Optimization of Location and Size of Distributed Generation using Simulated Annealing Algorithm

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Abstract- The continuous demand for electrical energy, Constraining distribution lines to supply remote areas and system reliability are the major issues which have increased the commissioning of Distributed Generation (DG). However, the problem of locating and sizing of DGs has been a concern over the past decade. The problem of siting and sizing of DGs has been a concern over the past few years. The installation of DG units at non optimal places can result in an increase in system losses, resulting in the non-optimal voltage profile in the system, which thereby results in increase in costs and producing an effect opposite to the desired. The main idea of this paper is to find the proper location for DGs in order to improve the voltage profile and reduce the power loss of the entire system. The work uses forward and backward sweep load flow algorithm for performing load flow calculations and simulated annealing algorithm for finding location and size of the DG. The efficacy of the proposed methodology is tested on IEEE 33 and IEEE 69 bus radial distribution systems. The results are simulated in MATLAB® and the utilization of DGs for improvement of the system voltage profile is acknowledged.

Keywords: Distribution systems, Distributed generation (DG), Load flow

1. INTRODUCTION

The second industrial revolution has forced the society to depend on electrical energy and this dependence on electrical energy will keep increasing in the future. Furthermore, due to the increased energy consumption there is a need to expand the electricity generating facilities which causes increased CO_2 emissions, if the electricity is generated in conventional power plants. To cope with the environmental impact of conventional power plants and reduce the greenhouse gas emissions the Ministry of New and Renewable Energy (MNRE) policy is to generate 20% of the total consumed energy with renewable energy sources by the year 2020 which was achieved two years ahead of schedule by

June 2018. The need for increasing the production of renewable energy is growing resulting in the further increase in number of renewable energy sources such as wind turbines and solar panels.

A development which has a significant impact on the distribution grid is the introduction of small-scale generation, better known as Distributed Generation (DG). In the literature many definitions of DG exist. In [1] DG is defined as “Electric generation facilities connected to a local electric power system through a point of common coupling”. While in [2] DG is defined as “Electrical generation that is not centrally planned, not centrally dispatched, and connected to the distribution grid.” An overview of definitions of DG is seen in [3] where it is stated that the definition given in [4] is a good approach without noting the specific characteristics of DG such as DG-technology, DG-rating or mode of operation. In this paper Distributed Generation is defined as in [4] as “An electric power source connected directly to the distribution network or to the customer side of the meter”. An extensive overview of the state-of-the-art in DG technology including the classification, characteristics and modeling is given in [5, 6].

Most of the literature has considered power losses of the system as an objective function to be minimized for locating the site for DG installation. The power losses of the systems depend on DG location, as well as DG size. It is found that as DG penetration increases, losses start to decrease and reach to a minimum value and if DG penetration level further increases, losses begin to increase marginally. If DG penetration levels increase enough, the losses can be even higher than without a connected DG [7]. A number of publications have looked at optimizing the location and size of DG based on various criteria. In [8] the authors used an optimal power flow (OPF) technique to maximize DG capacity. In [9] the authors used a heuristic approach to determine the optimal DG location and size.

In recent years, many Meta – heuristic and evolutionary computational techniques are used as a method for the design of a new distribution system and for the resizing of an existing one. In respect with this paper, a Genetic – Tabu search algorithm has been described for optimal DG allocation in distribution networks [10]. Methods presented in [10] determined only the location of DG, whereas, as said above, the system losses depend on both location and size of the DG [11]. Genetic algorithm and PSO are applied to find the optimal DG placement [12, 13]. Very recently the siting and sizing of DG was implemented by artificial bee colony algorithm [14].

In this paper a successful attempt has been done in integrating the DG with the distribution grid. The problem of locating the optimal site and also determining the optimal size of the DG is done simultaneously using Simulated Annealing (SA) algorithm.

2. LOAD FLOW FOR RADIAL DISTRIBUTION SYSTEM

The steady-state operating condition of the power system is required for operation and planning studies of a distribution system for various load demands. Distribution networks have recently acquired a growing importance because their extension has quite increased and also because their management has become quite complex. Distribution systems operate at low voltage lines and have a high R/X ratio.

This high R/X ratio factor of the distribution systems makes them ill conditioned and so the need of new and efficient method for the analysis of distribution system arises.

2.1. Forward-Backward sweep algorithm

It is a compensation based algorithm, which has both forward sweep and backward sweep [15], as described below is used to develop the distribution load flow analysis program using the designed objects. During backward sweep the branch currents are calculated and during forward sweep bus voltages are calculated and all parameters are expressed in per unit quantities.

2.1.1 Backward sweep

Calculate the net nodal current injections using equation

$$I_j^k = I_{s,j} - \left(I_{L,j}^k + I_{sh,j}^k \right) \quad (1)$$

Where,

k = Iteration number

I_j^k = Net current injection at bus 'j'

$I_{s,j}$ = Injected current by any source's' at bus 'j'

$I_{L,j}^k$ = Load current at bus 'j'

$$I_{L,j}^k = \left(\frac{S_{L,j}}{V_j^{k-1}} \right)^* \quad (2)$$

$S_{L,j}$ = Complex load power

$I_{sh,j}^k$ = Current of the shunt device connected at bus 'j'

$$I_{sh,j}^k = Y_{sh,j} V_j^{k\text{-}1} \quad (3)$$

$Y_{sh,j}$ = Admittance of the shunt element

Calculate branch currents in all feeders using equation

$$I_{br,j}^k = I_{br,j+1}^k - I_j^k \quad (4)$$

Where,

$I_{br,j+1}^k$ = current in the j+1th branch or current leaving the jth bus

$I_{br,j+1}^{k}$ = 0 if the bus ‘j’ is the terminal node of a feeder

$= \sum_{e} I_{br,e}^{k}$ if the bus ‘j’ is the fork node,

e = emanating feeder sections from the fork node

Perform the above calculations for the feeders terminating at the terminal node and then for the remaining feeders that are terminating at the fork node. This branch current calculation begins at the last branch and terminates at the first branch of each feeder.

2.1.2 Forward Sweep

Since the root node is at sub-station, the voltage across this node is always at 1 Per Unit (P.U) Forward sweep starts from the feeder connected to the root node and continues to the feeders emanating from this feeder.

The voltages across each bus are obtained as follows.

$$V_{j}^{k} = V_{j-1}^{k} - Z_{j} I_{br,j}^{k} \quad (5)$$

Where Z_j – Impedance of the branch prior to bus ‘j’

This loop of backward sweep followed by forward sweep is terminated if the convergence is achieved determined by the maximum variation between the two consecutive iteration bus voltages is lower than the specified tolerance value which is set to 0.0001

2.1.3 Total Power loss

After load flow analysis is performed the total active power loss and bus voltage profiles are obtained as follows.

The peak power loss of the line section connecting buses j and j+1 can be computed as

$$P_{Loss}(j, j+1) = r_j . \frac{(P_j^2 + Q_j^2)}{|V_j|^2} \quad (6)$$

Total power loss of the systems, $P_{T,Loss}$, may then be determined by summing up the losses of all line sections of the feeder, which is given as

$$P_{T,Loss} = \sum_{j=1}^{b} P_{Loss}(j, j+1) \quad (7)$$

Where, b is the total number of line sections in the system

Once the load flow analysis is performed the next step is to determine the optimal locations and sizing of DG for minimizing the total active power loss of the system. Simulated Annealing method is used to determine the optimal location and size of the DG. The method is described in the next section.

3. SIMULATED ANNEALING

Simulated Annealing method is used to determine the optimal location and size of the DG. The method is described in the next section. Simulated Annealing The concept of simulated annealing was first introduced in the field of optimization in the early 1980"s by Kirkpatrick et.al. [16, 17] Simulated annealing is a robust, combinatorial optimization algorithm based on probabilistic methods which has been applied successfully for many industrial, mechanical and electrical problems. It is effectively useful in finding global optima in the presence of large numbers of local optima.

Annealing refers to an analogy with thermodynamics, specifically with the way that metals cools slowly starting from a high temperature In order to achieve a state of minimum internal energy, it is cooled slowly so that thermal equilibrium is achieved at each temperature. Thermal equilibrium can be characterized by the Boltzmann distribution

$$P_T\{X = x\} = \frac{e^{-E_x / K_B^T}}{\sum\limits_{allstates} e_i^{-E_i / K_B^T}} \qquad (8)$$

Where X is a random variable indicating the current state, is the energy of state *x* is Boltzmann's constant, and *T* is temperature. The evolution of the state of a solid in a heat bath toward thermal equilibrium can be efficiently simulated by a simple algorithm based on Monte Carlo techniques which was proposed by Metropolis *et.al* in 1953 [18]. The *Metropolis algorithm* takes the current state *x*, and generates a new state *y* by applying some small perturbation. The transition from state *x* to state *y* is then accepted with probability.

$$\begin{aligned} p_{accept}(x, y) &= 1, \quad \text{if} \quad E_x - E_y \le 0 \\ &= e^{-\left(E_x - E_y\right)/K_B T}, \quad E_x - E_y > 0 \end{aligned} \qquad (9)$$

If accepted, *y* becomes the current state and the procedure is repeated. This acceptance rule is known as the *Metropolis criterion*. Given a particular combinatorial optimization problem let the solution *x* correspond to the current state of the solid, the cost function *f(x)* correspond to the energy of the current state, and the control parameter *T* correspond to the temperature of the solid. The simulated annealing consists simply of iterating the Metropolis algorithm for decreasing values of the artificial temperature parameter *T*.

4. OBJECTIVE FUNCTION

The mathematical formulations of optimization problem for the DG unit application with the proposed technique are as follows:

$$objective\ function = f = \min \sum_{i=0}^{n} \left(\frac{P_i^2 + Q_i^2}{V_i^2} \right) \times r_{i+1} \quad (10)$$

Where, n = number of buses

P_i = Active power demand at bus 'i'

Q_i = Reactive power demand at bus 'i'

V_i = Voltage magnitude at bus 'i'

r_i = resistance of the line connecting the bus 'i' and its precedent bus

The solution steps for the proposed approach using Simulated Annealing algorithm are presented in flowchart in Figure 2.

5. TEST RESULTS

In order to evaluate the effectiveness of the proposed algorithm, it has been tested on two standard distribution test systems, 33-Bus Radial distribution system and 69-Bus Radial distribution system. The proposed method was implemented in MATLAB 7.8 software and was run under 2.93GHz, 2GB RAM, INTEL-PC

The line data and bus data of the test systems are found in [14, 19]. The load flow results carried with forward backward sweep algorithm are available in Appendix.

5.1. Test results for 33 – Bus Radial Distribution System

The voltage profile of the system before DG installation is shown in Figure 1

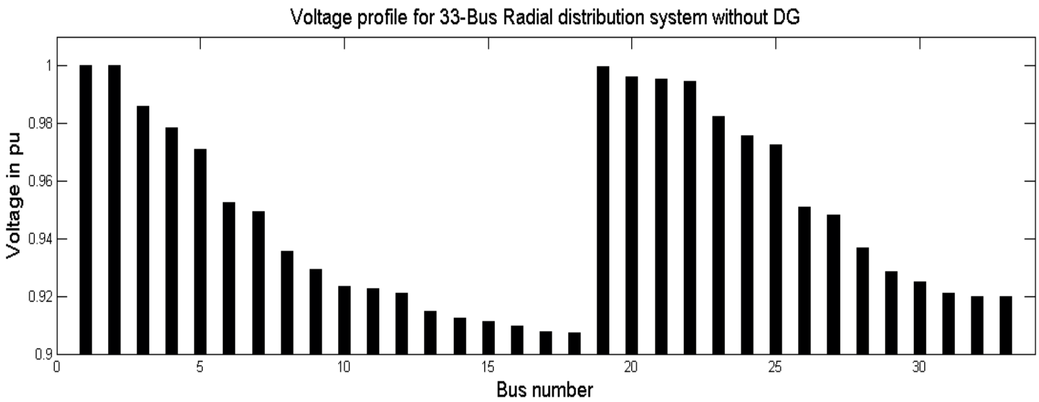


Figure 1: Voltage Profile For 33-Bus Radial Distribution System Without DG

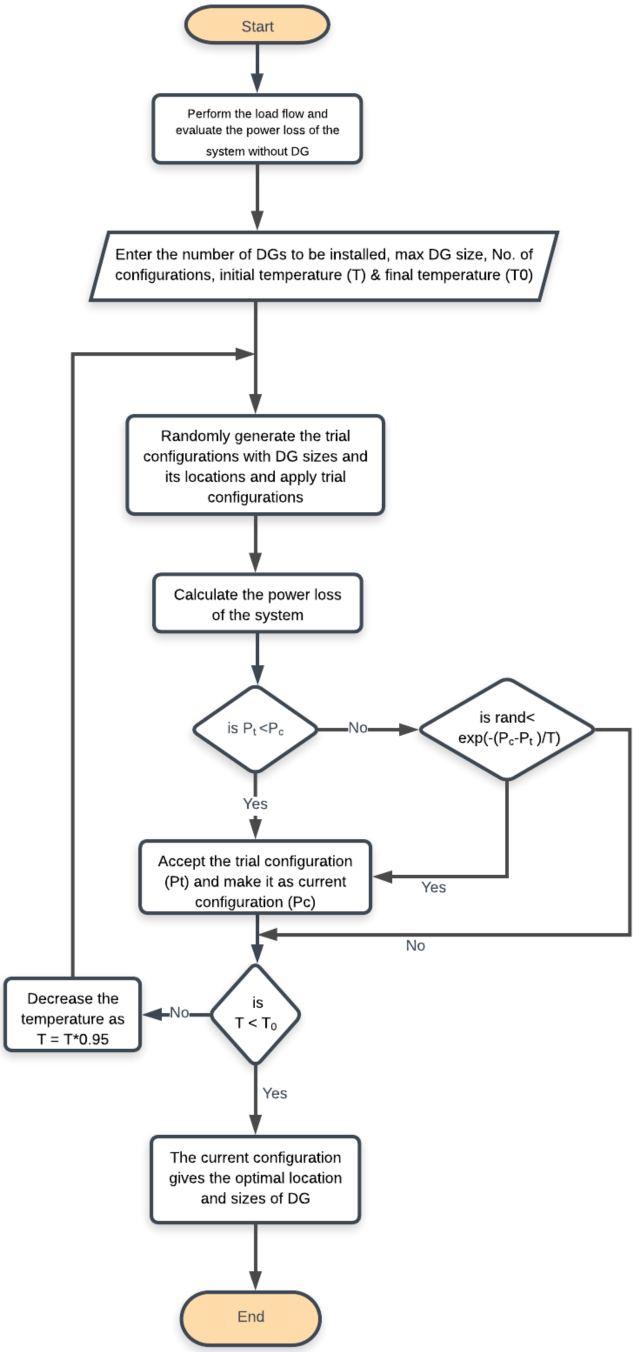


Figure 2: Flowchart of Process Using Simulated Annealing Algorithm

From the load flow analysis it is found the minimum voltage of the system is 0.9071 P.U at bus 18. and the total power loss of the network is 209.51 KW. Now the proposed method for simultaneous location and sizing of DG using Simulated Annealing is implemented. The test cases considered were as follows

Case 1: The test case 1 includes multiple DG allocations and the DG unit is controlled to supply active power only. The maximum rating of DG unit is set as 2MW.

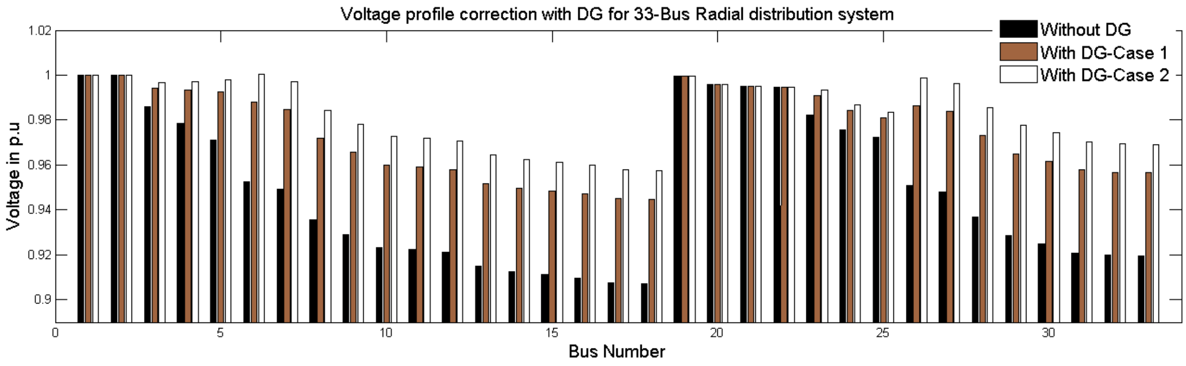
Case 2: This case includes multiple DG allocations. However, the DG unit is controlled to supply both active and reactive power. The maximum rating of DG unit is set as 3MVA.

Exhaustive analysis was performed on these two test cases and the results are compared and contrasted and are presented in Table.1

Table 1: Consolidated results for two test cases for 33 – Bus Radial Distribution System

	Without DG	Case 1	Case 2
Total active power loss without DG (Kw)	209.5163	-	-
Total active power loss (Kw) (Best)	-	86.9172	31.1674
Total active power loss (Kw) (Mean)	-	87.6293	31.6982
Standard deviation	-	0.4767	0.5303
Loss Reduction in (Kw)	-	121.5051	177.0231
Loss Reduction in (%)	-	57.9932	84.4913
Optimal locations for DG at buses	-	13, 30	30, 13
Optimal Ratings of DGs (Mw)	-	Bus 13: 0.7465 Bus 30: 1.1397	Bus 13: 1.1567 Bus 30: 0.8593
Optimal Ratings of DGs (MVAr)	-	-	Bus 13: 0.7169 Bus 30: 0.5325
Optimal Ratings of DGs (MVA)	-	Bus 13: 0.7465 Bus 30:1.1397	Bus 13: 1.3608 Bus 30: 1.0109
Total installed capacity (MW)	-	1.8862	2.0160
Total installed capacity (MVAr)	-	-	1.2494
Total installed capacity (MVA)	-	1.8862	2.3717
V_{min} (p.u)	0.9071	0.9647	0.9814

With the proposed algorithm the optimal locations for DG allocation in both the test cases were at buses 13 and 30. The optimal ratings of DG units with two test cases can be seen in the Table 4.2. The proposed algorithm is executed for 10 independent runs. The best value among all the 10 runs and the mean value of all the runs were presented in the Table 1. With test case 1 i. e, the DG was intended to supply active power only, the total active power loss (Best) was obtained as 86.9172 Kw. With test case 2 i.e, the DG was intended to supply both active and reactive powers, the total active power loss (Best) was obtained as 31.1674 Kw. It can also be seen that there is a reduction in active power loss of 57.99% with case 1 and 84.49 % with case 2. The minimum voltage profile of the system is improved to 0.9647 P.U with Case 1 and 0.9814 P.U with Case 2. The voltage profile correction with DG for two test cases can be clearly observed in Figure 3.



. Figure 3: Voltage profile correction with DG for 33-Bus Radial distribution system

The convergence curve for the Simulated Annealing algorithm for test cases 1& 2 can be seen in Figures 4 & 5. The SA algorithm is getting converged for the optimal solution after 69th iteration for case 1 and 20th iteration for case 2.

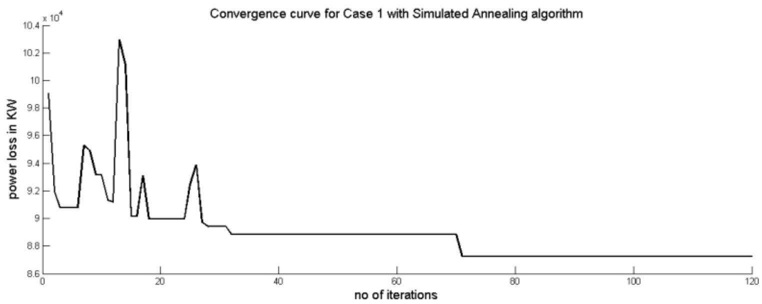


Figure 4: Convergence curve with SA algorithm for test case 1

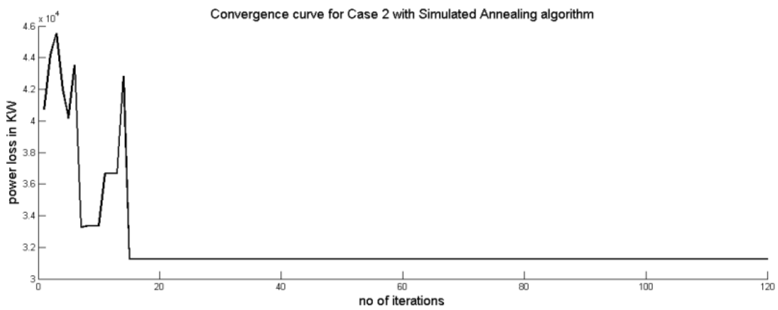


Figure 5: Convergence curve with SA algorithm for test case 2

5.2. Test results for 69 – Bus Radial Distribution System

From the load flow analysis it is found the minimum voltage of the system is 0.9092 P.U at bus 65 and the total power loss of the network is 225.027 KW. Now the proposed method for simultaneous location and sizing of DG using Simulated Annealing is implemented for 10 independent runs and the best solution among all the runs along with the mean values are presented in Table 2. The different test cases considered for 33-Bus Radial distribution system remains same for this system.

Table 2: Consolidated results for two test cases for 69 – Bus Radial Distribution System

	Without DG	Case 1	Case 2
Total active power loss without DG (Kw)	225.027	-	
Total active power loss (Kw) (Best)	-	71.7010	7.9692
Total active power loss (Kw) (Mean)	-	72.3166	8.6076
Standard deviation	-	0.3535	0.5385
Loss Reduction in (Kw)	-	152.628	216.0514
Loss Reduction in (%)	-	67.8265	96.011
Optimal locations for DG at buses	-	18, 61	18, 61
Optimal Ratings of DGs (Mw)	-	Bus 18: 0.6519 Bus 61: 1.8442	Bus 18: 0.5634 Bus 61: 1.8599
Optimal Ratings of DGs (MVAr)	-	-	Bus 18: 0.3491 Bus 61: 1.1527
Optimal Ratings of DGs (MVA)	-	Bus 18: 0.6519 Bus 61: 1.8442	Bus 18: 0.6628 Bus 61: 2.1882
Total installed capacity (MW)	-	2.4961	2.4233
Total installed capacity (MVAr)	-	-	1.5018
Total installed capacity (MVA)	-	2.4961	2.8509

V_{min} (P.U)	0.9092	0.9818	0.9943

The voltage profile correction with DG for two test cases can be clearly observed in Figure 7.

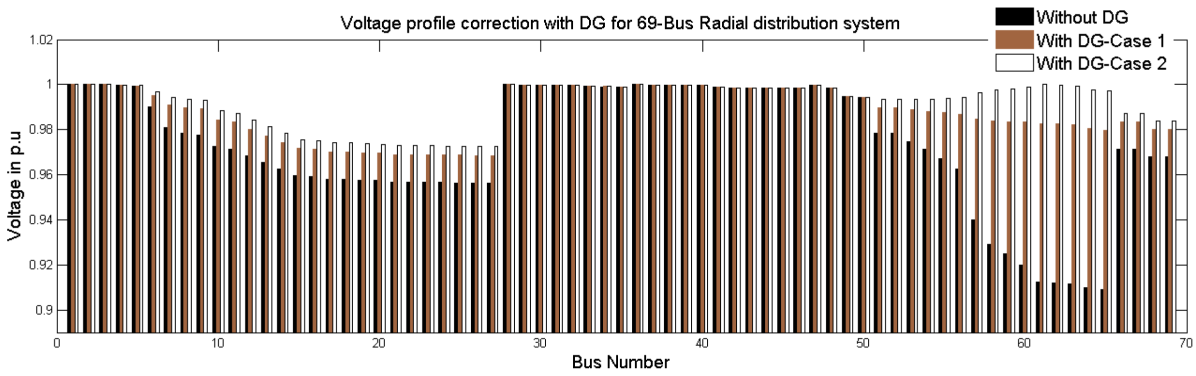


Figure 8: Voltage profile correction with DG for 69-Bus Radial distribution system

The total active power loss without DG was observed as 225.027 KW. The minimum voltage magnitude of 0.9092 P.U can be seen at Bus 65. With the proposed algorithm the optimal locations for DG allocation in both the test cases were at buses 18 and 61. The optimal ratings of DG units with two test cases can be seen in the Table 2. The total active power loss (Best) was reduced to 71.7010 KW in Case1 whereas it came down to 7.9690KW in case 2, thereby a reduction in active power loss of 57.99% with Case 1 and 84.49 % with Case 2. The minimum voltage profile of the system is improved to 0.9818 P.U with Case 1 and 0.9943 P.U with Case 2.

The convergence curve for the Simulated Annealing algorithm for test cases 1& 2 is not shown however, The SA algorithm is converged for the optimal solution after 64th iteration for Case 1 and 90th iteration for Case 2.

6. CONCLUSION

This paper proposed a method with an objective of reducing the active power loss of the system based on Simulated Annealing algorithm. The proposed method was implemented on IEEE 33 and 69-bus radial distribution systems and the results obtained were encouraging.

Extensive simulation work has been carried out by considering two different test cases on the proposed method of optimal siting and sizing of DG using Simulated Annealing and the results corroborate that there is a substantial reduction in the total active power loss of the system and concurrently the voltage profile of the system is greatly enhanced

7. APPENDIX

7.1. Load Flow Results for 33-Bus Radial distribution system

Table 5: Voltage magnitudes of the system after load-flow for 33 – Bus Radial distribution system

Bus #	Voltage in (P.U)	Bus #	Voltage in (P.U)	Bus #	Voltage in (P.U)	Bus #	Voltage in (P.U)	Bus #	Voltage in (P.U)
1	1.0000	8	0.9323	15	0.9079	22	0.9916		
2	0.9970	9	0.9260	16	0.9065	23	0.9793	29	0.9254
3	0.9829	10	0.9201	17	0.9044	24	0.9726	30	0.9218
4	0.9754	11	0.9193	18	0.9038	25	0.9693	31	0.9176
5	0.9680	12	0.9178	19	0.9965	26	0.9476	32	0.9167
6	0.9495	13	0.9116	20	0.9929	27	0.9450	33	0.9164
7	0.9460	14	0.9093	21	0.9922	28	0.9336		

7.2. Load Flow Results for 69-Bus Radial distribution system

Table 6: Voltage magnitudes of the system after load-flow for 69 – Bus Radial distribution system

Bus #	Voltage (P.U)	Bus #	Voltage (P.U)	Bus #	Voltage (P.U)	Bus #	Voltage (p.u)	Bus #	Voltage (p.u)
1	1.0000	14	0.9624	27	0.9563	40	0.9995	53	0.9747
2	1.0000	15	0.9595	28	0.9999	41	0.9988	54	0.9714
3	0.9999	16	0.9590	29	0.9999	42	0.9986	55	0.9669
4	0.9998	17	0.9581	30	0.9997	43	0.9985	56	0.9626
5	0.9990	18	0.9581	31	0.9997	44	0.9985	57	0.9401
6	0.9901	19	0.9576	32	0.9996	45	0.9984	58	0.9291
7	0.9808	20	0.9573	33	0.9993	46	0.9984	59	0.9248
8	0.9786	21	0.9568	34	0.9990	47	0.9998	60	0.9198
9	0.9774	22	0.9568	35	0.9989	48	0.9985	61	0.9124
10	0.9724	23	0.9568	36	0.9999	49	0.9947	62	0.9121
11	0.9713	24	0.9566	37	0.9997	50	0.9942	63	0.9117
12	0.9682	25	0.9564	38	0.9996	51	0.9785	64	0.9098
13	0.9653	26	0.9564	39	0.9995	52	0.9785	65	0.9092
		66	0.9713	67	0.9713	68	0.9679	69	0.9679

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