An Improved Heuristic Approach for Conductor Size Selection in Planning of Branched Radial Feeder Distribution Systems

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Abstract:-In this paper, a method has been developed for finding optimal conductor sizes of each segment in radial distribution system. Nonuniform loading, increase in load, load factor, cost of energy, cost of power of feeder have been considered. The optimal conductor sizes are selected by minimizing the total cost of energy and power subject on voltage drop along the feeder at far end nodes. A method has been developed for solving this optimization problem. The proposed approach is simple to implement and gives near optimal solution with little computational efforts. The method developed is applicable to straight as well as branched radial feeder.

It is tested on number of test feeders. The effectiveness of considering diversity factor and cost of power along with other factors and efficiency of proposed approach is illustrated with the help of an example.

Key words:- Conductor size selection, heuristic, economical criteria, branched feeder

1 **Introduction**

The increasing cost of equipment, labor, and construction has made it necessary to consider the optimal planning of distribution system [1-4]. As feeders share a major portion of total cost of distribution systems, the optimal planning of feeder is also a necessity. From economical point of view, the feeder conductors are selected according to their current carrying capacity and losses so that the total cost of the system is minimized.

A.W.F.Houser et al. [5] studied the problem of multiconductor considering uniform load distribution along the feeder using enumeration technique, while load is non-uniform in nature. M. Ponnavaikko et al. [6] developed a model, which consists of nonuniform loading and permissible voltage drop along the length of the feeder for optimal conductor cross-section for various sections of the radial feeders. The problem was formulated as multistage decision dynamic programming problem. However, the method developed face limitations when applied to branched radial feeders or having large number of load points along the feeder due to increase in computational efforts. P.S. Nagendra Rao [7] developed an algorithm considering the model developed in [6]. This method also faces dimensionality problems when number of load point increases. Tram et al. [8] developed a computer algorithm based on some realistic assumptions. But the technique developed is not easy to implement. Z. Wang et al. [9] proposed an approach for conductor size selection utilizing an economical current density based method and heuristic approach in combination. In this approach, the computational efforts involved are large because an index (Increase in cost/Decrease in voltage) is defined for all feeder segments in each modification of conductor size.

The cost of power along with other factors is also important. But none of the models developed in [5-9] consider this cost. The cost of equipments, materials, operation and maintenance increases (due to inflation) with time thereby result into a continuous increase in cost of power and energy. Although cost of conductor increases at slower rate as compared to cost of energy, yet it is necessary to consider the increasing trend of cost (cost of power and cost of energy) in the total cost of the conductor for optimal conductor size selection.

In this paper, cost of power is incorporated in addition to nonuniform loading, increase in load, load factor, cost of energy in the model developed in [6]. In this paper, a very simple and efficient method is proposed for optimal conductor size selection using economical criteria and heuristic approach in combination. In economical criteria, only discrete sizes of conductors are considered and in heuristic approach, all feeder segments are not considered simultaneously for modification but in two steps; firstly feeder segments near to source end are considered, then far end segments are taken into account which helps in reducing computational efforts. The efficiency of the proposed method is proved through the example by taking the discrete sizes of conductors as available in the inventory. On comparison with other methods ([8] and [10]), it is found that the proposed method gives better results with less computational efforts.

2 Problem Formulation

The problem of conductor size selection is to minimize the total cost of the feeder consisting of the cost of conductor and cost of losses subject to constraint of permissible voltage drop at each far end nodes. In this section, cost of power and diversity in load peaks at load points is incorporated in mathematical model developed in [7] as:

$$\mathrm{Min}C = \sum_{l \in n} (T\cos t_l) \tag{1}$$

$$T\cos t_l = (Ccon_l + Closs_l) \tag{2}$$

$$Ccon_l = C_{line} L_l A_l \tag{3}$$

$$Closs_l = 26.28 \rho\, gro L_l I_l^2 / A_l \tag{4}$$

$$K_{gr} = \sum_{p=1}^{m} (1+g)^{2p} (Cp_p^{'} + Ce_p llf_p)/(1+dr)^p \tag{5}$$

$$K_c = (1+g)^{2m} (llf_m) \tag{6}$$

$$K_{ag} = \sum_{p=m+1}^{F} (Cp_p^{'} + Ce_p llf_p)/(1+dr)^p \tag{7}$$

$$Cp_P^{'} = Cp_p / 8760 \tag{8}$$

where C is the cost to be minimized; ($T\cos t_l$) is total cost of the feeder which consists of cost of conductor ($Ccon_l$) and cost of losses ($Closs_l$) in proportional to cross-section area A_l for feeder segment l in *mm²*; n is total number of feeder segments; L_l is the length of feeder segment in k*m*; C_{line} is cost of line in *Rs.* per *mm²/km*. I_l is the diversified current in feeder segment l; gro is a factor related to present worth of the cost of energy and power losses considering the effect of increase in load, load factor and cost of energy and power over the life of feeder and can be formulated from [7]; ρ is resistivity of conductor material in *ohm-mm²/km*; Cp_b and Ce_b are the cost of power and energy in b^{th} year respectively; LLF_b is load loss factor in b^{th} year; dr is the annual discount rate; g is the annual load growth rate; m is the load growth period; F is the life of feeder in years.

2.1 Voltage drop at each end node:

As the feeders are designed for a particular voltage regulation, so the voltages drop ($Vdrop_l$) at each end node of the feeder should be less than equal to the maximum allowable voltage drop as:

$$\sum_{l \in s(e)} Vdrop_l \le Vd_{allow} \qquad e \in N \tag{9}$$

Voltage drop at l^{th} feeder segment $Vdrop_l = (V_{1l} / A_l + V_{2l}) I_l$

$$\tag{10}$$

$$\text{where} \quad V_{1l} = \sqrt{3} \rho L_l \cos\theta \tag{11}$$

$$V_{2l} = \sqrt{3} L_l x \sin\theta \tag{12}$$

Vd_{allow} is maximum allowable voltage drop in the feeder*;* N is the set of end nodes; $e \in N$ be an end node of a feeder; $s(e)$ is set of segments connecting e^{th} end node to source point; θ is the power factor angle of the load; x is the average reactance per phase of a distribution line in *ohms/km*.

3 Solution Approach

In this section, a simple approach for optimal conductor size selection is presented. The presented approach utilizes economical criteria in combination with heuristic approach. Initially conductors are selected on the basis of economy. Constraint is checked for these economical cross-sections, if satisfied, an optimal solution is obtained. Otherwise using heuristic approach these conductors' cross-sections are modified to obtain an optimal solution.

3.1 Economical Criteria of Selection of Conductors

From economical point of view, the conductors are placed according to their current carrying capacity. Also in [9], an economical current density based method is proposed for economical conductor size selection. But in this method computational effort involved are more, as first of all, for each feeder segment continuous cross-section area is calculated, then replaced by nearest discrete size of conductor available or by minimum of the total cost corresponding to two nearest discrete sizes of conductors available. To reduce these computational efforts, the inherent feature of bigger size of conductors for feeder segments near to source end, due to decreasing nature of current from source to far end is exploited as following:

For economical design, conductor cross-section should be such that the capital cost of conductor is equal to present worth of cost of losses [10]. Though this is applicable to continuous variable, but this condition is exploited here for discrete size of conductor section also.

3.2 Heuristic Approach

Due to radial nature of feeders, feeder segments near to source end carry more current as compared to far end, so the size of conductors near to source end is bigger than far ends. Utilizing this inherent feature, a heuristic approach is developed. In this approach, firstly feeder segments near to source end are modified to obtain an optimal solution, if total decrease in voltage drop for these feeder segments can satisfy constraint given by Eq. (10). Otherwise far end feeder segments are modified as in step (5).

4 Algorithm

1). Determine peak load current in each feeder segment as following:

- Calculate diversified KVAkm *(*α_l*)* for each feeder segment l*:*

$$\alpha_l = D_l L_l \tag{13}$$

where D_l is the diversified demand in KVA at feeder section l.

- Obtain maximum of α_l from the existing set e (j).
- Determine voltage drop per α_l and voltage drop in each feeder segment as:

$$\delta V = V_{allow} / \max(\alpha_l) \tag{14}$$

$$Vd_l = \delta V \alpha_l \tag{15}$$

- Obtain voltage (KV_j) at each end node:

$$KV_e = KV_0 - VS_l \ , e \in N; \text{ where } VS_l = \sum_{l \in s(e)} Vd_l \tag{16}$$

- Determine voltage at each node using relation

$$KV_i = KV_{i+1} + Vdrop_i \ ; \text{ where } Vdrop_{l+1} = 0 \tag{17}$$

- Using diversified demand (D_l) for feeder section l and voltage (KV_l) at section node l determine current I_l for $l \in n$ as:

$$I_l = D_l / (\sqrt{3} KV_l) \tag{18}$$

2). Determine initially most economical conductor cross-section for each feeder segment *l*, relaxing the constraints. Start from the far end feeder segment *l* with smallest size *k* of conductor available in the inventory on the basis of economy as:

- Calculate cost of conductor ($Ccon_l$) and cost of losses ($Closs_l$) corresponding to smallest size of conductor using (3) & (4). If the cost of losses is less than equal to the cost of conductor section for feeder segment *l*, then the k^{th} conductor section will be economical.
- Otherwise, compare the total cost ($T\cos t_l$) of feeder segment *l* for conductor size *k* and *k+1* using (2) to select an economical conductor cross-section.

If for segment *l*, k^{th} conductor is selected, then the next feeder segment *l*-1 towards source should not have *k*-1^{th} conductor as the section towards source carries more current as compared to far end.

3). Calculate voltage drop in each feeder segment and at end nodes using Eq. (11) and Eq. (17) respectively. Calculate current corresponding to this $Vdrop_l$ as in step 1. Check for constraint given by Eq. (9), if satisfied then this is an optimal design. Otherwise go to next step.

4). Calculate increase in cost and decrease in voltage drop corresponding to cross-section k (Economically selected) and k+1, if k+1<Ncn for feeder segment $l \in st$ (st is set of segments for which the total cost is compared during economical criteria, as stated in step 3) as:

$$\Delta V = Vdrop(k+1) - Vdrop(k) \tag{19}$$

$$\Delta COST_l = COST(k+1) - COST(k) \tag{20}$$

where Ncn is the highest conductor size option available in the inventory.

5). Calculate total decrease in voltage drop corresponding to segments $l \in st$ (i.e. $-\Delta V = \sum_{l \in st} (\Delta V_l)$). If total decrease in voltage drop is sufficient to satisfy the constraint ($-\Delta V + (\sum_{l \in s(e)} Vdrop_l - Vd_{allow})$), then modify the conductor cross-section $l \in st$ using the most economical combination of decrease in voltage drop to satisfy the constraint and corresponding increase in cost. If voltage constraint is satisfied, an optimal design is obtained. Otherwise go to next step.

6). Calculate increase in cost and decrease in voltage drop corresponding to feeder segments $l \in Q$ (Where Q is a set of feeder segments for which cost corresponding to one conductor cross section is calculated.), which are not used earlier in step (4). Calculate total decrease in voltage drop and follow the same procedure as in step (5). If still no solution is obtained, then there is no feasible solution.

5 Results

The proposed approach is tested on large number of 11 *kV* radial distribution feeders. In this paper, a 19-segment branched radial feeder is considered as shown in Fig 1.The detail of the data is given in Appendix. The cross-sectional area available in inventory, line data and load data is given in Table 4 and 5 respectively in Appendix. Results obtained are tabulated in Table 1-3.

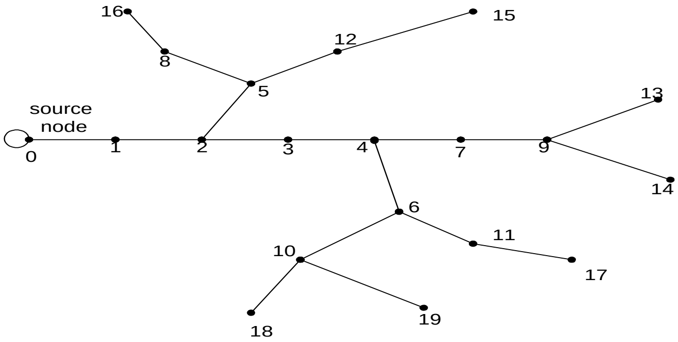

Fig 1 19-segment Branched radial feeder

The results for the given example are tabulated in Table 1-2. Firstly conductors are selected for each feeder segment using economical criteria as tabulated in 2nd column of Table 1. Voltage constraint is checked for these conductors sizes as given by Eq. (9), which result voltage drop at end nodes [15 16 14 13 17 19 18] in *kV* as 0.4796 0.4915 0.7561 0.7997 0.7103 0.7050 and 0.7002 respectively which is less than the maximum allowable voltage drop. So these economically selected conductors give an optimal solution with an annual total cost of *Rs.* 17377 as mentioned in 3rd column of Table 2.

To illustrate the effectiveness of the proposed method, the given example is solved and compared with the method proposed in [8] and [10] as tabulated in Table 2 and 3 and graphically shown in Figs 2, 3 and 4. On comparison, it is observed that the result obtained with the present approach is better than [8] and [10]. On comparing annual total cost of present, [8] and [10] approaches, it is found that the present approach costs less annual cost of Rs 17377 while conductors sizes selected in [8] and [10] result a high annual total cost of Rs. 177714 and 183489 respectively. It is clear from Fig 3, that the cost is continuously decreasing for method in [8],[10] and proposed method.

At the same time the present approach involves less computational time as shown in 3rd column of Table 3 than the approach in [8] and [10], because all feeder segments are not considered at the same time , but in two steps as explained in heuristic approach. It is also clear from Fig 5 that the computational time for proposed method is less than others.

Table 1
Economical and optimal conductor

Segment Number	Economically Selected Conductors Using Economical Criteria	Optimal Solution
1	Squirrel	Weasel
2	Squirrel	Weasel
3	Squirrel	Squirrel
4	Squirrel	Squirrel
5	Squirrel	Squirrel
6	Squirrel	Squirrel
7	Squirrel	Squirrel
8	Squirrel	Squirrel
9	Squirrel	Squirrel
10	Squirrel	Squirrel
11	Squirrel	Squirrel
12	Squirrel	Squirrel
13	Squirrel	Squirrel
14	Squirrel	Squirrel
15	Squirrel	Squirrel
16	Squirrel	Squirrel
17	Squirrel	Squirrel
18	Squirrel	Squirrel
19	Squirrel	Squirrel

Table 2
Comparison of techniques

Segment Number	Conductor obtained by [8]	Conductor obtained by [10]	With proposed Method
1	Weasel	Rabbit	Weasel
2	Weasel	Weasel	Weasel
3	Weasel	Weasel	Weasel
4	Weasel	Weasel	Weasel
5	Weasel	Squirrel	Squirrel
6	Weasel	Squirrel	Squirrel

7	Weasel	Squirrel	Squirrel
8	Squirrel	Squirrel	Squirrel
9	Squirrel	Squirrel	Weasel
10	Squirrel	Squirrel	Squirrel
11	Squirrel	Squirrel	Squirrel
12	Squirrel	Squirrel	Squirrel
13	Squirrel	Squirrel	Squirrel
14	Squirrel	Squirrel	Squirrel
15	Squirrel	Squirrel	Squirrel
16	Squirrel	Squirrel	Squirrel
17	Squirrel	Squirrel	Squirrel
18	Squirrel	Squirrel	Squirrel
19	Squirrel	Squirrel	Squirrel

Table 3
Comparison of annual cost and computational time

	Annual Total Cost (Rs.)	Computational Time (sec)
With [8]	183489	0.1560
With [10]	17771	0.3120
Proposed Method	17377	0.112

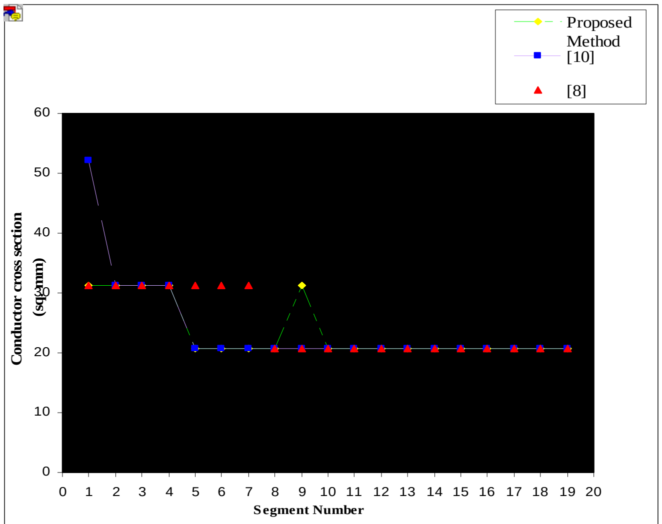

Fig2. Comparison of conductor options selected

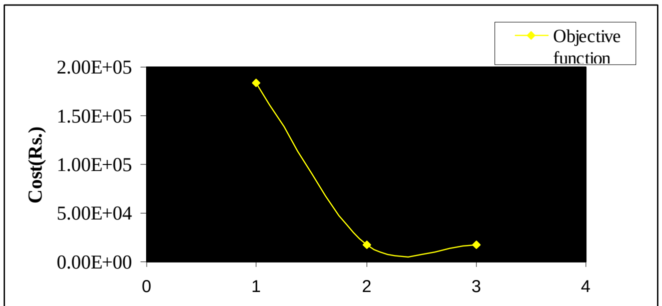

Fig3 Objective function value(Rs.) for diffreent methods

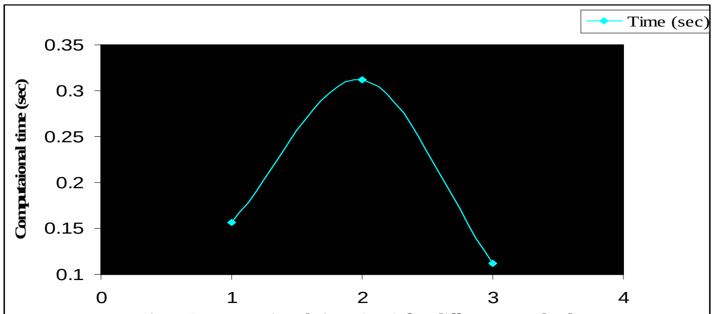

Fig4. Compuataional time (sec) for different methods

6 Conclusions

In this paper, a generalized model, along with a simple and efficient approach for optimal conductor size selection in radial distribution system is presented. The presented approach utilizes simple economical criteria and heuristic approach for conductor size selection. The solution obtained with the present approach is better than existing techniques and it also takes less computational time as compared to other existing techniques. The proposed approach does not face dimensionality problem even for large number of feeder segments or branched radial feeder with large number of load points because of considering feeder segments in two steps for modification. The method presented is applicable to straight as well as branched radial feeders having large number of load points along the feeder.

APPENDIX

ρ=28.1 *ohm-mm*^{2}*/km*,, *x*=0.38 *ohm/km*, Present load factor=0.25, Improvement in load factor/annum=0.02, *g*=0.05, *t*=30 years, *dr*=2.15, C_e=0.3 *Rs./kWh*, *Cp*=3.15 Rs/kWh (constant), V_{allow}=790 volts, *m*=15 years, Power factor=0.8, C_{line}=260/*mm*^{2}*/km*. Table 4 and 5 gives cross-section areas available in the inventory, line and node load data for 19-segment branched feeder respectively.

Table 4
Cross-section area available

Type of Conductor	Area of Cross-section (mm2)
Rabbit	52.21
Weasel	31.21
Squirrel	20.71

Table 5
Line and load data of 19-segment branched feeder

Segment Number	From Bus	To Bus	Length (km)	kW demand at each node
1	0	1	1.0	320
2	1	2	1.1	70
3	2	3	1.2	10
4	3	4	1.0	-100
5	2	5	1.3	170
6	2	6	1.7	190
7	4	7	1.6	100
8	5	8	1.6	80
9	7	9	1.2	20
10	6	10	1.4	40
11	6	11	1.5	60
12	5	12	1.5	40
13	9	13	1.5	280
14	9	14	1.5	100
15	12	15	1.2	80
16	8	16	1.2	80
17	11	17	1.6	60
18	10	18	1.5	30
19	10	19	1.5	50

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