages along the feeder are in the acceptable range. If the voltage regulation cannot be satisfied at the same time, the DG can be placed around x_0 to satisfy the voltage regulation rule while decreasing the power loss as much as possible or the DG size can be increased. The analytical procedure to determine the optimal point to place DG on a radial feeder is given as follows:

1. Find the distributed load $I_d(x, T_i)$ along the feeder.
2. Get the output current of DG $I_{DG}(T_i)$.
3. Use equations (9) & (11) to calculate $\overline{P_{loss}}(x_0)$ and find the solution x_0 of equation (13).
4. Use equations (6) & (10) to check whether the voltage regulation is satisfied.
5. If all the voltages are in the acceptable range, then the calculated x_0 is the optimal spot (X_{op}) to add DG.
6. If x_0 doesn't meet the voltage regulation rule, then move the DG to see whether there is a point around point x_0,where all bus voltages are in the acceptable range.
7. If no point on the feeder can satisfy the voltage regulation rule, then increase the size of DG and repeat steps (2) to (7).
8. Sometimes more than one DG may be needed. Under this situation, the feeder can be divided into several segments and steps (1) to (7) can be applied to each segment.

2.7 Optimal Placement of DG in Networked Systems

The theoretical analysis for placing a DG in networked systems is different and more complicated than in a radial feeder. To simplify the analysis, only one DG is considered to be added to the system. Consider the system shown in Figure below with a DG added to the system to reinforce it. The system has N buses and loads, and the DG is located at a bus, say bus j. The main external power is injected into bus 1, which is taken as slack bus. The objective is to find the bus to install the DG so that the total system power loss is minimized and the voltage level at each bus is held in the acceptable range, 1 ± 0.05 p.u.

Before the DG is added to the system, the bus admittance matrix is

$$Y_{bus}^0 = \begin{bmatrix} Y_{11}^0 & Y_{12}^0 & \cdots & Y_{1j}^0 & Y_{1N}^0 \\ & \vdots & \ddots & \vdots & \\ Y_{N1}^0 & Y_{N2}^0 & \cdots & Y_{Nj}^0 & Y_{Nj}^0 \end{bmatrix}$$

Assuming that the DG is located at bus j, the system admittance matrix is changed from Y_{bus}^0 to Y_{bus} by considering that bus 1 and bus j are connected together. Actually there is no line to connect those buses together, but the imaginary line will help in finding the optimal location to add DG. Y_{bus} Has one dimension less than Y_{bus}^0 except when the DG is located at bus 1. If the DG is at bus 1, Y_{bus} matrix will be the same as Y_{bus}^0. To obtain the new matrix Y_{bus} when the DG source is connected, we treat the system as connecting bus 1 *and* j by eliminating bus j in Y_{bus}^0.
The new matrix is:

$$Y_{bus} = \begin{bmatrix} Y_{11} & Y_{12} & \cdots & Y_{1k} & Y_{1(N-1)} \\ \vdots & & \ddots & & \vdots \\ Y_{(N-1)1} & Y_{(N-1)2} & \cdots & Y_{(N-1)k} & Y_{(N-1)(k-1)} \end{bmatrix}$$

Where,

$Y_{11} = Y_{11}^0 + Y_{jj}^0 + 2Y_{1j}^0$

$Y_{1k} = Y_{1k}^0 + Y_{jk}^0, k = 2, \dots\dots, j-1$

$Y_{1k} = Y_{1(k+1)}^0 + Y_{j(k+1)}^0, k = j, \dots\dots, N-1$

$Y_{k1} = Y_{1k}, k = 2, \dots\dots, N-1$

$Y_{ik} = Y_{ik}^0, 2 \leq (i, k) \leq j-1$

$Y_{ik} = Y_{i(k+1)}^0, 2 \leq i \leq j-1, j \leq k \leq N-1$

$Y_{ik} = Y_{(i+1)k}^0, j \leq i \leq N-1, 2 \leq k \leq j-1$

$Y_{ik} = Y_{(i+1)(k+1)}^0, j \leq (i, k) \leq N-1$

$$Z_{bus} = Y_{bus}^{-1} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1k} & Z_{1(N-1)} \\ \vdots & & \ddots & & \vdots \\ Z_{(N-1)1} & Z_{(N-1)2} & \cdots & Z_{(N-1)k} & Z_{(N-1)(k-1)} \end{bmatrix}$$

Suppose complex load power of the original system:

$S_L^0 = [S_{L1}^0, S_{L2}^0, \dots\dots, S_{Li}^0, \dots\dots, S_{LN}^0]$

Complex generated power of the original system:

$S_G^0 = [S_{G1}^0, S_{G2}^0, \dots\dots, S_{Gi}^0, \dots\dots, S_{GN}^0], i = 1, 2, \dots\dots, N$

And, $S_{Li} = 0$, for $i = 1$ (slack bus);

$S_{Li} = S_{Li}^0$, for i = load buses;

$$S_{Li} = \begin{cases} P_{Li}^0 - P_{Gi}^0 + j0 & P_{Li} > P_{Gi} \\ 0 & P_{Li} \leq P_{Gi} \end{cases}, \qquad \text{for } i = P - V \text{ buses.}$$

Note that at the slack bus (bus 1) $S_{Li} = 0$, it is assumed that the real and reactive power consumed by the load is supplied directly by the external generation at that bus. Also, at a voltage controlled (P-V) bus, $Q_{Li} = 0$ it is assumed that the load reactive power can be supplied by the external power source at the P-V bus.

To find the optimal point to place the DG, we set up an objective function for DG at each bus j as follows:

$$f_j = \sum_{i=1}^{j-1} R_{1i}(j)|S_{Li}|^2 + \sum_{i=j+1}^{N} R_{1j}(j)|S_{Li}|^2, j = 2, \dots\dots, N \qquad (23)$$

Where, $R_{1i}(j)$ is the equivalent resistance between the bus 1 and bus i when DG is located at bus $j, j \neq 1$.

$$R_{1i}(j) = \begin{cases} Real\,(Z_{11} + Z_{ii} - 2Z_{1i}) & ; i < j \\ Real\,(Z_{11} + Z_{(i-1)(i-1)} - 2Z_{1(i-1)}) & ; i > j \end{cases} \qquad (24)$$

When the DG is located at bus $1 (j = 1)$,the objective function will be:

$$f_1 = \sum_{i=1}^{N} R_{Li} |S_{Li}|^2 \qquad (25)$$

Note that in this case, $Y_{bus}(Z_{bus})$ will be the same as $Y_{bus}^0(Z_{bus}^0)$ and $R_{11} = 0$.

The goal is to find the optimal bus m where the objective function reaches its minimum value.

$$f_m = Min(f_j), j = 1,2, \dots \dots \dots, N \qquad (26)$$

The theoretical procedure to find the optimal bus to place DG in a networked system can be summarized as follows:

1. Find the matrix Y_{bus}^0 and set up the load vector S_L.
2. Compute Y_{bus} and the corresponding Z_{bus} for different DG locations.
3. Calculate the equivalent resistances according to (24).
4. Use (23) and (25) to calculate objective function values for DG at different buses and find the optimal bus m.
5. If all the voltages are in the acceptable range when the DG is located at bus m, then bus m is the optimal site.
6. If some bus voltages do not meet the voltage rule, then move the DG around bus m to satisfy the voltage rule.
7. If there is no bus that can satisfy the voltage regulation rule, try a different size DG and repeat steps (5) and (6).

Here we assumed that only one DG source is added to the system, it can be easily extended to the systems with multiple DG sources. By connecting all the DG buses and slack bus together through imaginary lines, the new Y_{bus} matrix and the corresponding objective function can be established by the method presented above.

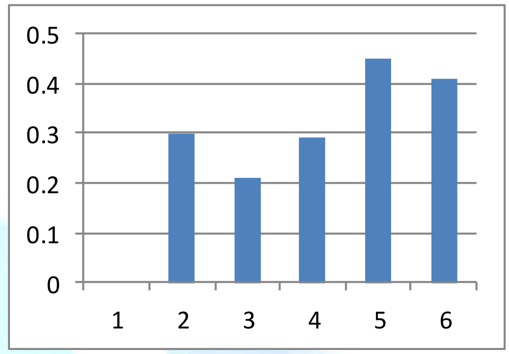
3. Simulation Results

3.1 Simulation results of case studies with time invariant loads and DGs

Line Loading	*Optimal Bus No. (Simulation)*	*Optimal Place (Theoretical)*	Total Power Losses (kW)	
			Without DG	With DG
Uniform	6	6	1.7785	0.2106
Central	6	6	0.2589	0.0275
Increasing	8	8	0.8099	0.0606

3.2 Power losses of the system with a 5MW DG

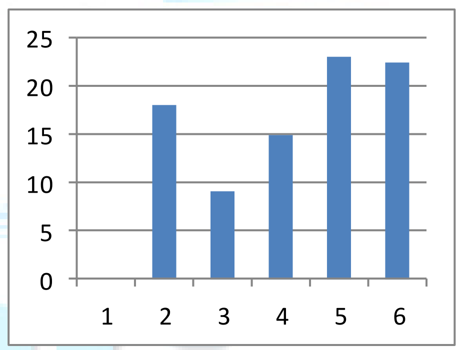
Power Loss (MW)



DG Location (Bus number)

3.3 Values of the objective function

Value of the Objective Function



DG Location (Bus Number)

4. Conclusions

Analytical approaches are presented in this paper to determine the optimal location for placing DG in both radial and networked systems 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 were also 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 here can be effective, instructive and helpful to system designers in selecting proper sites to place DGs.

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