

An Efficient Method for Optimal Placement and Sizing of Multiple Distributed Generators in a Radial Distribution Systems

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ABSTRACT

This article presents a simple and efficient approach for the placement of multiple Distributed Generators (DG) in a radial distribution system. The approach determines the optimal locations and size of DGs with the objective of improving the voltage profile and loss reduction. Loss sensitivity factors (LSF) are used to select the candidate locations for the multiple DG placements and Simulated Annealing (SA) is used to estimate the optimal size of DGs at the optimal locations determined. The proposed method is applied to the 33bus and 69bus radial distribution systems. The solutions obtained by the proposed method are compared with other existing methods. The proposed method has outperformed the other methods in terms of the quality of solution.

Keywords: Distributed Generator, loss sensitivity factors, loss reduction, optimal sizing, optimal placement, voltage stability index.

Nomenclature

$P_{T, Loss}$	total real power loss
MW	mega watt
Mvar	mega volt ampere reactive
DG	distributed generator
WODG	without distributed generator or base case
WDG	with distributed generator
GSA	grid search algorithm
CSA	clonal selection algorithm
GA	genetic algorithm
RDS	radial distribution system

INTRODUCTION

Utilities are continuously planning the expansion of their existing electrical networks in order to face the load growth and to properly supply their customers. Studies have indicated that as much as 13% of total power generated is wasted in the form of losses at the distribution level [1]. As a result, loss reduction in distribution systems is one of the greatest challenges to many utilities around the world. Reconfiguration and capacitor placement are 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]. To reduce these losses, DGs are installed at distribution level. Distributed Generation (DG) can be defined as small-scale generation, which is not directly connected to the bulk transmission system and is not centrally dispatched. Generation is now being connected at distribution level, which has led to changes in the characteristics of the network [4]. Distributed generation (DG) is expected to play an important role in the future generation system. They are owned by a customer, utility or another entity, and connected to the grid at a distribution voltage level [5]. Distributed resources are strategically located and operated in the system to defer or eliminate system upgrades, improve voltage profile, reduce system losses, reinforce grid, and to improve system reliability and efficiency. Recent studies have predicted that by year 2010, distributed generation will account for up to 25% of all new generation [6]. In the last few years, there has been significant contribution to research in the field of DG resource planning. Normally, DGs are integrated in the existing distribution system, and the planning studies have to be performed for optimal location and size of DGs to achieve maximum benefits. Studies have indicated that inappropriate selection of the location and size of DG may lead to greater system losses than the losses without DG [7].

REVIEW OF PREVIOUS METHODS

Analytical approaches for optimal placement of DG with unity power factor is to minimize the power loss of the system. A "2/3 rule" is used to place DG on a radial feeder with uniformly distributed load,

where it is suggested to install DG of approximately $2/3$ capacity of incoming generation at approximately $2/3$ of the length of line. In above approaches size of DG is not optimized. Line loading constraint is not considered during optimization [8]. In [9], has been presented a new optimization algorithm based on integrating the use of genetic algorithms and Tabu-Search methods to optimal allocation of dispersed generation resources in distribution networks. The proposed algorithm finds how much distribution losses can be reduced if is presented generations are optimally allocated at the demand side of power system. A significant improvement of the proposed algorithm results, over that obtained by genetic algorithm, has been achieved in this literature. Hedayati.et.al. [10] proposed a method based on continuous power flow. In this method they first determine the most sensitive buses to voltage collapse. After that, the DG units with certain capacity will be installed in buses via an objective function and an iterative algorithm. In [11], proposed an analytical expression to calculate the optimal size and an effective methodology to identify the corresponding optimum location for DG placement for minimizing the total power losses in primary distribution systems. The analytical expression and the methodology are based on the exact loss formula. The effect of size and location of DG with respect to loss in the network is also examined in detail. The Genetic Algorithm (GA) based method to determine size and location is used in [12]. GA's are suitable for multi-objective problems like DG allocation, and can give near optimal results, but they are computationally demanding and slow in convergence.

The potential benefits of DG largely depend on its location and size; many of the studies regarding DG address the problem of its optimal placement and sizing. The intent may be the minimization of total network supply costs, which includes generators operation and losses compensation [13]. In [14], Introduced DG in a distribution network has considerable advantages such as reducing power loss and cost, environmental friendliness, voltage improvement, postponing system upgrades and enhancing system reliability and continuity of service. Practical application of the DG, however, proves difficult. Social, economic and political factors affect the final optimal solution. Solution techniques for DG deployment rely on optimization methods.

The technique proposed here finds the optimal location and size of the DG to minimize the total system power loss for radial distribution feeder systems by solving two independent sub-problems: (i) location and (ii) size. A sufficient sensitivity test for the first problem is sug-

gested. Determining the optimal DG size is done using a new heuristic curve-fitted technique that reduces the search-space by selecting fewer DG-tests. Four DG sizes, which are carefully selected based on the system's total load demand percentages, are used to determine the optimal solution. The authors in [15] proposed a methodology to determine the optimal location and size of a DG in distribution systems to maximize the benefit/cost ratio. The objective function was to minimize the power loss subject to acceptable reliability and voltage levels. The method utilized a combination of GA techniques with other methods to evaluate the DG impacts on system loss, reliability and voltage profile.

The proposed optimal sitting and sizing of the DG was based on a preselected list of candidate places, and a respective list of candidate units that can be installed at each location. In [16], a hybrid method was proposed to determine the optimal (predefined) number of deployed DG in the distribution networks. The suggested GA-OPF technique solved the static optimization problem (single-time period analysis) utilizing the economic dispatch formulation. The method was reported to enable distribution network operators to strategically connect a predefined number of DGs among a large number of potential combinations. The sensitivity factor deployed to determine the optimum location and size of DG in order to minimize the total power loss was proposed in [17]. Authors in [18] categorized the impacts of DG on the distribution systems as positive, such as voltage profile improvement and negative, such as increased system loss and short-circuit level, and used these to formulate a multi-objective function. Nevertheless, this problem formulation is flawed, because DG would lead to increase in loss only when it is sited in improper locations, and so its impact cannot be considered negative in all cases. In [19-20] the simple genetic algorithm (SGA) approach was adopted, for the optimization problem. Authors [21], proposed a GA approach to optimal location and sizing of DGs in a distribution system and results are compared with nonlinear optimization. In [22], a two stage methodology is presented for the optimal DG placement. In the first stage, Fuzzy set approach is used to find the optimal locations and in the second stage, Clonal Selection Algorithm (CSA) of Artificial Immune System is used to size the DGs. To find the optimum size and location of DG, classical grid search algorithm is used in [23] which are based on successive load flows. It is too costly because of computation time, that it takes hours even days depending upon size of the system and power steps.

In [24], proposed analytical expressions for finding optimal size and

power factor of four types of distributed generation (DG) units. DG units are sized to achieve the highest loss reduction in distribution networks. The proposed analytical expressions are based on an improvement to the method that was limited to DG type, which is capable of delivering real power only. Three other types, e.g., DG capable of delivering both real and reactive power, DG capable of delivering real power and absorbing reactive power, and DG capable of delivering reactive power only, can also be identified with their optimal size and location using the proposed method. The method has been tested in three test distribution systems with varying size and complexity and validated using exhaustive method. Results show that the proposed method requires less computation, but can lead optimal solution as verified by the exhaustive load flow method. In [25] proposed an adaptive weight particle swarm optimization (APSO) for solving optimal distributed generation (DG) placement. APSO has ability to control velocity of particles.

Research Objective

The objective is to minimize the real power loss within acceptable voltage limits. Four types of DG are considered including DG supplying real power only, DG supplying reactive power only, DG supplying real power and consume reactive power, DG supplying real power and reactive power, representing photovoltaic, synchronous condenser, wind turbines, and hydro power, respectively. The test systems include 33-bus and 69-bus radial distribution systems. With a given number of DGs in each type, APSO could find the optimal sizes and locations of multi-DG which result in less total power system loss than basic particle swarm optimization (BPSO) and repetitive load flow. Moreover, if the number of DG increases from one to three, the total power loss will decrease for all types. In this article, the optimal locations of DGs are identified based on loss sensitivity factors and Simulated Annealing (SA) which takes the number and location of DGs as input has been developed to determine the optimal size(s) of DG at any power factor to minimize real power losses in distribution systems.

PROBLEM FORMULATION

Optimal DG placement in a radial distribution system means to find best locations of radial network that gives minimum total power

loss ($P_{T, Loss}$) while satisfying certain operating constraints. The operating constraints are voltage profile of the system, current capacity of the feeder and radial structure of the distribution system. The objective function for the minimization of power loss is described as follows:

$$\begin{aligned} \text{Min } F &= \min (P_{T, Loss}) \\ \text{Subjected to constraints:} \\ P_{DGimin} &\leq P_{DGi} \leq P_{DGimax} && \text{Power Flow Balance} && (1) \\ V_{imin} &\leq V_i \leq V_{imax} && \text{Bus Voltage Limits} && (2) \\ I_{i,i+1} &\leq I_{i,i+1 \text{ max}} && \text{Branch Load Capacity} && (3) \end{aligned}$$

Where V_i is the voltage magnitude of bus i , V_{min} and V_{max} are bus minimum and maximum voltage limits, respectively. $I_{i,i+1 \text{ max}}$ is the maximum loading on branch $i,i+1$. I_i is the current flowing through the i^{th} branch, which is dependent on the locations and sizes of the DGs. A set of simplified feeder-line flow formulations is employed. Next, considering the single-line diagram depicted in Figure 1, recursive equations (4) to (6) are used to compute the power flow.

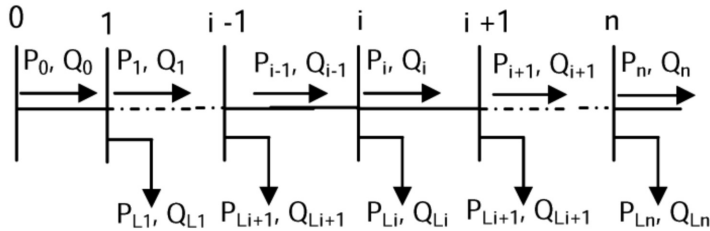


Figure 1. Single-line diagram of a main feeder

Because of the complexity of the large scale distribution system, network reconfiguration problem is normally assumed as symmetrical system and constant loads. Therefore, the distribution lines are represented as series impedances of the value ($Z_{i,i+1} = R_{i,i+1} + jX_{i,i+1}$) and load demand as constant and balanced power sinks $S_L = P_L + j Q_L$.

The real and reactive power flows at the receiving end of branch $i+1$, P_{i+1} and Q_{i+1} , and the voltage magnitude at the receiving end, $|V_{i+1}|$ are expressed by the following set of recursive equations:

$$P_{i+1} = P_i - P_{Li+1} + R_{i,i+1} \cdot \frac{P_i^2 + Q_u^2}{|V_i|^2} \tag{4}$$

$$Q_{i+1} = Q_i - Q_{Li+1} + X_{i,i+1} \cdot \frac{P_i^2 + Q_u^2}{|V_i|^2} \quad (5)$$

$$|V_{i+1}|^2 = |V_i|^2 - 2 \left(R_{i,i+1} \cdot P_i + X_{i,i+1} \cdot Q_i \right) + \left(R_{i,i+1}^2 + X_{i,i+1}^2 \right) \cdot \frac{P_i^2 + Q_i^2}{|V_i|^2} \quad (6)$$

Equations (4) – (6) are known as the distinct flow equations. Hence, if P_0 , Q_0 , V_0 at the first node of the network is known or estimated, then the same quantities at the other nodes can be calculated by applying the above branch equations successively. This procedure is referred to as a forward update. Similar to forward update, a backward update is expressed by the following set of recursive equations:

$$P_{i-1} = P_i + P_{Li} + P_{i,i+1} \cdot \frac{P_i'^2 + Q_i'^2}{|V_i|^2} \quad (7)$$

$$Q_{i-1} = Q_i + Q_{Li} + X_{i,i+1} \cdot \frac{P_i'^2 + Q_i'^2}{|V_i|^2} \quad (8)$$

$$|V_{i-1}|^2 = |V_i|^2 - 2 \left(R_{i,i-1,i} \cdot P_i' + X_{i,i-1,i} \cdot Q_i' \right) + \left(R_{i-1,i}^2 + X_{i-1,i}^2 \right) \cdot \frac{P_i'^2 + Q_i'^2}{|V_i|^2}$$

Where $P'_L = P_i + P_{Li}$ and $Q'_L = Q_i + Q_{Li}$

Note that by applying backward and forward update schemes successively one can get a power flow solution. The power loss of the line section connecting between buses i and $i+1$ is computed as

$$P_{\text{Loss}(i,i+1)} = R_{i,i+1} \cdot \frac{P_i'^2 + Q_i'^2}{|V_i|^2} \quad (9)$$

The total power loss of the feeder PF, Loss is determined by summing up the losses of all line sections of the feeder, which is given by

$$P_{T, Loss} = \sum_{i=0}^{n-1} P_{T, Loss}(i, i+1) \quad (10)$$

Where the total system power loss $P_{T, Loss}$ is the sum of power losses of all feeders in the system.

Loss Sensitivity Factors

The locations for the placement of DGs are determined using loss sensitivity factors. The estimation of these locations basically helps in reduction of the search space for the optimization procedure. We consider a distribution line with an impedance $R + jX$ and a load of $P_{eff} + jQ_{eff}$, connected between 'p' and 'q' buses. Then loss sensitivity factors can be expressed as follows:

$$\frac{\partial P_{Line loss}}{\partial Q_{eff}} = \frac{(2 * R[k] * Q_{eff}[q])}{(V[q])^2} \quad (11)$$

$$\frac{\partial Q_{Line loss}}{\partial Q_{eff}} = \frac{(2 * X[k] * Q_{eff}[q])}{(V[q])^2} \quad (12)$$

The loss sensitivity factors ($\partial P_{line loss} / \partial Q_{eff}$) are calculated from the base case load flows and the values are arranged in descending order for all the lines of the given system or according to Eq. 11, buses will be ranked and some buses are locations as the one which have the most sensitivity for DG placement in order to have the best effect on loss reduction. A vector bus position 'bpos[i]' is used to store the respective 'end' buses of the lines arranged in descending order of the values ($\partial P_{line loss} / \partial Q_{eff}$). The descending order of ($\partial P / \partial Q_{eff}$) elements of 'bpos[i]' vector will decide the sequence in which the buses are to be considered for compensation. This sequence is purely governed by the ($\partial P / \partial Q_{eff}$) and hence the proposed loss sensitive factors become very powerful and useful in DG Placement. At these buses of 'bpos[i]' vector, normalized voltage magnitudes are calculated by considering the base case voltage magnitudes given by ($norm[i] = V[i] / 0.95$). Now for the buses whose $norm[i]$ value is less than 1.01 are considered as the locations requiring the multiple DG Placement. These candidate buses are stored in 'rank bus' vector. It is worth note that the 'Loss Sensitivity factors' decide the sequence in which buses are to be considered for compensation placement and the 'norm[i]' decides whether the buses needs compensation or not. If the voltage at a bus in the sequence list

is healthy (i.e., $\text{norm}[i] > 1.01$) such bus needs no compensation and that bus will not be listed in the 'rank bus' vector. The 'rank bus' vector offers the information about the possible potential or locations for DG placement. The sizing of DGs at buses listed in the 'rank bus' vector is done by using Simulated Annealing i.e., locations determined by loss sensitivity factors are given as input. So the objective function is now only dependent on the sizes of the DGs at these locations.

SIMULATED ANNEALING

SA algorithm principle

A technique to obtain near-to-optimum solution of optimization problems entitled SA was proposed by Kirk Patrik, Gelatt and Vecchi in 1983. SA has been tested in several optimization problems showing great ability for not being trapped in local minima. Due to its implementation simplicity and good results shown, its use has been growing since mid 80s [26]. SA is not new to power system optimization, it has already implemented in distribution system reconfiguration problem [27]. There are three most important parameters of the SA technique require solving any optimization problem as follows:

1. The annealing temperature, this parameter permits the SA not to be entrapped in local minima through the use of Boltzmann's function.
2. The number of iterations at constant temperature. A low number of iterations will result in being trapped in local.
3. Cooling strategy, if the annealing temperature is decreased too fast the algorithm will be trapped in the local.

SA components

- a) **Initialization:** The initial configuration or solution of a DG size is set with their upper and lower limits which are determined by

$$X_i = \text{round} (U^*(X_{\max} - X_{\min}) X_{\min}) \quad (13)$$

Where X_i is the size of DG number i , U is a uniform randomly generated number between 0 and 1, and X_{\min} and X_{\max} are the lower limit and upper limit of the location, respectively.

- b) Perturbation process:** The trial neighborhood solution matrix is generated by perturbing the current solution matrix as shown in Figure 2; where Nl is the size of DG, $X_{Nl}(k)$ is the DG size at iteration k , and $X_{Nl}^{(k+1)}$ is the DG size at the next iteration.
- c) Schedule of Cooling:** Cooling schedule is an annealing process with rated of cooling. The schedule can be determined by

$$T_k = r * T (k-1) \quad (14)$$

Where T_k is the temperature at iteration k , and r is the reduction rate.

- d) Probability of Acceptance:** the probability (P) is designed for decision movement of the current solution (S_c), and it is given by

$$P = \exp \frac{(F(S)_t - F(S)_c)}{K_b T_k} \quad (15)$$

Where S_t is the trial Solution, S_c is the current solution, T_k is the temperature, and kb is the Boltzmann constant. When P is higher than the uniform randomly generated (0, 1), the S_t is accepted as the next current solution (S_c^{t+1}).

SA algorithm to solve optimal DG sizes:

- Step 1: Read the system data, power factor and constraints
- Step 2: Run base case radial load flow
- Step 3: Identify the locations for DG placement using Loss Sensitivity Factors
- Step 4: Input identified locations to SA
- Step 5: Set the temperature (T), iteration (K), (K_o), and the reduction rate (r)

- Step 6: Generate the initial solution and set it as the current solution (S_c).
- Step 7: Set the best solution found so far $S_b = S_c$.
- Step 8: Generate trial solutions (S_t) around the best solutions
- Step 9: If $F(S_t) < F(S_b)$, set $S_b = S_t$. Otherwise,
If $\exp(F(S_t) - F(S_c)/kbT_k) > \text{random}(0-1)$, set $S_b = S_t$
Else S_b is not updated. Set $K_o = K_o + 1$.
- Step 10: If $K_o > K_{\text{omax}}$ go to step 11. Otherwise, go to step 8
- Step 11: Reduce temperature by equation (9).
- Step 12: Check the stopping criterion. If satisfied, terminate the search, else set $K = K + 1$, and go to step (6).

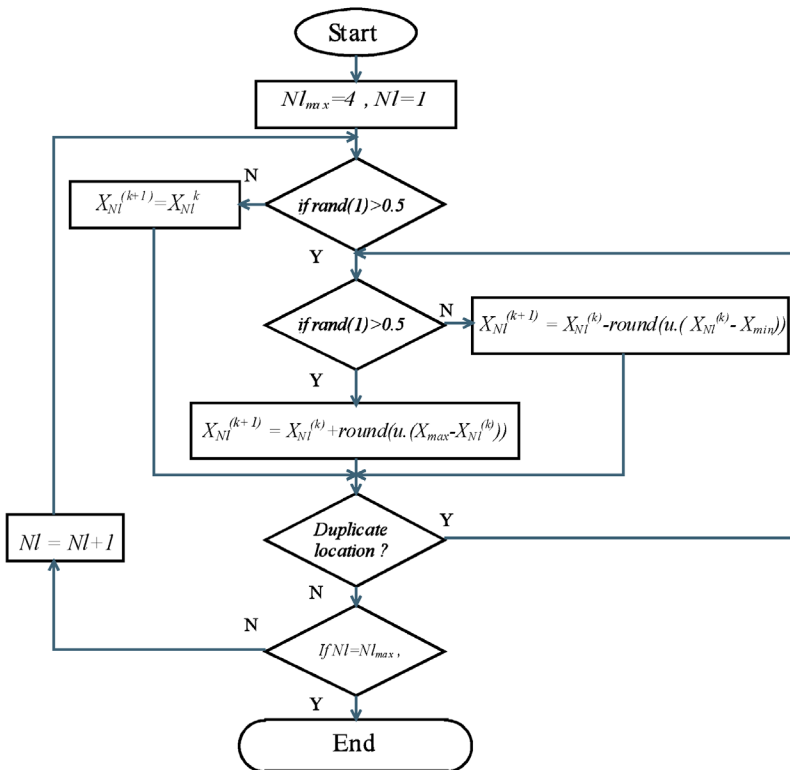


Figure 2. SA perturbation process: NI is the size of DG, $X_{NI}(k)$ is the DG size at iteration k , and $X_{NI}^{(k+1)}$ is the DG size at the next iteration.

RESULTS AND DISCUSSIONS

The proposed method has been programmed using MATLAB R2010b and run on a Core 2 Duo, 1.78-GHz personal computer with 2 GB RAM. The effectiveness of the proposed method for loss reduction by multiple DG placements is tested on 33bus [28] and 69bus [29] radial distribution systems. Power factor of the load is taken as $\cos \Theta = 0.866$. The system loads are considered as spot ones. Initially Forward –Backward Sweep load flow is conducted for 33bus and 69bus test systems. The total real power loss, loss sensitivity factors and bus voltages has been calculated. The locations for DG placement are taken from Loss Sensitivity Factor method and with these locations; sizes of DGs corresponding to global solution are determined by using SA Algorithm described in previous section. The parameters of SA are given in Table 1.

Table 1. Assigned parameters to SA

Parameter	Value
Population	20
Initial Temperature	50
Final Temperature	10
Cooling Rate	0.9

The sizes of DGs are dependent on the number of DG locations. Note that the developed method will work at any system power factor. Table 2 and Table 3 shows the summary of results i.e., optimum locations, corresponding optimum size of DGs, total real power loss with and without DGs, computational time and minimum bus voltages with and without DGs of all the test systems. Reduction in real power loss for the three test systems is 76.21% and 79.94, respectively. As can be seen from results of various systems the location and size of DG can play an important role in loss reduction and improvement in voltage profile of primary distribution systems. Figure 3 and Figure 4 illustrates the improvement in voltage profile of all the three test systems. The constringency characteristics of power loss of the SA algorithm of all the test systems are shown in Figure 5 and Figure 6 respectively. To demonstrate the validity of the proposed method the results of proposed method is compared with standard existing methods in the literature.

Table 2. Summary and comparison results of 33bus radial distribution system

System	Total Load MW/Mvar	Method	Bus No.	Opt. Size MW/Mvar	WODG P _{Loss} (kW)	WDG P _{Loss} (kW)	Comp. Time (s)	Min. Voltage WODG/WDG
33bus[28]	3.72/2.3	CSA[22]	32	0.2701/0				
			30	1.8233/0	203	90.29	28.93	0.90118/0.9349
			31	0.1503/0				
33bus[28]	3.72/2.3	Acharya's[11] GSA[23]	6	2.49/0	211	111.24	0.652	0.90377/0.9423
			6	2.60/0	211	111.03	128.64	0.90377/0.9425
			17	0.719/0.415				
33bus[28]	3.72/2.3	Proposed	18	0.113/0.065	210	51.523	0.2114	0.9071/0.9806
			33	1.043/0.602				

Table 3. Summary and comparison results of 69bus radial distribution system

System	Total Load MW/Mvar	Method	Bus No.	Opt. Size MW/Mvar	WODG P _{Loss} (kW)	WDG P _{Loss} (kW)	Comp. Time (s)	Min. Voltage WODG/WDG	
69bus[29]	3.80/2.69	GA[21]	62	0.736/0					
			18	0.519/0	225	73.76	1453.36	0.9092/0.9433	
			61	0.809/0					
69bus[29]	3.80/2.69	Acharya's[11] SSR[31]	61	1.807/0	224.9	81.33	4.109	0.90919/0.9522	
			17	0.512/0					
			61	1.821/0	224.6	71.5	0.397	0.90922/0.9801	
69bus[29]	3.80/2.69	GSA[23]	61	1.863/0	225	83.22	275.92	0.90919/0.9682	
			26	0.656/0.378	224	48.22	0.2511	0.9059/0.9897	
69bus[29]	3.80/2.69	Proposed	65	1.606/0.927					

The comparison is shown in Table 2 and Table 3 for the test systems. It is observed that savings by SA algorithm are higher than the existing methods. From the above tables it is clear that beyond producing the results that matches with those of existing methods, proposed method has the added advantage of easy implementation of real time constraints

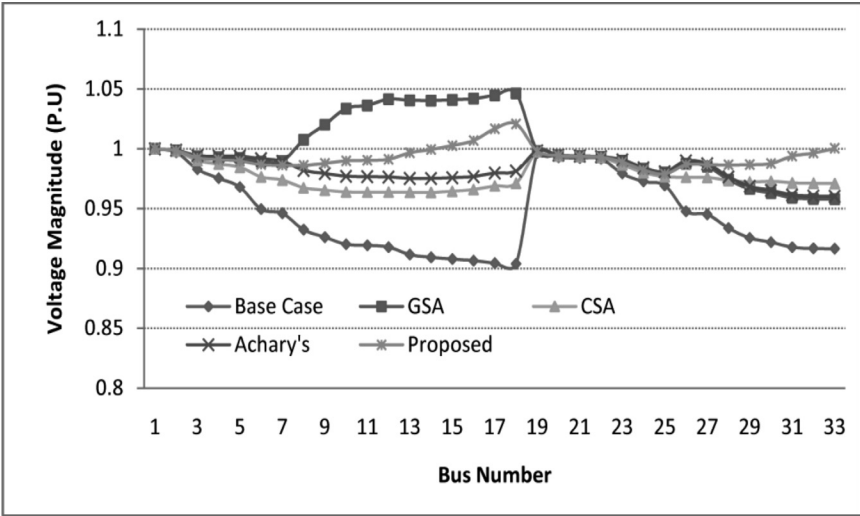


Figure 3. Voltage profile improvement and comparison of results for 33bus RDS

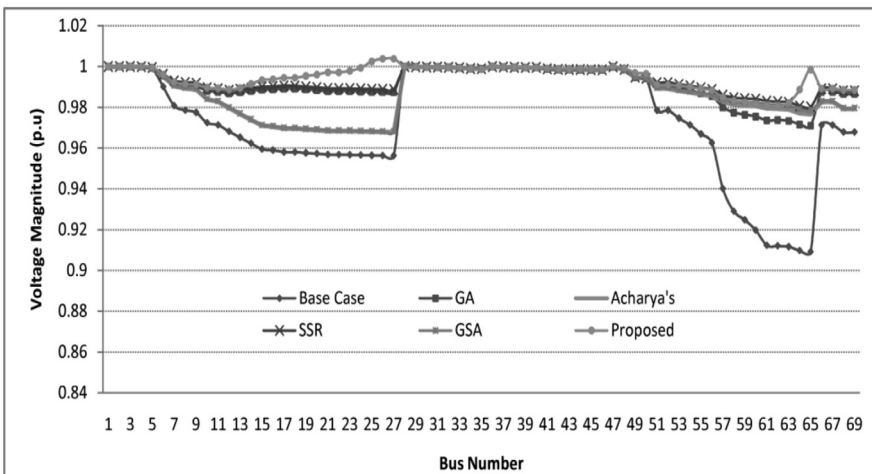


Fig. 4 Voltage profile improvement and comparison of results for 69bus RDS

on the system like time varying loads, discrete DG units etc., to effectively apply it to real time operation of a system.

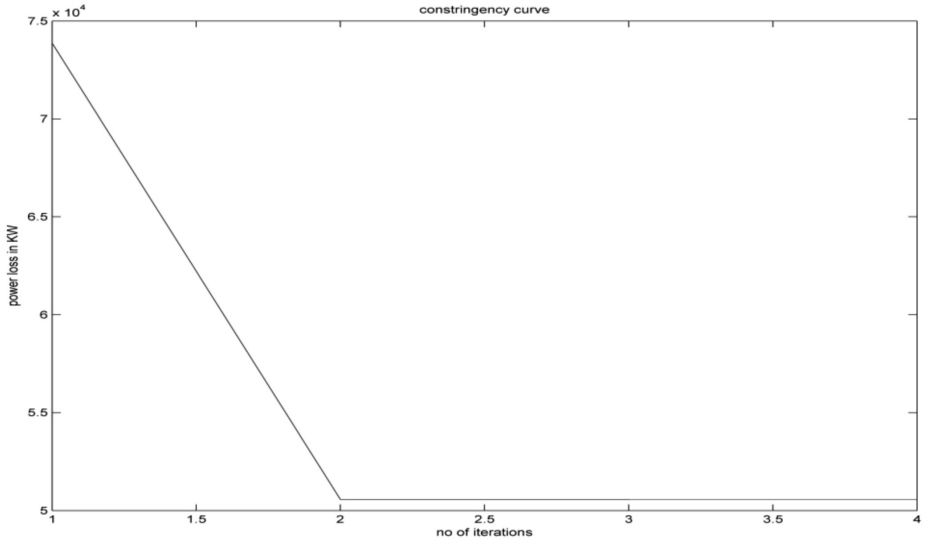


Fig. 5 Constringency characteristics of SA algorithm for 33bus RDS

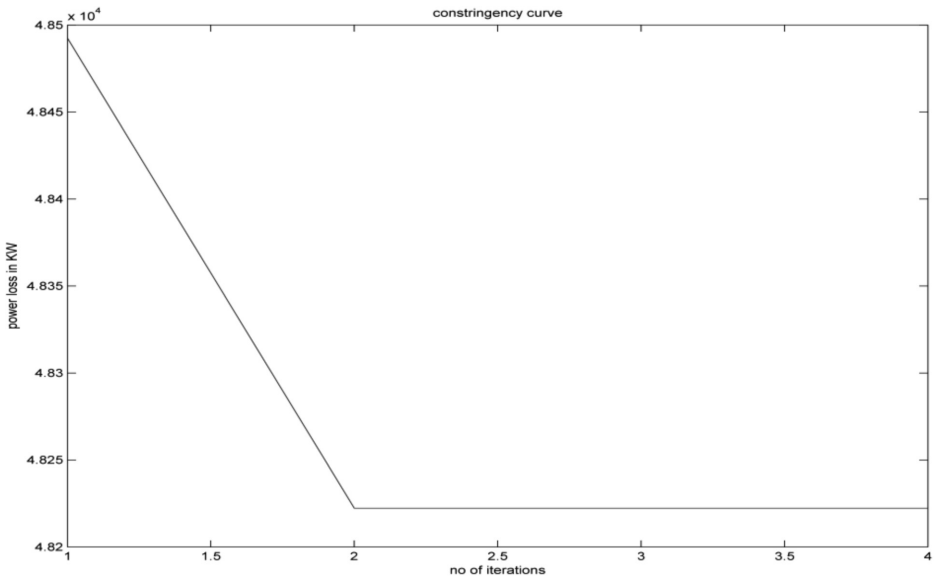
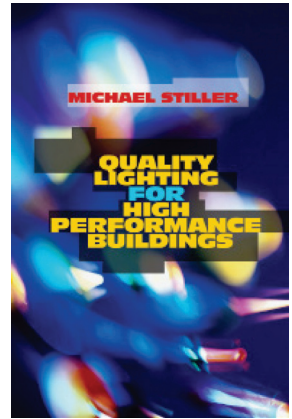


Fig. 6 Constringency characteristics of SA algorithm for 69bus RDS



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CONCLUSIONS

In this article, an efficient method is discussed to find the optimal locations and sizes of DGs for maximum loss reduction in large scale radial distribution systems. The Loss Sensitivity Method is proposed to find the optimal DG locations and SA algorithm is proposed to find the optimal DG sizes. The proposed method was validated by comparing its results with those of other existing methods. The results show that the SA algorithm is simple in nature than GA and PSO. Thus, SA takes less computation time. By installing DGs at all the potential locations, the total real power loss of the system has been reduced drastically and the voltage profile of the system is also improved. It can be concluded the proposed method is efficient in terms of computation time and it can be implemented on any large scale radial distribution systems. However, this article does not consider other benefits of DG as well as the economics of it. Inclusion of the real time constrains such as time varying loads and discrete DG unit into the proposed algorithm are the future scope of this work. Additional further research may include the economic evaluation of DG placing and sizing in a radial system using a life-cycle cost approach.

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