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SIMULATED ANNEALING FOR FEEDER ROUTING OF RADIAL DISTRIBUTION SYSTEM

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ABSTRACT

The main objective of the distribution system planning is to determine the substation location, size and its service area, number of feeders and their routes. The planning problem is solved by classical methods to non traditional soft computing techniques, hence in this work, soft computing technique known as Simulated Annealing is used. Simulated Annealing is a thermal process for obtaining low energy states of a solid in a heat bath. The process contains two steps. Firstly increase the temperature of the heat bath to a maximum value at which the solid melts. Secondly, decrease carefully the temperature of the heat bath until the particles arrange themselves in the ground state of the solid. With this optimization procedure, the objective of the work, to minimize the total annual cost is obtained. The total annual cost includes the capital recovery, energy loss and interruption costs. The feasibility of proposed algorithm is applied on 25 nodes distribution network.

KEYWORDS: Simulated Annealing, Feeder Routing, Distribution System Planning, and Power Flow

INTRODUCTION

Distribution system planning is important to ensure that the growing need of electricity is satisfied by the distributors. Planning starts at customer level, distribution system directly connected to customer any failure in the system would affect the customers. Therefore proper planning of the distribution system is very important for continuity of power. Distribution System Planning (DSP) involves optimal selection of feeder routes, number of feeder, substation size and location [1]. In this work selection of optimal feeder routes is obtained by the proposed method. Several optimization techniques have been implemented to solve the problem of feeder routing. In the past mathematical approach were applied such as branch and bound method for the optimisation of distribution system

[2], mixed integer programming [3] applied to the distribution system problem was found feasible, [4] solved the optimal feeder routing using dynamic programming and geographical information systems GIS facilities, which is effective. Another tool to achieve the optimisation goal is ant colony system algorithm (ACS) [5]. This methodology is meta-heuristic in nature and is very flexible, robust in minimising the investment cost. The reduction in the cost during the planning of distribution system, meeting the constraints is obtained by branch exchange method [6].

The effectiveness of Genetic Algorithm [7-9] is seen in the designing of the distribution system by reducing the solution time. In this paper, Simulated Annealing is the solution strategy for the optimal feeder routes in the planning of the radial distribution system. Simulated annealing [10] is proven to be feasible in planning of the distribution network. In this method the minimum cost solution is obtained by steepest descent approach, further the obtained solution is modified by simulated annealing. This method is faster, taking less consumption time. The merits of Simulated Annealing combined with Genetic Algorithm [11] helps in solving optimization problem. This algorithm avoids being trapped in local minima, which outstands this algorithm from other computing methods.

PROBLEM FORMULATION

The total annual cost of the distribution system planning is the summation of the fixed cost, energy cost and interruption cost. It is expressed as

$$C = C_f + C_l + C_i$$

where

C_f is fixed yearly cost

C_l is energy loss cost

C_i is interruption cost

The constraints to be satisfied:

- Capacity constraint $P \leq U$

  U is the vector of capacity limits.

- The flow in the network model is radial.
- The voltage at demand nodes at any time should be within specified limits.

The fixed yearly cost recovery is the capital recovery cost which is represented as

$$C_f = g \sum_{k \in M} C_k$$

Where C_k is the cost of branch k of the main feeder and g is the yearly recovery rate of fixed cost. Cost of the branch indicates both the line and substation cost. M is the set of all possible branches in a particular radial path. The power loss in distribution system varies with various factors such as level of losses through transmission and distribution lines, transformer, capacitor etc.

Power loss can be divided into real and reactive power. The real power is due to the resistance of the lines. The real power loss draws more attention as it reduces the efficiency of transmitting energy to the customers. The cost of energy losses 'C_l' may be represented as

$$C_l = 8760\, \beta\, p \sum_{k \in M} (I_k)^2 r_k$$

$$\beta = 0.15\, \alpha + 0.85\, \alpha^2$$

Where p cost per unit of energy lost, β loss factor, r_k branch resistance, I_k branch current at peak load and α load factor. In the radial networks, there is no alternative supply route and the outage of a branch interrupts the delivery to all the consumers supplied through this branch. Hence, the cost of outage can be calculated using the following expression

$$C_i = C_i\, \alpha\, d \sum_{k \in M} \lambda_k \sqrt[3]{}U_r I_k$$

Where C_i cost per unit of energy not delivered, α load factor, d repair duration, λ_k branch failure rate, U_r network rated voltage and I_k branch current at peak load.

SIMULATED ANNEALING

Simulated Annealing is inspired from the metallurgy annealing where the solid kept in heat bath is melted into liquid by increasing the temperature and then slowly decreasing the temperature such that the crystals of solid rearrange themselves in the structure. This slow cooling decreases the probability of accepting worse solution. This physical annealing process is analogous to the determination of near-global or global optimum solutions for optimization problems. This configuration is equivalent to the current solution of an optimization problem.

The energy of the atoms is analogous to the cost of the objective function and the final ground state is corresponds to the global minimum of the cost function. A new candidate solution is randomly generated in the neighbourhood of the current one. The move to the new candidate feasible solution is accepted if it is superior to the current one (i.e., a reduction in the objective function for a minimization problem). However, an inferior candidate solution has a chance of acceptance with a probability given by the Boltzmann distribution:

$p = \exp(\Delta E / kT)$

where,

E = change in objective function value

k = Boltzmann's const

T = current temperature

A uniformly distributed random number is drawn in the range [0, 1]. The move to the inferior solution is accepted if the random number is less than *p;* otherwise the move is discarded. Note that such an acceptance avoids getting trapped on a local optimal solution and therefore expands the search space.

The last accepted solution for each temperature forms the initial solution of the next stage. The temperature is lowered and the algorithm proceeds until a stopping criterion is satisfied. Simulated annealing can deal with highly nonlinear models, chaotic and noisy data and many constraints. Its main advantages are its flexibility and its ability to approach global optimality.

LOAD FLOW

The flow of active, reactive power is known as load flow. Power flow analysis is used to determine the steady state operating condition of the system. The goal of the distribution system power flow function is to study the distribution networks under various loading conditions and configurations. Provided with bus voltage magnitudes and phase angles output from the power flow function, one can derive more information for the distribution network, including real and reactive power flow in each line, line section power loss, and the total real and reactive power at each bus. Radial Distribution Systems (RDS) require special load flow methods to solve power flow equations owing to their high R/X ratio. Hence methods like Newton Raphson cannot be applied.

A method name Backward/Forward sweep based on Kirchhoff's current law (KCL) and Kirchhoff's voltage law (KVL) for evaluating the node currents and voltages iteratively is applied for figure 1. In this approach, computation of branch current depends only on the current injected at the neighbouring node and the current in the adjacent branch. This approach starts from the end nodes and moves towards the root node during branch current computation. The node voltage evaluation begins from the root node and moves towards the nodes located at the far end of the main lines that is to the end nodes. This method is also known as ladder iterative method. It can be classified as:

Backward Sweep Method

Forward Sweep Method

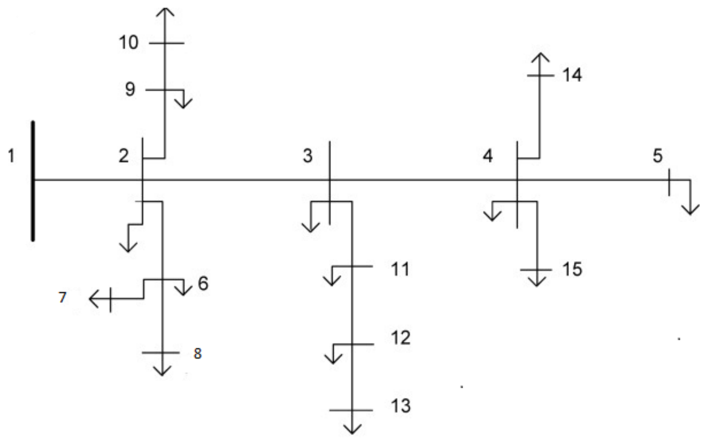

Figure 1: Radial Distribution Networks for 15 Nodes

The calculation is done as follows:

Forward Sweep

- Assume rated voltage V_{rated} at the end node voltages (V 5,V 7, V 8, V10, V 13, V14, V15) in figure 1
- Start with the node 14 and compute the node current I 5 = (S5/V5)*
- Apply the Kirchhoff's current law to determine the current flowing from node 4 toward node 5: I (4−5) = I5.
- Compute with this current the voltage V 4 = V5 +Z (4−5)*I (4−5).
- Node 4 is a junction node.
- Select node 13 and compute the node current I 13 =(S13/V13)*
- Apply the Kirchhoff's current law to determine the current flowing from node 12 toward node 13 I (12−13) = I13
- Compute with this current the voltage V 12 = V 13 +Z (12−13)*I (12−13)
- And in this way the forward sweep is applied and reached till the root node.
- Using the current *I* (1−2) compute the voltage *V*1. At the end of the forward sweep the magnitude of the compute voltage *V*1 is compared to the magnitude of the rated voltage *V* rated. Error = (Vrated-V1)

If the error is less than a specified tolerance, the solution has been achieved. A typical tolerance is 0.001 per unit. If the error is greater than this tolerance, the backward sweep begins. The backward sweep begins at the node 1 with the rated voltage and the current from the forward sweep method.

Backward Sweep

- Start with node 1 and V 1 = V rated.
- Compute the voltage V 2 = V 1− Z (1−2)*I (1−2).
- Compute the voltage V 3 = V 2− Z (2−3)*I (2−3).
- In this way the backward sweep continues till the end node.
- Compute the voltage V 5 = V 4− Z (4−24)*I (4−24).

After the backward sweep the first iteration is completed. At this point the forward sweep will be repeated, only this time starting with the new voltage at end nodes. These steps will be repeated until the error is less than the specified tolerance. This load flow is thus applied on the test case considered. Henceforth this method is superior in number of iteration, computationally efficient, accuracy is high.

RESULTS AND DISCUSSIONS

To check the feasibility of the proposed method, it is applied on distribution system. The graph of available network routes for a rural 10 kV network that should be planned is displayed in Figure 2. There are 25 load points (transformers 10 kV/0.4 kV) and 42 available route segments/branches for their supply from the source 35 kV/10.5 kV substation at node 1. The edges determine the branch number which is the distance between two nodes that is given in km. The details about the branch number and the length associated with it are given in the Appendix. Total load in the network is 2.55 MVA. The substation cost has been included with the feeder related cost for every outgoing line emanating from substation is 75k$.

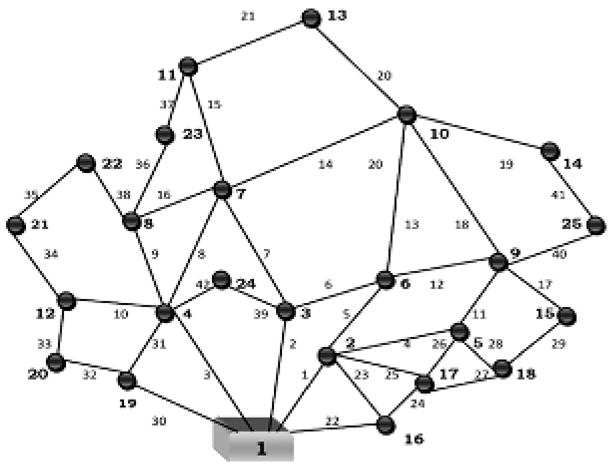

Figure 2: Graph of Available Supply Routes for 25 Load Nodes Distribution Network

Prior to the proposed algorithm, an initial solution is obtained for the above network. In initial solution the capital cost is reduced but loss and energy not delivered costs is increased. Further Simulated Annealing is applied with the initial temperature T_i. This temperature is further increased $T_{i+1} = T_i/(1+b.T_i)$ with i=i+1. When temperature is high local search is carried out and routes which minimize the total distance are accepted. As the temperature decreases, this probability of accepting a bad solution is decreased. Figure 3 shows the initial solution of the test case obtained by steepest descent. It is observed from Table I that the fixed recovery cost had considerably reduced when compared to the optimal solution.

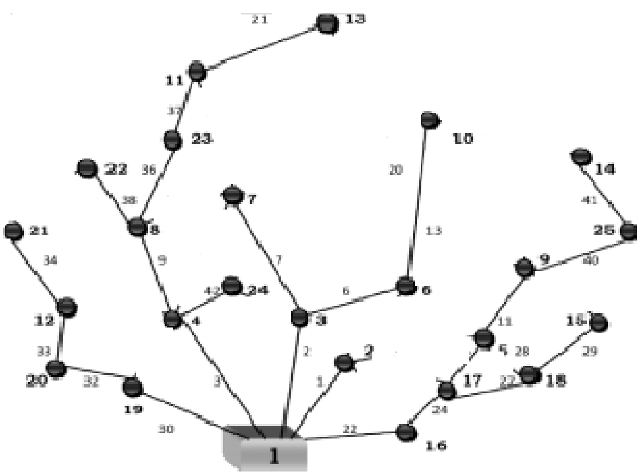

Figure 3: Initial Solution

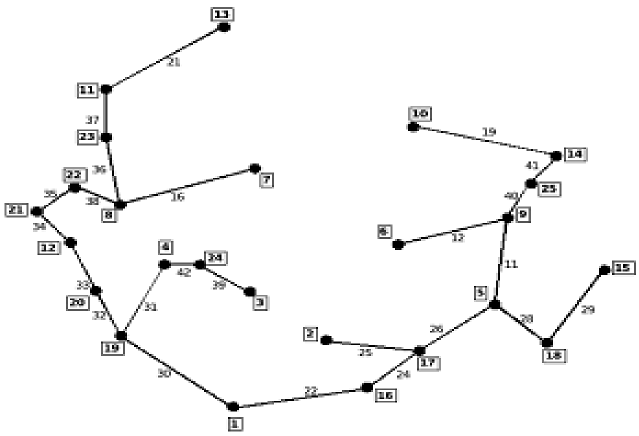

Figure 4: Optimal Solution

The optimal solution graph is shown in Figure 4 through the Simulated Annealing. Also Table 1 shows that there is decrease in the energy loss cost and decrease in the interruption cost which thereby reduces the total annual cost of the radial distribution system.

Table 1: Annual Cost in US$ for 25 Nodes Radial Distribution Network

Solution	C_f	C_l	C_i	Total Cost C
Initial	26650	17507	2080	46237
Optimal	28150	14222.49	1570	44372.49

Table 1 shows the total cost of the system considered and the individual cost component for the optimal route obtained by the proposed algorithm. This is the optimal solution for the test case discussed. Therefore, it is shown from the results that using the proposed optimization technique, the annual cost of the test system is reduced. The proposed technique is developed on MATLAB R2009.

CONCLUSIONS

The major advantage of Simulated Annealing is its flexibility and robustness as a global search method which helps in solving combinatorial optimisation by minimising the total annual cost of the distribution system. This method performs in less amount of time. The computational efficiency and speed of Backward and Forward load flow in distribution system is relatively good compared to the classical methods. Due to the simplicity in the load flow, it is widely used. From the test result on 25 nodes system, it is concluded that the proposed algorithm is effective for obtaining the optimal feeder route and reduces the computational time. Hence Simulated Annealing can be used in distribution system planning.

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APPENDICES

Table 1: Consumption at Load Points

Load point No.	2	3	4	5	6	7
Load, KVA	250	160	100	100	50	100
Load point No.	8	9	10	11	12	13
Load, KVA	100	250	160	100	160	100
Load point No.	14	15	16	17	18	19
Load, KVA	100	100	150	80	40	100
Load point No.	20	21	22	23	24	25
Load, KVA	40	60	40	80	100	30

Table 2: Length of Graph Branches

Branch No.	1	2	3	4	5	6
Length, km	2.10	1.65	2.20	2.00	1.50	1.75
Branch No.	7	8	9	10	11	12
Length, km	1.75	1.75	1.00	1.00	1.25	1.50
Branch No.	13	14	15	16	17	18
Length, km	1.75	2.00	2.00	1.75	1.25	1.75
Branch No.	19	20	21	22	23	24
Length, km	1.75	2.75	1.75	1.50	1.05	0.75
Branch No.	25	26	27	28	29	30
Length, km	1.05	1.00	1.50	0.75	1.25	1.55
Branch No.	31	32	33	34	35	36
Length, km	1.00	0.75	0.75	0.50	0.50	1.05
Branch No.	37	38	39	40	41	42
Length, km	0.50	0.65	0.75	0.45	0.50	0.40

Table 3: Complementary Line Data

Branches No.	Impedance Ω/km	Failure Rate fl./(km yr)	Repair Duration, h
1,2,3,22,30	1.2+j0.4	0.2	3
Remaining	2.1+j0.4	0.2	3

Table 4: Cost and Complementary Load Data

Power Factor	Load Factor	c_i US$/kWh	c_l US$/kWh	c_k kUS$/km	g
0.9	0.6	4	0.1	15	0.01