International Journal of Electrical and Computer Engineering.
ISSN 0974-2190 Volume 2, Number 1 (2010), pp. 31--42
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Optimal Conductor Selection in Radial Distribution System using Plant Growth Simulation Algorithm

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Abstract

An optimal branch conductor selection of radial distribution systems using plant growth simulation algorithm is presented in this paper. The objective of this problem, formulated as an optimization problem, is to minimize the overall cost of annual energy losses and depreciation on the cost of conductors. The optimal conductor determined by this method will maintain acceptable voltage levels and satisfy the maximum current carrying capacity of the radial distribution system. The proposed method takes into account the effect of load growth on the conductor selection and the cost of energy losses. The effectiveness of the proposed method is tested on a practical 26 node radial distribution system with and without load growth.

Keywords: Conductor Selection, Plant Growth Simulation Algorithm (PGSA), Radial Distribution Systems, Load Growth

Introduction

Distribution system is one which distributes power to various users through feeders, distributors and service mains. Feeders are large current carrying capacity conductors to carry the current in bulk to the feeding points. This conductor is often the biggest contributor to power losses in distribution system. The distribution power loss is significantly high because of too long and heavily loaded distribution feeders. Therefore, line conductors are loaded below their thermal limit. Studies have revealed that the distribution system I2 R losses account for about 13% of total power generated. A portion of these losses are due to reactive currents in distribution systems. In the optimal distribution planning the reduction of distribution loss is very essential to improve the overall efficiency of power delivery. The power utilities are compelled to reduce the power losses by adopting best practices especially at distribution level. An important practice of the planning process is the selection of conductor for design and upgrading of distribution systems. It is, therefore, necessary to determine the adequate size of conductor to minimize the cost of annual energy losses and capital cost of the feeders.

The size of conductor should be selected mainly based on engineering and economic considerations. Few research papers using different methods are being published for finding the best set of conductors in designing radial distribution system. Funkhouser and Huber [1] worked on a method for determining economical aluminum conductor steel reinforced (ACSR) conductor sizes for distribution systems. They showed that three conductors could be standardized and used in combination for the most economical circuit design for the loads to be carried by a 13 KV distribution system. They checked the voltage regulation to ensure that the sizes selected are adequate for a growing uniformly distributed load. The study done by Ponnavaikko and Rao [2] proposed an optimal conductor gradation procedure for radial distribution systems. Using the proposed method, the sensitivity of all the dependent variables on the conductor gradation can be analyzed. A novel method for selecting optimal branch conductor of radial distribution feeders based on evolutionary programming (EP) has been presented in [3]. Tram and Wall [4] developed a fast computer algorithm for optimal conductor selection to provide feeder voltage support, while recognizing feeder loading requirements. In this algorithm lateral branches as well as regulators along the feeder are considered. Anders et al. [5] analyzed the parameters that affect the economic selection of cable sizes. The effects of variations of several key parameters of the model were thoroughly investigated by the authors. N.Sreenivasulu et al. [6] presented an algorithm for optimal conductor selection. Wantg et al. [7] formulated an integer programming approach to the optimization problem of conductor size in planning radial Power Distribution Systems. Various factors that affect the selection of conductors are given in [8]. Upon considering all the factors the utilities select four or five conductors to meet their requirement.

In this paper, Plant Growth Simulation Algorithm (PGSA) is proposed to select the optimal type of conductor for radial distribution systems. The effect of load growth for a period of five years is considered to test this method. The optimal type of conductor determined by this method will satisfy the maximum current carrying capacity and maintain acceptable voltage levels of the radial distribution systems. Besides, it gives the maximum saving in capital cost of conducting material and cost of energy loss.

Load Flow Method

In any radial distribution system, the electrical equivalent of a typical branch connected between node 1 and 2, having a resistance r(1) and inductive reactance x(1) is shown in Fig.1. From Fig.1, current flowing in branch-1 is given by

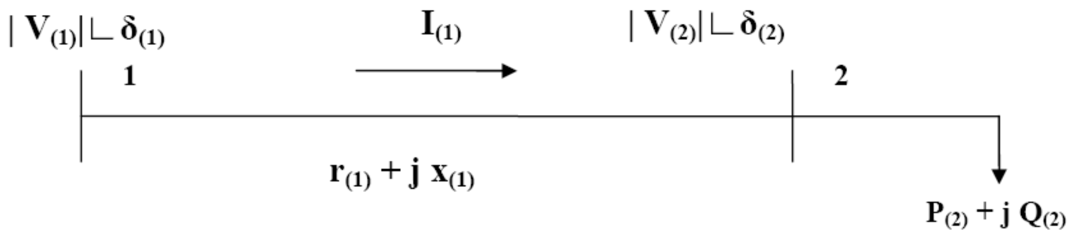


Figure 1 : Single line diagram of a typical branch

$$I_{(1)} = |V_{(1)}| \angle\delta_{(1)} - |V_{(2)}| \angle\delta_{(2)} / (r_{(1)} + jx_{(1)}) \tag{1}$$

$$I_{(1)} = \left(P_{(2)} - jQ_{(2)}\right) / V_{(2)} \angle\delta_{(2)} \tag{2}$$

From eqns. (1) and (2)

$$\frac{P_{(2)} - jQ_{(2)}}{|V_{(2)}| \angle -\delta_{(2)}} = \frac{|V_{(1)}| \angle -\delta_{(1)} - |V_{(2)}| \angle -\delta_{(2)}}{r_{(1)} + jx_{(1)}}$$

Separating real and imaginary parts, the real part is

$$|V_{(1)}||V_{(2)}| \cos(\delta_{(1)} - \delta_{(2)}) = |V_{(2)}|^2 + \{P_{(2)} r_{(1)} + Q_{(2)} x_{(1)}\} \tag{3}$$

and the imaginary part is

$$|V_{(1)}||V_{(2)}| \sin(\delta_{(1)} - \delta_{(2)}) = \{P_{(2)} x_{(1)} - Q_{(2)} r_{(1)}\} \tag{4}$$

$$\begin{aligned} &\Rightarrow |V_{(2)}|^4 + 2|V_{(2)}|^2 \left(r_{(1)} P_{(2)} + x_{(1)} Q_{(2)} - 0.5|V_{(1)}|^2\right) + \\ &(r_{(1)}{}^2 + x_{(1)}{}^2)(P_{(2)}{}^2 + Q(2)^2) = 0 \end{aligned} \tag{5}$$

Equation (5) has a straightforward solution and does not depend on the phase angle, which simplifies the problem formulation. In a distribution system, the voltage angle is not so important because the variation of voltage angle from the substation to the tail end of the distribution feeder is only few degrees. Note that from the two solution of $|V_{(2)}|_2$ only the one considering the sign of the square root of the solution of the quadratic equation gives a realistic value. The same is applicable when solving for $|V_{(2)}|$. Therefore from equation (5), the solution of $|V_{(2)}|$ can be written as

$$\begin{aligned} |V_{(2)}| = \{ &\{(r_{(1)} P_{(2)} + x_{(1)} Q_{(2)} - 0.5|V_1|^2)^2 \\ &-(r_{(1)}{}^2 + x_{(1)}{}^2)(P_{(2)}{}^2 + Q_{(2)}{}^2)\}^{1/2} \\ &-(r_{(1)} P_{(2)} + x_{(1)} Q_{(2)} - 0.5|V_{(1)}|^2)\}^{1/2} \end{aligned} \tag{6}$$

$$|V_{(i+1)}| = \Big\{\Big\{(r_{(j)}P_{(i+1)} + x_{(j)}Q_{(i+1)} - 0.5|V_{(i)}|^2)^2 - (r_{(j)}{}^2 + x_{(j)}{}^2)(P_{(i+1)}{}^2 + Q_{(i+1)}{}^2)\Big\}^{1/2} - (r_{(j)}P_{(i+1)} + x_{(j)}Q_{(i+1)} - 0.5|V_{(i)}|^2)\Big\}^{1/2} \tag{7}$$

where, node no., i=1,2,…,nd
branch no., j=1,2…,nd-1
nd= total no. of nodes

The active and reactive power losses in branch 'j' are given by

$$Ploss[j] = \frac{r_{(j)}\left\{P^2{}_{(i+1)} + Q^2{}_{(i+1)}\right\}}{|V_{(i+1)}|^2} \tag{8}$$

$$Qloss[j] = \frac{x_{(j)}\left\{P^2{}_{(i+1)} + Q^2{}_{(i+1)}\right\}}{|V_{i+1)}|^2} \tag{9}$$

The total active and reactive power losses of the system are

$$TPL = \sum_{j=1}^{nd-1} Ploss[j] \tag{10}$$

$$TQL = \sum_{j=1}^{nd-1} Qloss[j] \tag{11}$$

Where Ploss[j], Qloss[j] =Active and reactive power losses of branch 'j'
TPL, TQL = Total active and reactive power losses of the system

Objective Function

The objective is to select optimal size of the conductor in each branch of the system, which minimizes the sum of depreciation on capital investment and cost of energy losses. The problem of choice of the optimal size of conductor for each feeder segment is presented as an optimization problem using plant growth simulation algorithm.

In detail, the objective function for optimal selection of conductor for branch j with k type conductor is

$$\text{Min F (j, k)= CL (j, k) + CC (j, k)} \tag{12}$$

i) Cost of energy losses (CL): The annual cost for the loss in branch j with k type conductor is,

$$CL(j, k) = \text{Peak loss}(j, k)\,[Kp + Ke \times Lsf \times 8760] \tag{13}$$

where,

Kp = Annual demand cost due to power loss (Rs. /KW)
Ke = Annual cost due to energy loss (Rs. /KWh)
Lsf = Loss factor
Peak loss (j, k) = Real power loss of branch ‘j’ under peak load conditions with ‘k’ type conductor

ii) Depreciation on capital investment (CC): The annual capital cost for branch ‘j’ with ‘k’ type conductor is,

$$CC(j, k) = á \times [\text{cost}(k) \times \text{Len}(j)] \tag{14}$$

where,

á = Interest and depreciation factor
Cost (k) = Cost of k type conductor (Rs. /km)
Len (j) = Length of branch j (km)

Loss factor is defined as ratio of energy loss in the system during a given time period to the energy loss that could result if the system peak loss had persisted throughout that period. In British experience, loss factor is expressed in terms of the load factor (Lf) as

$$Lsf = 0.2\, Lf + 0.8\, Lf^2 \tag{15}$$

Implementation of PGSA to Conductor Selection

The plant growth simulation algorithm [9], which characterizes the growth mechanism of plant phototropism, is a bionic random algorithm. It looks at the feasible region of integer programming as the growth environment of a plant and determines the probabilities to grow a new branch on different nodes of a plant according to the change of the objective function, and then makes the model, which simulates the growth process of a plant, rapidly grow towards the light source (global optimum solution).

Growth Laws of a Plant

The following facts have been proved by the biological experiments.

1) The higher the morphactin concentration of a node, the greater the probability to grow a new branch on the node.
2) The morphactin concentration of any node on a plant is not given beforehand and is not fixed; it is determined by the environmental information of the node, and the environmental information of a node depends on its relative position on the plant.

Probability Model of Plant Growth

By simulating the growth process of plant phototropism, a probability model is established. In the model, a function **g(Y)** is introduced for describing the environment of the node ***Y*** on a plant. The smaller the value of **g(Y)**, the better the environment of the node ***Y*** for growing a new branch. The main outline of the model is as follows: A plant grows a trunk **M** from its root **B_0**. Assuming there are *k* nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} that have better environment than the root B_0 on the trunk M, which means the function **g(Y)** of the nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} and B_0 satisfy **$g(B_{Mi}) < g(B_0)$** *(i=1, 2, 3….k)*, then the morphactin concentrations C_{M1}, C_{M2}, C_{M3} .... C_{Mk} of the nodes B_{M1}, B_{M2}, B_{M3} .... B_{Mk} can be calculated using

$$C_{Mi} = \frac{g(B_0) - g(B_{Mi})}{\triangle_1} (i = 1, 2, 3...k)$$

$$\triangle_1 = \sum_{i=1}^{k} (g(B_0) - g(B_{Mi})) \qquad (16)$$

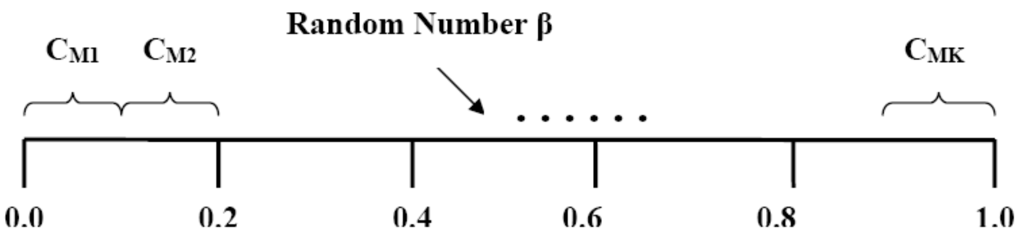


Figure 2 : Morphactin concentration state space

The significance of (16) is that the morphactin concentration of a node is not dependent on its environmental information but also depends on the environmental information of the other nodes in the plant, which really describes the relationship between the morphactin concentration and the environment.

Equation (16) can be used to derivate $\sum_{i=1}^{k} C_{Mi} = 1$, which means that the morphactin concentrations $C_{M1}, C_{M2}, C_{M3}......C_{Mk}$ of the nodes $\beta_{M1}, B_{M2}, B_{M3},....B_{Mk}$ form a state space shown in Fig. 2. Selecting a random number β in the interval [0,1] and will drop into one of $C_{M1}, C_{M2}, C_{M3}.........C_{Mk}$ in Fig. 2, then the corresponding node that is called the preferential growth node will take priority of growing a new branch in the next step. In other words, B_{MT} will take priority of growing a new branch if the selected β satisfies $0 \le \beta \le \sum_{i=1}^{T} C_{Mi} (T = 1)$ or $\sum_{i=1}^{T-1} C_{Mi} < \beta < \sum_{i=1}^{T} C_{Mi} (T = 2, 3...k)$. For example, if random number β drops between an interval [1,2], which means $\sum_{i=1}^{1} C_{Mi} < \beta \le \sum_{i=1}^{2} C_{Mi}$, then the node will grow a new branch *m*.

Complete algorithm for the proposed method of conductor selection

1. Input the system data such as line and load details of the distribution system, constraints limits etc;
2. Form the search domain by taking the number of branches in the system as decision variables which corresponds to the length of the trunk and the branch of a plant;
3. Give the initial solution X_o (X_o is a vector with length equal to no. of branches/decision variables) which corresponds to the root of a plant, and calculate the initial value of objective function (Total cost);
4. Let the initial value of the basic point X_b, which corresponds to the initial preferential growth node of a plant, and the initial value of optimization X_{best} equal to X_o, and let F_{best} that is used to save the objective function value of the best solution X_{best} be equal to f (X_o), namely, $X_b = X_{best} = X_o$ and F_{best} = f(X_o).
5. Initialize iteration count, *count*=1;
6. Search for new feasible solutions. Starting from basic point $X^b = [x_1^b, x_2^b..x_i^b...x_n^b]$, where X^b corresponds to the initial conductor type of each branch. (n is no. of branches).

Step (6a):
For $j=1$ to m where m is the number of available conductor types.

Step (6b):
Let X_p be a new solution obtained by replacing i_{th} decision variable by j_{th} conductor type.

Step (6c):
For the found solution X_p check it out the constraints, if it satisfies then go to next step, otherwise abandon the possible solution X_p.

Step (6d):
Calculate the objective function f (X_p), and compare f (X_p)< f (X_b), if it does not satisfy abandon the possible solution X_p and increment 'j' then go to step (6b).

7. Save the best possible solution from obtained feasible solutions.
8. If *count* >N_{max} go to step 12; otherwise go to next step.
9. Calculate the probabilities C_1, C_2, … C_k of feasible solutions X_1, X_2, X_3, … X_k by using equation (16), which corresponds to determining the morphactin concentration of the nodes of a plant.
10. Calculate the accumulating probabilities ΣC_1, ΣC_2,….ΣC_k of the solutions X_1, X_2, … X_k. Select a random number β from the interval [0 1], β must belong to one of the intervals [0 ΣC_1], [ΣC_1, ΣC_2], ….,[ΣC_{k-1}, ΣC_k], the accumulating probability of which is equal to the upper limit of the corresponding interval, and it will be the new basic point X_b for the next iteration, which corresponds

to the new preferential growth node of a plant for next step.

11. Increment *count* by *count*+1 and return to step 6;
12. Output the results and stop.

Illustrative Example

In this section, the effectiveness of the proposed algorithm is demonstrated through an illustrative example consisting of 26-node radial distribution system. The results are presented with and without load growth.

Before analyzing the results, it is worth mentioning that presently in India, utilities are using three or four different types of conductors for distribution feeders. The conductor data is given in appendix (Table. A.). The single line diagram for practical 26-node radial distribution systems in India is shown in Fig.3. The line and load data are given in [6].

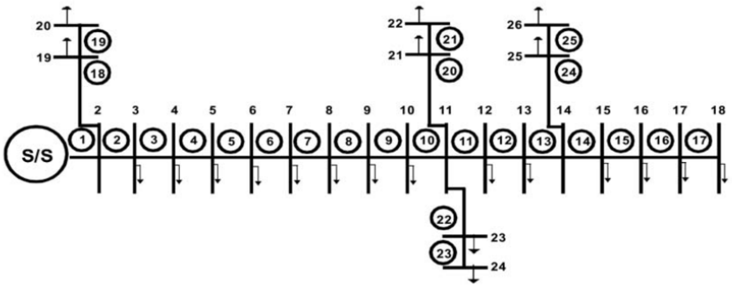


Figure 3 : Practical 26-node radial distribution system

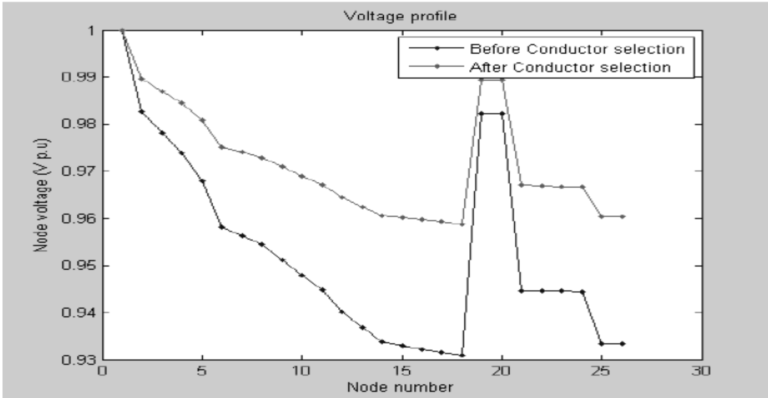
Without load growth

Based on PGSA, the results of conductor type selection without considering the load growth are presented in Table.1. The voltage profile of 26-node radial distribution system is shown in fig.4. It can be seen from Table.2, that the minimum voltage is improved from 0.9309 p.u to 0.958801 p.u. The improvement in voltage regulation is 2.79%. The total real power loss reduction after conductor selection is 80.916 KW. From Tables 1 and 2, it can be seen that reconductoring is necessary for all the branches except 17, 19, 23 and 25. Total cost reduction after conductor selection is Rs. 2,57,706/-. The result of objective function is shown in fig.5.

Table 1 : Modifications in the feeder conductor type after conductor selection of 26 node system without load growth

Branch Number	Existing Conductor in base case (From)	Modified Conductor by proposed PGSA method (To)
1 to 16, 18,20,24	Weasel	Mink
17,19,23,25	Weasel	Weasel

21,22	Weasel	Squirrel



Fgirue 4 : Voltage Profile for 26-node radial distribution system before and after conductor selection without load growth

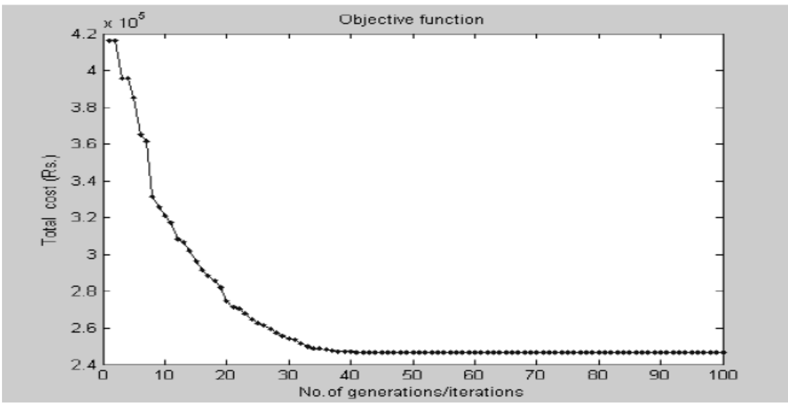


Figure 5 : Objective function for 26-node radial distribution system without load growth

Table 2 : Summary of results of 26-node system without load growth

Description	**Before conductor Selection**	**After Conductor Selection by proposed PGSA method**	**Improvement**
Min.Voltage (p.u)	0.9309	0.958801	0.027901
Real Power Loss (KW)	154.79	73.880840	80.90916
Total Cost (Rs.)	5,04,082.76	2,46,377.04	2,57,705.72

With load growth

In a distribution system load growth takes place with time. The conductor losses are higher if the rate of load growth is large. The effect of load growth, assuming a rate of load growth of 0.7 and growth period of 5 years, is illustrated in this section. In this method, the effect of change in load factor and future cost of energy is not taken into consideration. Based on the proposed algorithm, the results of conductor type selection with load growth for 5 years are presented in Table.3. The voltage profile is shown in fig.7. From Table.3 and 4, it can be seen that reconductoring is necessary for all the branches except 19, 21 to 23 and 25. It is seen that minimum voltage is improved from 0.900282 p.u to 0.941592 p.u. Total real power loss reduction after conductor selection is 172.333702 KW. Total cost reduction after conductor selection is Rs 5, 50,267.31 /-. The result of objective function is shown in fig.8.

Table 3 : Modifications in the feeder conductor type after conductor selection of 26 node system with load growth

Branch Number	**Existing Conductor in base case (From)**	**Modified Conductor by proposed PGSA method (To)**
1 to 18,20,24	Weasel	Mink
19,21 to 23,25	Weasel	Weasel

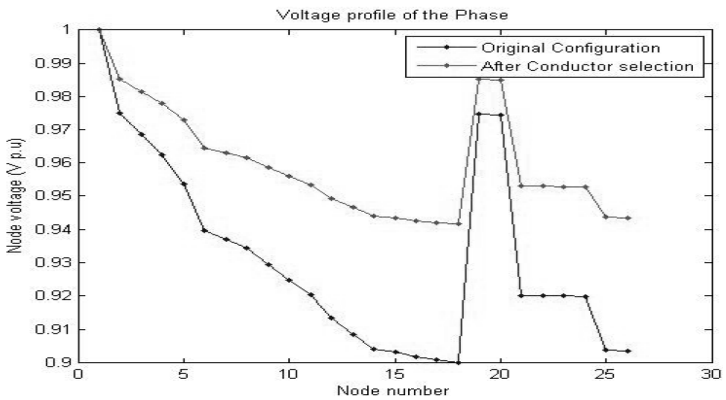


Figure 7 : Voltage Profile for 26-node radial distribution system before and after conductor selection with load growth

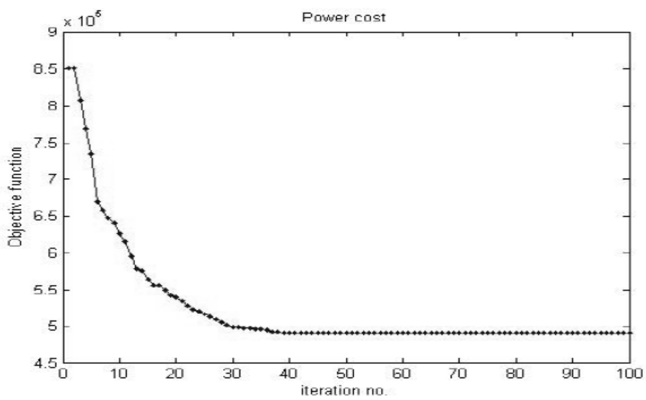


Figure 8 : Objective function for 26-node radial distribution system with load growth

Table 4 : Summary of results of 26-node system with load growth

Description	Conductor Selection		Improvement
	Base case	PGSA	
Min. Voltae (p.u.)	0.900282	0.941592	0.04131
Real Power Losses (KW)	322.043776	149.710074	172.333702
Total Cost (Rs.)	10,39,806.62	4,89,539.31	5,50,267.31

Conclusion

It is very challenging to select an optimal set of conductors for designing a distribution system. In this paper, an algorithm has been proposed for selecting the optimal branch conductor using Plant Growth Simulation Algorithm. The proposed method selects the optimal branch conductor by minimizing the sum of cost of energy losses and depreciation cost of feeder conductor. In addition the algorithm keeps the maximum current carrying capacity and minimum voltage within prescribed limit. The proposed algorithm has been implemented on 26-node practical radial distribution systems in India and considered the effect of load growth for 5 years.

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Appendix

Table A : Conductor Data

Type of Conductor	**Area of cross Section (mm2)**	**Resistance Ohm/km**	**Reactance Ohm/km**	**Maximum current carrying capacity CMAX (Amp.)**	**Rs/km**
Squirrel	12.90	1.3740	0.3915	115	1260
Weasel	19.35	0.9116	0.3820	150	1420
Ferret	32.26	0.6795	0.3760	181	1600
Rabbit	48.39	0.5449	0.3720	208	1785
Mink	50.00	0.4565	0.3660	234	1785