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Optimal Allocation of Distributed Generators in a Competitive Electricity Market

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This paper presents a sensitivity based technique for assisting network planners to determine the optimal location and capacity of distributed generators (DG) in a capacity and location constrained distribution network with the objective of minimization of losses in a competitive electricity market. The liberalization of electricity markets has changed the way power generation technologies are valued. The issues that need to be considered in the choice of rating and positioning of DG include both technical and commercial factors. The proposed methodology takes this aspect into consideration and only from among the practicable sites specified by the Distribution system planner both optimal locations and capacity of DGs are determined. It has been applied to a test system of nine bus radial distribution network considered as capacity and location constrained for implementing DG. The technique is efficient and very much useful as it can be directly applied to any distribution network having practical constraints for implementing DG. To show the effectiveness of this technique it was applied to IEEE 6-bus system without any location or capacity constraint and the result was compared with test results of other methods. It is interesting to note that over a wide range of DG penetration the proposed methodology results in largest reduction in loss per unit DG penetration.

Keywords: *distributed generation, optimal allocation, loss sensitivity index, loss reduction index*

1.0 INTRODUCTION

The necessity for flexible electric systems, changing regulatory and economic scenarios, energy savings and environmental impact have paved the way for the development of Distributed Generation (DG), which is predicted to play an increasing role in future power system. Distributed Generation is the application of small generators, distributed throughout a distribution system close to the customer sites. It is a viable alternative to conventional sources of electric power to be supplied for industrial, commercial and residential applications.

The issues that need to be considered for identifying the feasible sites for the implementation of Distributed Generation is discussed below [1]-[5].

DG technologies are typically installed for one or more of the following applications:

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- Energy independence
- Standby power
- Peak shaving
- Grid support
- Net energy sales (net metering)
- Combined heat and power (CHP)
- Premium power

Some of the benefits of the DGs are listed below:

- More reliable power, especially for those in areas where outages are common.
- Some DG equipment is able to provide high-quality premium power for sensitive applications.
- Cost savings can be realized by reducing the peak demand at a facility, therefore lowering demand charges.
- DG equipment can provide power to remote applications where traditional transmission and distribution lines are not an option.
- Environmental benefits of DG solutions include a reduction in emissions for some technologies.
- Reduction of losses in the distribution system: System losses are affected by changes in power flows in the distribution network. On-site generation will cut system losses by reducing power demand on the system.
- The electricity is also delivered either at or closer to the correct voltage for distribution.
- DGs can help to prevent power cuts. If there is a partial failure on the high voltage network, then an operating wind farm can prevent local customers from power cut.
- Deferral of upgrades to the transmission system: When a transmission system is congested, an appropriately located DG can reduce the congestion and thus can defer the need for an upgrade.
- Deferral of upgrades to the distribution system; If a distribution network is operating near capacity or needs to be upgraded to accommodate power flows from generator, DG installed at a transformer station, for example, may allow a distribution company to cope with the problem, delaying the need to upgrade distribution assets.

Following are some of the aspects to be considered in DG siting:

- Value of energy, reliability and power quality to the user
- Intermittent or available on demand
- Energy constrained or not
- Environmental acceptability
- Availability and cost of fuels for renewable resources
- Some locations more valuable than others and some locations more suitable for production than others
- Among the popular DG technologies photovoltaic and wind are location restricted, intermittent and not available on demand whereas gas turbines and fuel cells are available on demand and less restricted on location

The following factors play a role in determining the size, technology and profile of the DG to be selected:

- Back-up emergency power
- Peak shaving, load curtailment or participating in demand response/price response programs
- DG to provide base load and use the grid as back-up
- On-site opportunities to use waste heat

- Incentive programs to increase the value of the installation

Some of the applications of the popular DG technologies are listed below:

- Reciprocating engine – Backup power, base load, grid support and peak shaving.
- Fuel cells–Co-generation, grid support.
- PV arrays – Base load, peak shaving.
- Wind – Remote power, Grid support.
- Micro turbines – Standby Power, power quality, reliability, peak shaving, co-generation.
- Biomass – Co-generation, grid support.

Some of the limitations of the Popular DG technologies are given below:

- Photovoltaic: Very expensive at this time, though the prices are decreasing. The technical potential is potentially much greater but unlikely that sufficient photovoltaic arrays would be installed to resolve the transmission issues because of high cost.
- Wind energy: Intermittent source, influenced by the quality of the available wind resource.
- Biomass: Availability limited by the practicality of transporting, which could both increase the cost and decrease the public acceptance of the project.
- Fuel cells: Requires hydrogen for operation. Impractical to use hydrogen directly as a fuel source; instead, it must be extracted from hydrogen-rich sources such as gasoline, propane, or natural gas. Cost effective, efficient fuel reformers that can convert various fuels to hydrogen are necessary to allow fuel cells increased flexibility and commercial feasibility.
- Gas turbines: Low electric efficiency has limited turbines to primarily peaking unit and combined heat and power (CHP) applications.
- Micro turbines and small combustion turbines: Less efficient than larger combustion turbines, economical if they are co-generation units.
- Stirling engines: Limitations of materials, heat transfer efficiency and engine design currently constrain overall efficiency.

Opening up the electricity sector to competition is an important tool to improve efficiency of power generation and there by benefit the consumers. Producers have ceased to be protected by their exclusive rights to generate and supply electricity. Competitive markets provide the driving force for generators to innovate and operate in the most efficient and economic manner in order to remain in the business and recover their costs. The competitive electricity market thereby offers customers and industry participants a wide range of benefits.

Distributed generation will reduce system losses by reducing the total amount of electricity delivered through the distribution system. Customers with DG capture this benefit to some extent, as losses are reflected in distribution charges. The extent to which DG help avoid distribution losses will vary according to their locations. Thus the reduction in losses has a direct impact on the cost of electricity. Distributed generation output needs to be adjusted to reflect this.

The foreseeable large use of DG in the future requires the distribution engineers to properly take into account a number of significant impacts of DG on the operation of the distribution network.

The installation of DG in the network has technical, environmental and commercial challenges that need to be managed properly if the benefits are to be achieved. Technical challenges include the adequacy of the network's and associated plants thermal rating, fault levels and sufficient voltage support to ensure both the security and quality of electric supply. Environmental challenges depend on the generation technology chosen. Commercial challenges are the changing market conditions and regulations, energy and fuel prices, operating costs, maximum operating profit, and the value of reduced losses in the distribution network. The problem therefore is multi-faceted with a number of objectives some of which will inevitably conflict with one another [6].

In many cases because of the economical constraints and other barriers the DG capacity that is installed is only a small fraction of what can be installed based on the technical potential of the site.

New connections of DG must be evaluated to identify and quantify any adverse impact both technical and commercial. The economic implications can make potential schemes less attractive and in some instances has been an impediment to the development of DG technology.

In the light of the above discussion, in any distribution network not all the sites are practicable for DG implementation and therefore it is imperative to determine the optimal location from among the practicable sites only.

2.0 PROBLEM FORMULATION

The proposed methodology is to determine the optimal location and capacity of distributed generators in a capacity and location constrained distribution network with the objective of minimization of losses in a competitive electricity market.

In the proposed methodology optimal locations and size of DGs in a distribution network is determined from among the specified practicable sites by applying sensitivity based technique.

Some of the sites may not at all be feasible for DG implementation whereas for few other sites there could be a limitation on the maximum DG capacity that can be injected. There could also be a limit on the maximum number of sites at which DG can be implemented. The injection of DG capacity should be technically and commercially viable and practicable.

Since the producers of electricity are forced to pass the cost of electrical line losses to all customers in terms of higher energy cost, in competitive electricity market minimization of distribution losses is very important. Distributed generation will reduce system losses and to quantify this benefit of DG, an index is proposed called as Loss Reduction Index (LRI). It is given by

LRI = (Initial loss-final loss) x 100 / Total DG capacity injection.

The objective of the proposed methodology is minimizing the system losses giving due consideration to all such requirements.

Optimal DG placement is a constrained optimization problem where the objective function is to maximize the reduction in losses in the system, i.e.

$$\text{Max } \left[\sum_{ij} P_{Loss} - \sum_{ij} P_{Loss\ G}\right]$$

P_{Loss} is the power loss in the system without distributed generation and $P_{Loss\ G}$ is with distributed generation and *i,j* represent the series circuit element of each line.

The following are the constraints

Practicability constraints:

- Feasibility of the site for DG implementation.
- Capacity limitation constraint
  $P_{Gi} \le P_{Gi\ max}$
- Total no. of DGs limit
  $N_G \le N_{G\ max}$

Technical constraints:

- Voltage level limits

$$V_{i\,min} \leq V_i \leq V_{i\,max}$$

- Branch flow limits (they must remain below thermal limits)

$$S_{ij} \leq S_{ij\,max}$$

- Fault current limits (they must be less than the maximum fault current rating of the switchgear on each line)

$$I_{Fij} \leq I_{Fij\,max}$$

Optimal locations and size of DGs are determined from among the specified practicable sites by applying sensitivity based technique subject to the above constraints.

The optimal siting and sizing are combined in the methodology by applying DG at the optimal locations chosen from among the practicable sites only.

3.0 SOLUTION METHODOLOGY

3.1 Optimal Siting DG

A sensitivity analysis is used to select the candidate locations for the placement of DG in the system.

There have been previous works done where in sensitivity indices related to steady state stability, voltage control and power losses have been used to locate reactive power devices on the bulk power system [7,8] as well as for the placement of DG [9]. A similar approach has been used in this paper to select the candidate locations. The selected candidate locations are those where the placement of DG will have greatest effect in reducing the power losses.

The complex power loss is given by

$$P_{Loss} + j\,Q_{Loss} = VI^* = VY^*V^* \quad (1)$$

$$P_{Loss} = \sum_{i=1}^{N} \sum_{j=1}^{N} V_i\,V_j\,Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \quad (2)$$

N = Number of buses

Sensitivity of the systems real power loss with respect to the nodal real and reactive powers are given by:

$$(\partial P_{Loss}/\partial P) = (\partial P_{Loss}/\partial V)\,(\partial V/\partial P) \quad (3)$$

$$(\partial P_{Loss}/\partial Q) = (\partial P_{Loss}/\partial V)\,(\partial V/\partial Q) \quad (4)$$

Taking the partial derivatives of P_{Loss} of "(2)" with respect to V_i and δ_i gives

$$\partial P_{Loss}/\partial V_i = 2\sum_{j=1}^{N} V_j\,Y_{ij} \cos\theta_{ij} \cos(\delta_i - \delta_j) \quad (5)$$

$$\partial P_{Loss}/\partial \delta_i = -2V_i \sum_{j=1}^{N} V_j Y_{ij} \cos\theta_{ij} \sin(\delta_i - \delta_j) \quad (6)$$

The relationship between incremental loss and Jacobian is given as [8]

$$\begin{bmatrix} \partial P_{Loss}/\partial P \\ \partial P_{Loss}/\partial Q \end{bmatrix} = ([\mathbf{J}]^T)^{-1} \begin{bmatrix} \partial P_{Loss}/\partial \delta \\ \partial P_{Loss}/\partial V \end{bmatrix} \quad (7)$$

The loss sensitivity index [9] is defined as

$$LSI = w\,(\partial P_{Loss}/\partial P) + (1-w)\,(\partial P_{Loss}/\partial Q) \quad (8)$$

where w is the weighting factor, the value of which will depend on the X/R ratio of the network under consideration.

The buses are arranged in the descending order of their ranks based on loss sensitivity index. Those sites which are practicable with highest ranks are the candidate locations for the placement of DG.

3.2 Optimal Siting and sizing of DG

In the solution methodology, the optimal locations and the capacity allocations are determined by an iterative process [7].

At each iteration, a fixed incremental capacity of DG is introduced at the highest ranked site among the practicable sites and the power flow equations are solved. Check for the violation of any constraint is done and if any constraint is violated, the injection is transferred to the next highest ranked site among the practicable sites. The solution is reached when there is no decrease in the system losses with any further injection of DG.

3.3 Solution algorithm

Based on the solution methodology described in the previous section a solution algorithm has been developed and the flow chart is as shown in Fig. 1.

1. Run the power flow using Newton Raphson method and determine the initial power loss.
2. Determine loss sensitivity indices of all the sites and arrange them in the descending order of their ranks.
3. At every iteration, check whether the highest ranked site is a practicable site. If it is not a practicable site, check the next highest ranked site.
4. Apply the fixed incremental size DG at the highest ranked practicable site.
5. Run the power flow and check for the feasibility. If it is feasible go to step 7.
6. If any of the constraint is violated, discard the injection of the DG capacity and apply it to the next highest ranked practicable site and go to step 5.
7. Calculate the system losses. If the losses are less than the value of the previous iteration retain the DG injection and return to step 2.
8. Otherwise iterative process is terminated and the results are printed.

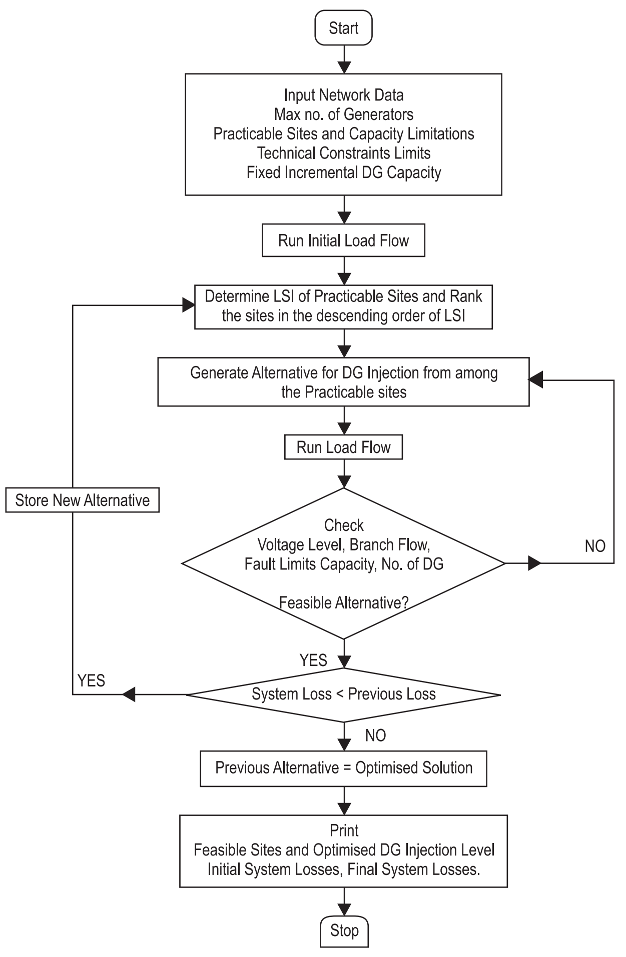

FIG. 1 FLOWCHART FOR OPTIMAL ALLOCATION FOR DISTRIBUTED GENERATORS

4.0 CASE STUDY AND NUMERICAL RESULTS

To ascertain the effectiveness of the developed methodology it was applied to IEEE six bus system and the simulation results were compared with the test results of other techniques. The proposed methodology was also applied to a nine bus radial distribution network assumed to be capacity and location constrained.

4.1 IEEE six bus system

The developed methodology was applied to IEEE six bus system shown in Fig. 2 without any capacity and location constraint. The simulation results are given in Table 1 and the initial LSI is as shown in Fig. 3 with the ranking of the load buses in the order 3-4-2-6.

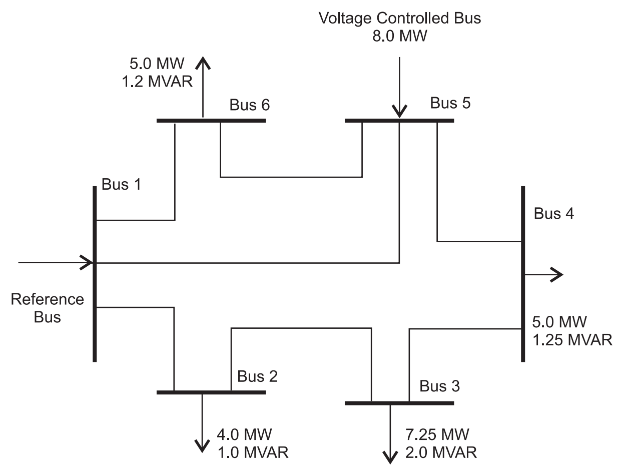

FIG. 2 IEEE SIX BUS SYSTEM

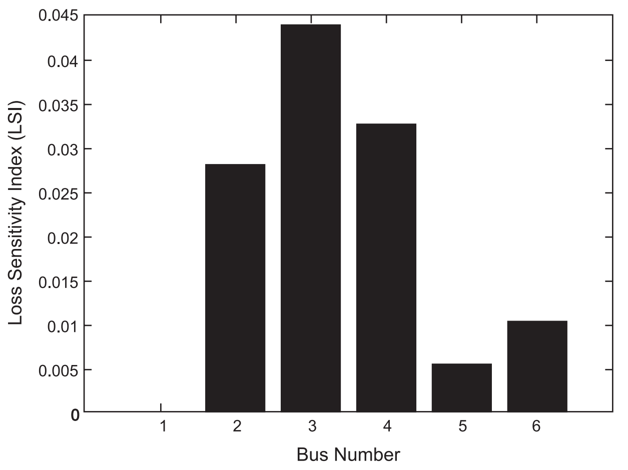

FIG. 3 INITIAL LOSS SENSITIVITY INDEX

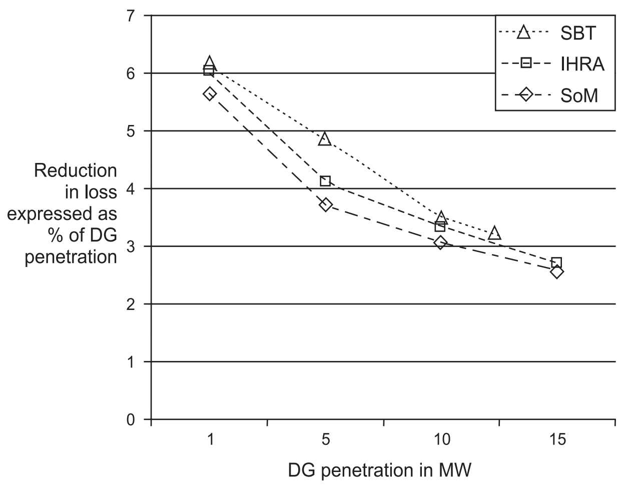

FIG. 4 LRI-REDUCTION IN LOSS EXPRESSED AS A PERCENTAGE OF DG PENETRATION.

The test results of the developed sensitivity based technique (SBT) are compared in Table 2 with the test results [10] of Improved Hereford Ranch Algorithm (IHRA), Improved Simple

TABLE 1

SIMULATION RESULTS

Injection at buses (MW)				Losses (MW)
2	3	4	6	
-	-	-	-	.4555
3.6	6.9	1	0.1	.0941

TABLE 2

COMPARISON OF SYSTEM LOSSES BY SBT, IHRA, ISGA AND SOM AT VARIOUS LEVELS OF DG PENETRATION

Total injection (MW)	Losses (MW)			
	SBT	IHRA	ISGA	SoM
1.0	0.3937	0.39507	0.39514	0.3985
5.0	0.2109	0.24960	0.24966	0.2687
10.0	0.1058	0.12141	0.12149	0.1479
11.6	0.0941	-	-	-
15.0	-	0.04981	0.04987	0.0693

Genetic Algorithm (ISGA) and second order method (SoM) and are graphically represented in Fig. 4.

The results are interesting and promising since it indicates that in the proposed methodology the Loss Reduction Index (LRI) which is the reduction in loss expressed as a percentage of DG penetration is largest over a wide range of DG penetration in comparison with other methods.

4.2 Nine bus radial system

Radial distribution systems serving loads far away from transmission and sub-transmission lines are widely used. Any DG units introduced in such lines will typically have low ratings (a few kilowatts upto a few megawatts), most likely installed by customers in their premises. However DG units in the tens of megawatts (upto 100MW) will most likely find their place in medium-voltage sub-transmission systems [11]. The nine bus radial test system used belongs to this category and the network is as shown in Fig. 5. As an example, buses 2, 3, 5, 6 and 9 have been considered as practicable sites with maximum permissible injection at bus no.5 as 55 MW only and also DGs can be installed at a maximum of three practicable sites. All the DGs are assumed to inject only real power.

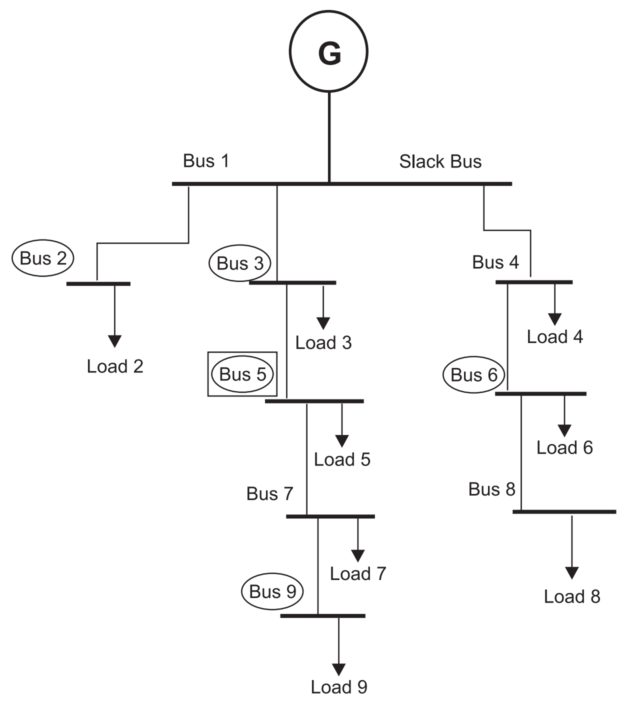

FIG. 5 NINE BUS RADIAL SYSTEM

From the simulation results the initial LSI of all the buses is as shown in Fig. 6. The practicable sites have the initial ranking in the order 9-6-5-3-2.

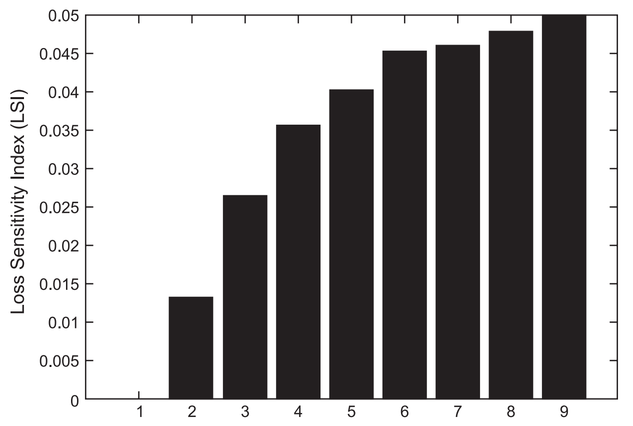

FIG. 6 INITIAL LOSS SENSITIVITY INDEX

Table 3 shows the results of simulation with DGs provided at three optimal locations among the five practicable sites. The total injection is 155 MW with the breakup of DG capacity as shown in the Table.

Table.IV gives the simulation results assuming that all the sites are practicable. In this case the DGs will be provided at the three most optimal sites of the network. These sites are the buses 7, 8 and 9. The total injection in this case is 149 MW.

Table.V gives the comparison of LRI- reduction in loss expressed as a percentage of DG penetration.

TABLE 3

SIMULATION RESULTS FOR SPECIFIED FIVE PRACTICABLE SITES

Injection at buses (MW)			Losses (MW)
5	6	9	
-	-	-	1.3911
55	72	28	0.4314

TABLE 4

SIMULATION RESULTS WITH ALL SITES PRACTICABLE

Injection at Buses (MW)			Losses (MW)
7	8	9	
-	-	-	1.3911
61	68	20	0.4314

TABLE 5

LRI-REDUCTION IN LOSS EXPRESSED AS A PERCENTAGE OF DG PENETRATION

Practicable sites	TotalInjection (MW)	LRI-Reduction in loss expressed as a percentage of DG penetration
All	149	0.644
2, 3, 5, 6 & 9	155	0.615

5.0 CONCLUSIONS

A sensitivity based technique for assisting network planners to determine the optimal location and capacity of distributed generators (DG) in a capacity and location constrained distribution network with the objective of minimization of losses in a competitive electricity market is presented.

Injection of DG capacity should be technically and commercially viable and practicable. In any distribution network not all the sites are practicable for DG implementation and therefore it is imperative to determine the optimal locations from among the practicable sites only. The developed methodology determines optimal allocation of DG taking all these aspects into consideration.

Since the producers of electricity are forced to pass the cost of electrical line losses to all customers in terms of higher energy cost, in competitive electricity market minimization of distribution losses is very important. Due consideration has to be given to the value of the reduced losses in the network. Distributed generation will reduce system losses and to quantify this benefit of DG an index is proposed called as Loss Reduction Index (LRI).

The results obtained from this technique has been compared with the test results of Improved Hereford Ranch Algorithm, Improved Simple Genetic Algorithm and second order method.

The results are interesting and promising since it indicates that in the proposed methodology LRI reduction in loss expressed as a percentage of DG penetration is largest over a wide range of DG penetration in comparison with other methods.

6.0 APPENDIX

TABLE A- 1

LOAD DATA FOR RADIAL SYSTEM UNDER STUDY (400 MVA BASE)

Bus	Load (pu)	PF
1	-	-
2	0.3000	0.91
3	0.1000	0.93
4	0.1250	0.94
5	0.0750	0.94
6	0.0750	0.94
7	0.0625	0.95
8	0.0500	0.94
9	0.0500	0.95

TABLE A-2

LINE DATA FOR RADIAL SYSTEM UNDER STUDY (400MVA BASE)

From	To	Line Impedance		Length (KM)
		r (pu/km)	x (pu/km)	
1	2	0.000625	0.00375	10
1	3	0.000625	0.00375	20
1	4	0.000625	0.00375	30
3	5	0.000625	0.00375	15
4	6	0.000625	0.00375	15
5	7	0.000625	0.00375	10
6	8	0.000625	0.00375	10
7	9	0.000625	0.00375	15

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