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Optimal Allocation of Multiple Distributed Generators for Network Loss Reduction & Voltage Profile Improvement

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***Abstract*— In the present energy scenario, increased concerns are shown towards distributed generation (DG) driven by renewable energy resources. DG is a small scale generating units that are connected near to customer load center or directly to the distribution network. Such DGs has capability of altering power flow, system voltage, and the performance of the integrated network. When DGs are integrated to existing distributed network, offers many techo-economical benefits. To maximize the availing benefits, optimal DG planning is necessary. The two critical issues of DG planning are: (1) Optimal placement of DG (2) Optimal sizing of DG. In this paper, the optimal locations for DG units are found out by using three sets of indices, such as Power loss reduction index (PLRI), Voltage deviation index (VDI), & Multi-Objective Ranking index (MORI) and optimal sizing of DGs at optimal locations is decided for both voltage profile improvement and network loss reduction. The buses with the lowest value of MORI are the candidate buses for allocation of DG units. The effectiveness of the proposed methodology has been tested on standard IEEE-33 bus radial distribution system using MATLAB 2014. The method has potential to be a tool for identifying the best locations and capacity of DGs to be installed for improving voltage profile and reducing power losses in a distribution system as the results are very much encouraging.**

***Index Terms*—Distributed Generation (DG), Multi-Objective Ranking Index (MORI), Optimal Allocation, Power Loss Reduction Index (PLRI), Voltage Deviation Index (VDI).**

I. INTRODUCTION

A. Distributed Generation

Distributed power generation is any small-scale power generation technology that provides electric power at a site closer to customers sites to meet specific customer needs, to support economic operation of the existing power distribution grid or both. A distributed power unit can be connected directly to the consumer or to a utility's transmission or distribution system. These technologies are usually-small enough to add in increments that better match today's rate of load growth characteristics. It has the potential to improve the reliability of the power system, reduce power and energy losses, improve voltage profile and offer clean, efficient, reliable and flexible on-site power alternatives. The Power systems consist of a number of DG technologies. Some of these technologies have been used for long time while others are emerging fast. DG technologies often consist of modular generators, and they offer a number of potential benefits. Some of DG technologies are small gas turbine, wind turbines, micro turbine, solar photovoltaic, fuel cells, biomass and small geothermal generating plants.

In order to achieve the maximum benefits from the integration of DG with distribution system it is essential to determine the best location and sizing of DG in a distribution system. The optimal allocation of DG in a distribution system as following technical and economic benefits such as Voltage support and power quality improvement, Utility system reliability improvement, Voltage profile improvement, Spinning reserve support during generation outages, Reduction in line losses and hence reduce demand for the grid, Environmental impact in terms of reduction in polluting emission as compared with traditional power plants, Transmission and distribution costs can be reduced since the DG units are closer to the customers, DG plants offer good efficiencies especially in co-generations and combined-cycles (for larger plants) and many more. The main applications of DG can be found in the applications involving Base load, Standby Power, Standalone systems, Peak load shaving, Rural and remote applications, Combined Heat & Power (CHP), & Grid support[5].

B. Review of Literature

F.Gonzalez-Longatt *et.* al [1] describe a brief summary of DG definitions, from different institution around the world. In this paper distributed generation is considered as source of electrical power connected to the distribution network or to the customer site, which is smaller than main generating plant. Nibedita Ghosh *et.* al [2] describe a load flow based approach for determining the optimum allocation of DG units in distribution system using ETAP software. The aim of this paper is to improve system voltage profile and loss minimization. Julius Kilonzi Charles *et.* al [3] presents a GA-PSO based approach, which utilizes combined sensitivity factor analogy to optimally locate and size a multi-type DG in IEEE 57-bus test system with the aim of reducing power losses and improving the voltage profile. Chiradeja and Ramkumar [4] presented a general approach and set of indices to assess and quantify the technical benefits of DG in terms of voltage profile improvement, environmental impact reduction. Maruthi Prasanna. H. A *et.* al [5] developed an analytical approach for optimal placement of combined DG and capacitor units in radial distribution system, in which the optimal location of combined DG and capacitor is found out by using two sets of indices such as PLRI and VDRI. The DG unit is placed with an objective of loss minimization and capacitor unit is placed for voltage deviation reduction. Seyed Reza Seyednouri *et.* al [6] proposed a PSO algorithm based approach to find the optimal location and sizing of PVDGs in distribution system to minimizing the power loss and improving voltage profile by penetrating PVDG. The proposed algorithm is tested on IEEE 33 bus system. The optimal sitting and sizing of DG units in electrical distribution system is found by using different algorithms, such as Imperialist Competitive Algorithm (ICA), Artificial bees colony Algorithm (ABCA), Fuzzy and Real Coded Genetic Algorithm (RCGA) to reduce the power losses and to improve the voltage profile of radial distribution system. These algorithms are tested on various IEEE test system [7-11].

From the literature survey it has been observed that many authors have emphasized the importance of distributed generators in a distribution system. Proper location of DG's in power system is important for obtaining their maximum potential benefits. In the present paper, the DG placement problem is solved by using indices such as VDI, PLRI & MORI, with an objective to improve voltage Profile and simultaneously reduce losses. Multi-Objective Ranking Index is used to determine candidate bus for placement of DG. The present methodology has been tested on IEEE-33 bus radial distribution test system and results show that there is considerable amount of reduction in system power losses and good improvement in system voltage profile.

The proposed paper is organized as follows: Section II defines the problem and constraints. In Section III, defines solution methodology, Section IV discusses the results obtained by the proposed method and finally, section V concludes the paper.

II. PROBLEM FORMULATION

The problem of optimal allocation of DGs in a distribution system consists of two main objectives and these objectives have to be met satisfying the three constraints. They are explained below.

A. Objectives

The two main objectives of this paper are:

1. Maximize

$$(P_{Loss} - P_{Loss(DG)}) \quad (1)$$

Where P_{Loss} is the total real power loss of a distribution system without DG: $P_{Loss\,(DG)}$ total real power loss of a distribution system with DG.

2. Minimize

$$VDI = \sum_{i=1}^{Nbus} \frac{(V_i - V_n)^2}{V_n^2} \quad (2)$$

Where, V_n is the Nominal Voltage in pu. In this paper, it is taken as 1 pu; V_i is the Voltage at the ith bus in pu.

B. Constraints

The above two objectives have to be met by satisfying the following constraints:

1. **Bus Voltage constraint:** The voltage at each bus should lie within the voltage limits.

   $V_{min} \le V_i \le V_{max}$ i=1, 2.......no of buses

   Where, V_{min} is the minimum acceptable voltage at any bus; V_{max} is the maximum allowable voltage at any bus; V_i is the voltage of any bus i.

2. **Line load ability limit:** Power flow in the line should not exceed the acceptable value.

   $P_{line\,(i,j)} < P_{line(i,j)max}$

   Where, $P_{line(i,j)}$ is the line flow between nodes i and j; $P_{line(i,j)}$ max is the maximum line flow capacity of line between nodes i and j.

3. **Number of DGs and capacity constraint:** The injected power should not exceed the sum of total load and the total real loss of the system.

$$\sum_{i=1}^{Nbus} P_{DGi} = \sum_{i=1}^{Nbus} (P_i + P_L) \quad (3)$$

   Where Nbus= total number of buses

C. Equations

In order to obtain the benefits from integration DG in distribution system, three sets of indices are used in this paper such as VDI, PLRI and MORI. They are explained below.

1) Voltage Deviation Index (VDI):

A voltage deviation index (VDI) as defined as the sum of the squared value of the absolute voltage difference between the nominal voltage and the actual voltage for all buses in the system. Smaller the deviation of bus voltage from the nominal voltage, the better the voltage condition of the system. VDI of the distribution system is given by,

$$VDI = \sum_{i=1}^{Nbus} \frac{(V_i - V_n)^2}{V_n^2} \quad (4)$$

Where, Vn is the Nominal Voltage in pu. In this paper, it is taken as 1 pu; Vi is the Voltage at the ith bus in pu.

The VDI is a measure of the voltage profile of the distribution system and it indicates how the voltage values of the distribution nodes are nearer to the specified voltage. It is expected that this value should be nearer to zero, so that all the nodes of the distribution system will be having voltage nearer to the specified voltage (1 pu) [5].

2) Power Loss Reduction Index (PLRI):

It is defined as ratio of real power loss when DG is connected to the i^{th} bus, to the real power loss without DG connection in the distribution system (Base case loss).

The Power Loss Reduction Index of i^{th} bus when DG is connected to that bus is given by,

$$\text{PLRI (i)} = \frac{PL_{DG}}{PL} \qquad (5)$$

Where, PL_{DG} is the distribution system real power loss when DG is connected to the i^{th} bus; PL is the distribution system real power loss without DG connection.

3) Multi-Objective Ranking Index (MORI)

The Multi-Objective Ranking Index (MORI) is produced by multiplying above two indices. This index is used to identifying the best location of DG in the distribution system, for both voltage profile improvement and loss reduction in the system.

The Multi- Objective Ranking Index of i^{th} bus when DG is connected to that bus is given by,

$$\text{MORI (i)} = \text{VDI (i)} \times \text{PLRI (i)} \qquad (6)$$

Where, VDI (i) is the voltage deviation index and PLRI (i) is the Power loss reduction index when DG is connected to the i^{th} bus.

The node with least value of MORI is taken as best node for DG placement for both voltage profile improvement and loss reduction.

III. Solution Methodology

Two solution methodologies have been developed in this section, one for simple single DG placement and other for multiple DG placements.

A. Solution methodology for simple single DG placement

The solution methodology is in two steps. First step is to identify the optimal location of DG. In this step optimal location of DG is determined by using index called multi-objective ranking index and then optimal size of DG is selected at optimal location.

1. Optimal location of DG using MORI:

The step by step computational procedure for DG location is as follows:

COMPUTATIONAL PROCEDURE

1. Run the base case load flow to obtain base case results.
2. By penetrating DG with 50% of the total feeder loading capacity at each bus at a time, the MORI is calculated using equation (6).
3. The bus with least MORI value will be picked as the best location for the DG placement

The flow chart for finding optimal location for DG placement is shown in Fig (1).

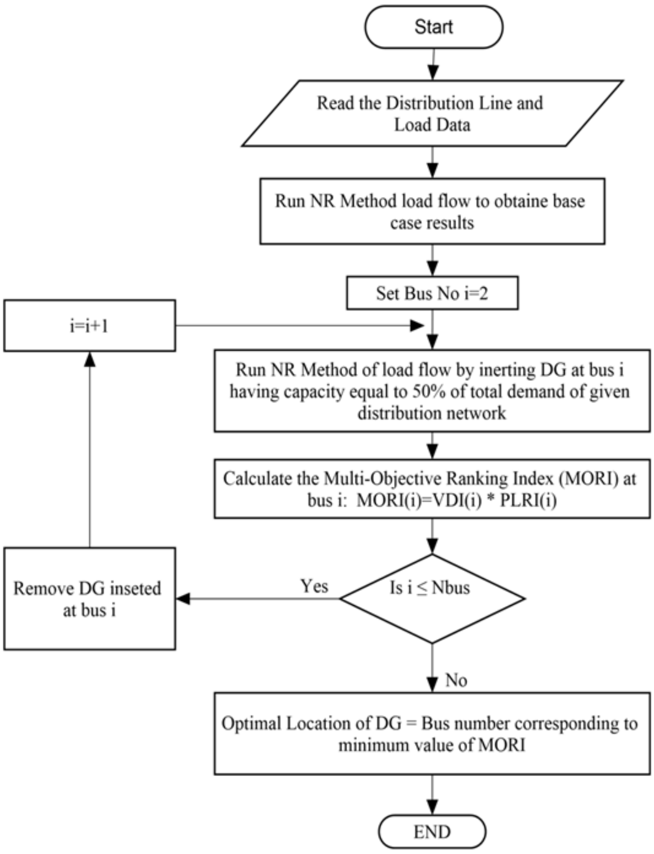

Figure 1: Flowchart for finding optimal location of DG in distribution system using MORI.

2. Optimal Sizing of DG at optimal location:

The step by step computation procedure for deciding optimal size of DG at optimal location is as follows:

1. First, the DG is placed at the bus with least MORI.
2. Keep power factor of DG constant, its size is varied from a minimum value to a value equal to feeder loading capacity in equal steps until the minimum real power loss is found.
3. The DG size which results in minimum real power loss is taken as optimal size at optimal location.

The flow chart for determining the optimal size of the DG to be placed at optimal location for loss minimization and voltage profile improvement is shown in fig (2).

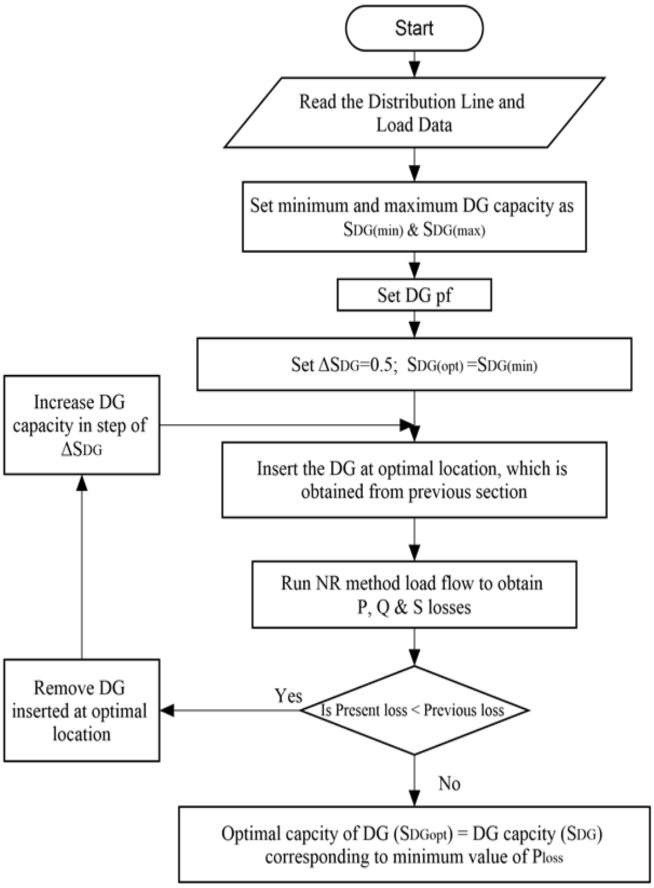

Figure 2: Flow chart for determining the optimal size of the DG to be placed at optimal location for loss minimization and voltage profile improvement.

B. Solution Methodology for multi DG placement

The solution methodology for multi DG placement is as follows:

1. Run the base case load flow to obtain base case results.
2. By penetrating DG with 10% of the total feeder loading capacity at each bus at a time, the MORI is calculated using equation (5).
3. Identify the bus corresponding to the minimum value of MORI.
4. The bus corresponding to the minimum MORI value when DG is inserted at the same bus will be taken as optimal location of DG in the distribution system.
5. Connect incremental size of DG with 5% of total feeder loading capacity at optimal location; simultaneously calculate the real power loss in each step.
6. The capacity of DG corresponding to minimum value real power loss will be taken as optimal size of DG at optimal location.
7. Fix the optimal size of DG at optimal location in distribution network by using following equation,

   New demand (S_{Dopt}) = (Previous demand (S_{Dopt}) – DG injection (S_{DGopt})).
8. Repeat the above steps until DG capacity reach 50% of the total feeder loading capacity.

IV. Case Study and Numerical Results

A. IEEE 33-Bus Radial Distribution System

The solution methodology has been tested on IEEE 33-bus distribution test system with the total load of 3.72 MW and 2.3 Mvar as shown in fig. 3. This radial distribution system having following characteristics: Number of buses=33; Number of lines=32; Slack Bus No=1; Base Voltage= 12.66kV; Base MVA=100MVA. A Newton-Raphson algorithm based load flow program is used to solve the load flow problem for radial distribution system. Simulation is done in MATLAB 2014 to solve load flow based algorithm of an IEEE 33-bus distribution system.

The method to allocate DG unit to reduce losses and improve voltage profile is demonstrated through the simulation of this test network.

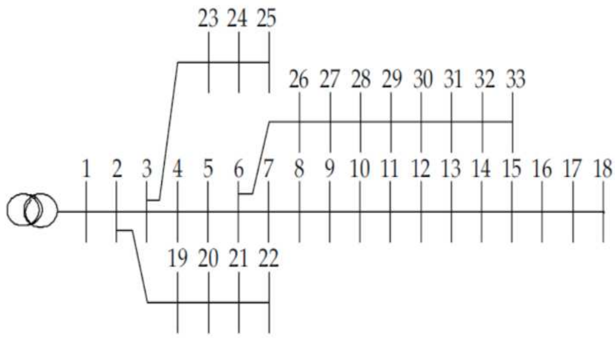

Figure 3: Single line diagram of standard IEEE-33 Bus system

B. *Results for the Base Case*

The active & reactive power losses of the system for the base case are 211 kW, 143.1 kvar respectively. Voltage magnitudes of the system are tabulated in Table I and base case voltage profile as shown in Fig. 4. It is seen that many buses are having voltage lower than 0.92p.u.

TABLE I
BASE CASE BUS VOLTAGE FOR IEEE-33 BUS TEST SYSTEM

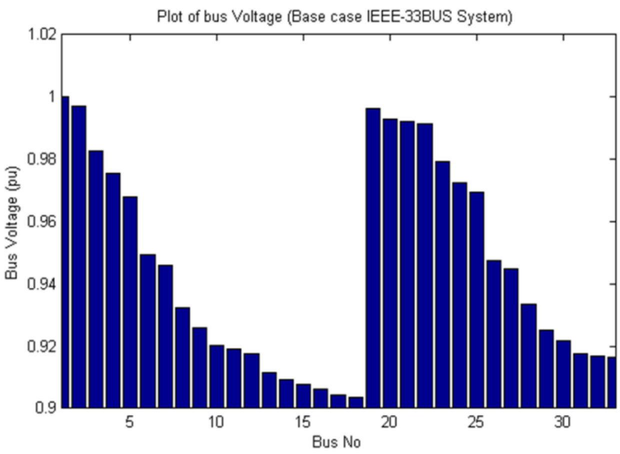

Figure 4: Base Case Voltage Profile for IEEE-33 bus system

C. Results for the Case of Simple Single DG Placement

Table II shows the variation of multi-objective ranking index (MORI) with DG placement. The MORI of each state is found by using Eq.5, after DG installation on each bus. Optimal location for DG having rating 50% of total load of distribution system found to be Bus No: 8 corresponding to minimum value of MORI.

TABLE II
VARIATION OF MORI WITH DG PLACEMENT

Bus No	MORI	Bus No	MORI	Bus No	MORI
2	0.1225	13	0.0175	24	0.0774
3	0.0759	14	0.0218	25	0.0849
4	0.0551	15	0.0264	26	0.0131
5	0.0386	16	0.0319	27	0.0121
6	0.0140	17	0.0420	28	0.0098
7	0.0113	18	0.0463	29	0.0093
8	**0.0054**	19	0.1244	30	0.0096
9	0.0055	20	0.1452	31	0.0124
10	0.0079	21	0.1517	32	0.0136
11	0.0085	22	0.1632	33	0.0151
12	0.0097	23	0.0757		

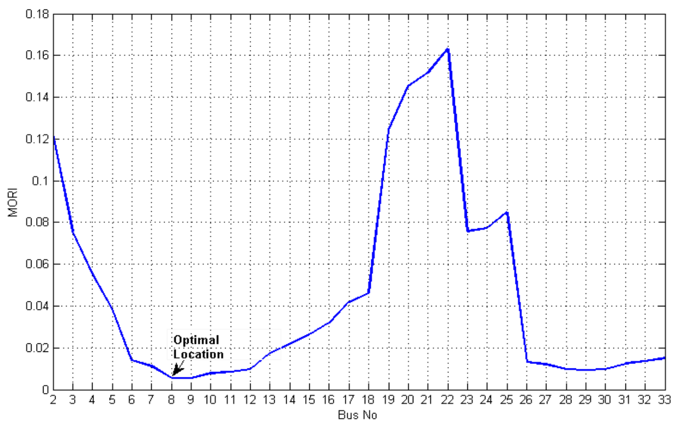

Figure 5: Variation of MORI with DG Placement

Table III gives the optimal capacity of the DG at optimal location. In this case the DG capacity is increased from minimum value to maximum one in steps of 0.5 at different pf and losses are calculated in each step. The DG capacity which gives minimum loss is taken as optimal size.

Bus No	Bus Voltage (p.u.)	Bus No	Bus Voltage (p.u.)	Bus No	Bus Voltage (p.u.)
1	1.0000	12	0.9177	23	0.9793
2	0.9970	13	0.9115	24	0.9726
3	0.9829	14	0.9092	25	0.9693
4	0.9754	15	0.9078	26	0.9475
5	0.9679	16	0.9064	27	0.9450
6	0.9495	17	0.9044	28	0.9335
7	0.9459	18	0.9038	29	0.9253
8	0.9323	19	0.9965	30	0.9218
9	0.9260	20	0.9929	31	0.9176
10	0.9201	21	0.9922	32	0.9167
11	0.9192	22	0.9916	33	0.9164

As shown in table III the optimal capacity of the DG at optimal location is 2MVA at 0.8 pf lag (i.e 1600 kW & 1200 kVAR). The minimum value of loss at this stage is 83.9kW.

TABLE III
COMPARISON OF REAL POWER LOSSES FOR OPTIMAL SIZING OF DG AT OPTIMAL LOCATION

Optimal Location = Bus No 8	**Real Power Loss (P_{loss}) in kW**		
DG Rating in MVA	**CASE 1 (UPF)**	**CASE 2 (0.9 pf lag)**	**CASE 3 (0.8 pf lag)**
0.5	165.0	155.8	155.6
1	135.2	117.4	117.0
1.5	120.4	94.3	93.7
2	**119.3**	**84.9**	**83.9**
2.5	130.9	87.9	86.6
3	154.3	102.3	100.6
3.5	188.7	127.3	125.0
4	233.6	161.9	159.0
Minimum Loss	**119.3**	**84.9**	**83.9**
Optimal DG Size (S_{DG}^{Opt}) in MVA	**2**	**2**	**2**

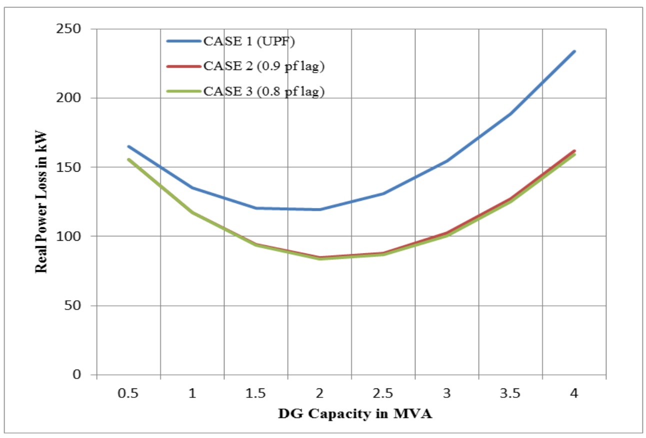

Figure 6: Comparison of real power losses after placement of DG for different cases.

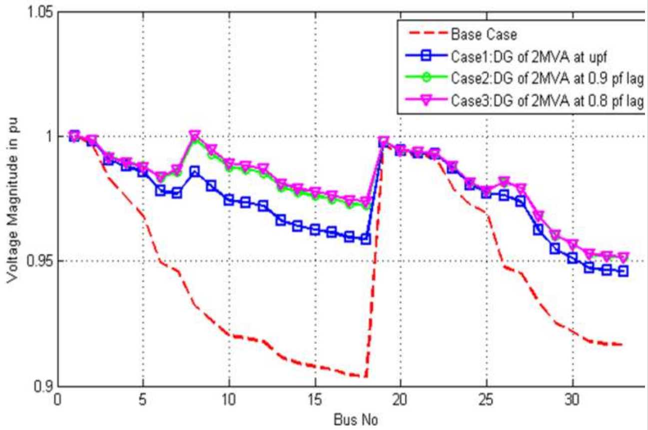

Figure 7: Comparison of System Voltage Profile after DG Placement with Base Case

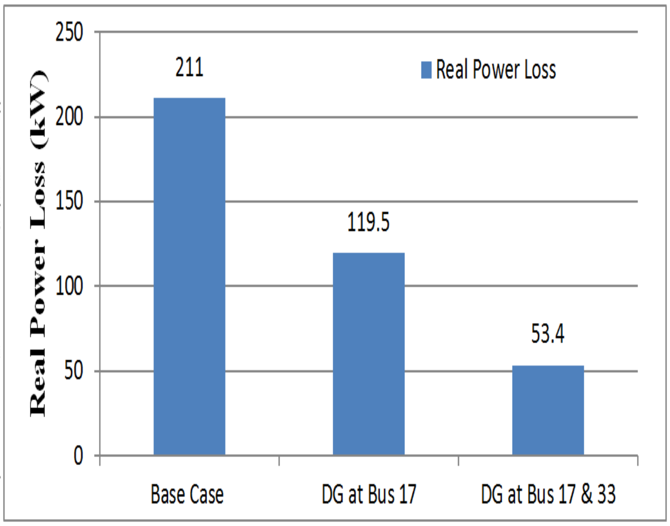

Figure 8: Real Power Loss for different DG placement Scenario

Fig. 7 shows the effect of DG placement on the system voltage profile, there is considerable improvement in the system voltage profile after allocation of DG. Before the placement of DG, minimum voltage in the system is at bus no. 18 is equal to 0.9038p.u. After installing the DG of optimal capacity, the minimum voltage at this bus has improved to 0.9739p.u.

D. Results for the Case of Multi DG Placement

In previous section, placement of single DG in the distribution system is discussed. More than one DG can be optimally placed in the distribution system. Table IV shows the load flow results of optimal size of DGs placed at optimal buses for two iterations.

The Optimal location for DG having rating 10% of total load of distribution system found to be Bus No: 17, 33 corresponding to minimum value of MORI. The optimal size of DGs at optimal locations is found to be 25% of the total load (i.e.928.75kW, 575kvar) corresponding to minimum value of real power loss.

From table IV we conclude that total real power loss of the system is decreases to some more extent as compare to base case loss of distribution system. The decrease in losses at each stage of placement of DG is pictorially shown in Fig. 8

TABLE IV
DG'S PLACEMENT ALGORITHM FOR TWO ITERATIONS

No of Iteration	DG No	Location	DG Capacity		Real power losses (kW)
			P_{DG} (kW)	Q_{DG} (kvar)	
1st iteration	1st DG	17	928.75	575	119.5
2nd iteration	2nd DG	33	928.75	575	53.4

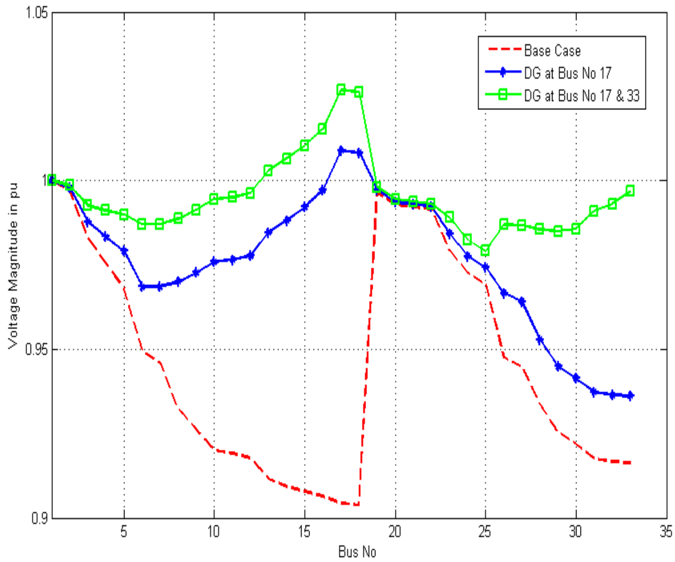

Figure 9: System Voltage profile for Multi DG Placement

Fig 9 shows the effect of DG's placement on the system voltage profile. Before the placement of DG's minimum voltage in the system is at Bus no. 18 and is equal to 0.9037p.u. After installing the first DG, the minimum voltage at this bus has improved to1.008 p.u. finally with first and second DG's installed, the minimum voltage at this bus has improved to 1.0262p.u.

V. CONCLUSION

Distributed Generation (DG) has various technical & economic benefits, when integrated in distribution system. These benefits always depend on placement and sizing of DG. To maximize the benefits it is necessary to find optimal allocation of DG in radial distribution system.

This paper presents simplified approach for optimal allocation of DG in distribution system in which optimal location is determined by using an index called Multi-Objective Ranking Index for improving node voltages and optimal capacity is determined at optimal location for minimizing power loss of the system.

The proposed method has been tested on IEEE-33 radial distribution test system using MATLAB 2014. The Results of this system reveal that integration of DG units at optimal locations is highly effective in terms of better voltage profile and reduced power losses of system.

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