OPTIMAL CABLE SELECTION IN RADIAL DISTRIBUTION NETWORKS CONSIDERING PLANNER'S DEFINED VOLTAGE DROP LIMIT

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OPTIMAL CABLE SELECTION IN RADIAL DISTRIBUTION NETWORKS
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Abstract
New computer algorithms are provided to determine the optimal cable size selection considering radial distribution networks and planner of power distribution defined allowable voltage drop all over the networks. The planner should properly populate the location of all load substations and the joint node location in the input data source. Distance calculation of the demand node to demand node and joint node to joint node etc. depends on the geographical location of the defined node. Cable size and type of all feeder segment determination depends on the total cost of the networks, cost of feeder losses etc. An acceptable voltage profile will be maintained all point of the entire networks. The resource of the cable inventory is also responsible for optimal selection of the cable. By using this proposed computer algorithm and program an example is solved successfully that is presented in the results.

1. INTRODUCTION
In distribution network design a large amount of data is required, e.g. information of present networks, design objectives, etc. Complicated calculations are necessary in some cases to optimize network configurations. The use of computers makes it possible to carry out sophisticated network-design calculations. Common tasks for computer-aided network design are to obtain quantitative information on the status of networks. Computer programs can also act as an efficient tool for long planning and the study of more complex aspects [2]. But in this case the main aim of using computer programs is to draw distribution network by using the geographical co-ordinates and to calculate the length of each segment of complete feeder route of distribution networks according to planning procedure. The high investment cost of electricity distribution systems and the increasing cost of energy, equipment and labor has caused design engineers to look for more efficient planning methods and techniques to reduce these costs [1]. The main contributions of this paper are i) selection the optimal cable size and type ii) measurement of cable length and node to node distance considering practical scenario iii) mapping of power distribution networks including precious direction change iv) to include zoom facilities in mapping iv) power losses and voltage drop determination v) required KVA rating for the demand node vi) Node current for each branch.

The factors of systems costs, voltage quality and losses are directly related to the network configuration. The financial justification of the solution in each selection of cable I related and therefore these factors are considered.

2. MAPPING OF FEEDER ROUTES
The methods of mapping of feeder routes will be more transparent if we consider all necessary things to explain it properly and precisely. Main program will handle the mapping after retrieving data from the data bank and getting the information about the initialization of graphics interfaces. Output of this program will be the mapping of entire networks. This output depends on the proper handling of related data structures.

2.1.1 Connection Sequence Selection Method
In practical situation to determine actual route flow from the practical design route it is very complex to ensure all direction is considered properly and implement it in the calculation module accurately.
Connection sequence selection method is a systematic numbering selection method for calculation of distance of towers. Systematic numbering of nodes and branches is not an essential criterion for calculation of distance of towers of distribution network but it will be better for node sequence selection.

Four types of nodes are considered in the distribution network. They are:
- nodes which will be used for getting more accurate distance
- load substation nodes
- joint nodes
- source substation node

Load substation nodes are to be numbered at first. On completion of the numbering of all the load substation nodes joint nodes have to be numbered. There are three types of joint nodes. Joint node of
- two or more than two load substation nodes
- load substation feeders
- load substation node and load substation feeder

The last number will be source substation node. It is not essential to follow this procedure of numbering. But if this procedure is followed it will be easy to find out the node number of the demand load substations, joint nodes and source substation. Extra nodes of each route will be numbered after finishing of numbering of source substation node. Any extra node number will be bigger than substation number and it will be start after the number of source substation.

On completion of the numbering of all nodes it is needed to arrange the node sequence selection. Figure 3.2 shows the typical distribution network.

For each feeder branch it is needed to mention the connecting node numbers. The node-to-node connection sequence will be

18 \rightarrow 1 18 \rightarrow 2 18 \rightarrow 3 19 \rightarrow 17 19 \rightarrow 18
20 \rightarrow 5 20 \rightarrow 6 21 \rightarrow 4 21 \rightarrow 20 22 \rightarrow 7
22 \rightarrow 8 22 \rightarrow 21 23 \rightarrow 9 23 \rightarrow 10 23 \rightarrow 11
24 \rightarrow 23 24 \rightarrow 22 25 \rightarrow 14 25 \rightarrow 15 26 \rightarrow 12
26 \rightarrow 13 26 \rightarrow 25 27 \rightarrow 16 27 \rightarrow 26 28 \rightarrow 19
28 \rightarrow 24 28 \rightarrow 27

Total number of load substations is 17. Joint nodes number is 18 to 27. 28 is the source substation node in fig. 2.1. Radial distribution network is shown in the 2.1 figure. There are a lot of hidden nodes between two adjacent nodes those make the mapping accurate and practical based.

The mapping of the node connection is shown as below:

![Figure 2.1: Typical distribution network](image)

3. **PROBLEM FORMULATION**

To determine the distance between two nodes, at first it is needed to select the location of the nodes. The location of nodes are stated by geographical co-ordinates then the distances are determined as follows:

The required distance between two nodes [2Jls]

\[ D_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \]

Total distance of a single route of n number of nodes is

\[ D_k = \sum_{i=1}^{n} D_{ik} \]

Total length of cable of complete route of network is

\[ D_t = \sum_{i=1}^{n} D_i \]

Calculated node number

\[ C_{NN} = A_{NN} + 1 \]

Calculated demand node number

\[ C_{DN} = A_{DN} + 1 \]

Total joint node number

\[ T_{NN} = C_{NN} - C_{DN} \]

Allowable voltage drop of the considered network

\[ VD^A = VD^L * V_L \]

The present worth factor for proposed network life

\[ PWF = (1 + IR/100.0)^{-PWL} \]

Node selection sequence is needed for optimal cable selection module. The memory location for this node selection is maintained as below:

- \( P_{2i(1-1)} \rightarrow N_{1i} \), \( P_{2i(1-1)+1} \rightarrow N_{1i} \)
- \( P_{2i(2-2)} \rightarrow N_{2i} \), \( P_{2i(2-2)+1} \rightarrow N_{2i} \)
- \( P_{2i(3-3)} \rightarrow N_{3i} \), \( P_{2i(3-3)+1} \rightarrow N_{3i} \)
\[ P_{2}(n-2) \rightarrow \mathbf{N}_1(n-1), \ P_{2}(n-3) \rightarrow \mathbf{N}_2(n-2) \]
\[ P_{2}(n-1) \rightarrow \mathbf{N}_3(n-1), \ P_{2}(n) \rightarrow \mathbf{N}_3(n) \]

Approximate transformer rating for the demand load
\[ ATR_{\text{RL}} = DL_{i} / \text{AEF} \]

Actual efficiency of the transformer
\[ \eta_{\text{eff}} = 1 - \left( \frac{P_{\text{real}} + P_{\text{loss}}}{P_{\text{in}}} \right) / (\text{AT} \times 1000) \]

Required transformer rating of demand node
\[ RT_{\text{req}} = DL_{i} / \eta_{\text{eff}} \]

The required rating of source substation
\[ RT_{\text{SS}} = \sum_{i=1}^{n} RT_{\text{in}}^{i} \]

Required transformer rating may not be standard transformer rating. It is needed to get associated standard transformer rating from the input data bank.

Actual efficiency of the source substation transformer
\[ \eta_{\text{eff SS}} = 1 - \left( \frac{P_{\text{real SS}} + P_{\text{loss SS}}}{P_{\text{in SS}}} \right) / (\text{AT} \times 1000) \]

Required transformer rating by using efficiency
\[ RT_{\text{SS}} = RT_{\text{req}} / \eta_{\text{eff SS}} \]

Required transformer rating, \( RT_{\text{SS}} \), may not be standard transformer rating. It is needed to get associated standard transformer rating from the input data bank. If \( RST_{\text{SS}} > AT_{\text{SS}} \) \( RST_{\text{SS}} \) will be actual source substation transformer rating.

The position of transformer and the position of rating of transformer is as below:
\[ P_{1} \rightarrow P_{1}^{i}, \ P_{2}^{i} \rightarrow P_{2}^{i}, \ P_{3}^{i} \rightarrow P_{3}^{i}, \ P_{4}^{i} \rightarrow P_{4}^{i}, \ P_{5}^{i} \rightarrow P_{5}^{i} \]
\[ P_{6}^{i} \rightarrow P_{6}^{i}, \ P_{7}^{i} \rightarrow P_{7}^{i}, \ P_{8}^{i} \rightarrow P_{8}^{i}, \ P_{9}^{i} \rightarrow P_{9}^{i}, \ P_{10}^{i} \rightarrow P_{10}^{i} \]

If source substation is associated with \( i \)th transformer of the internal data bank the associated parameter of that transformer will be used to find out the efficiency for that particular rating of the transformer and this efficiency will be used for the source substation.

The node current will be
\[ I_{n} = T_{i} \times 1000 / (\sqrt{3} \times V) \]

This current rating will be indicated for all nodes. But associated required transformer is essential input for the determination of particular node current.

To determine the feeder route selection it is needed to separate the demand load of the end point of the networks and the joint nodes. The sequence is the most important to generate the appropriate route determination.

The sequence of node number
\[ S_{1} \rightarrow S_{1}, \ S_{2}, \ S_{3}, \ S_{4}, \ S_{5}, \ S_{6} \]
\[ S_{2} \rightarrow S_{2}, \ S_{3}, \ S_{4}, \ S_{5}, \ S_{6} \]
\[ S_{3} \rightarrow S_{3}, \ S_{4}, \ S_{5}, \ S_{6} \]
\[ S_{4} \rightarrow S_{4}, \ S_{5}, \ S_{6} \]
\[ S_{5} \rightarrow S_{5}, \ S_{6} \]

\[ S_{6} \rightarrow S_{6} \]

Connection sequence of joint node
\[ J_{S_{m}} \rightarrow J_{S_{m}}, J_{S_{m}}, J_{S_{m}}, J_{S_{m}}, J_{S_{m}} \]
\[ J_{S_{m}}, J_{S_{m}}, DS_{m}, DS_{m}, DS_{m}, DS_{m} \]

The nth joint node of the sequence joint node set for mth joint node
\[ J_{S_{mn}} = DS_{n}, DS_{n}, DS_{n}, DS_{n}, DS_{n}, DS_{n}, DS_{n}, DS_{n} \]

The current flow of joint node
\[ I_{S_{mn}} = \sum (I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S}) \]

The current flow of nth joint node of the sequence joint node set for mth joint node if all connecting node are demand nodes
\[ I_{S_{mn}} = \sum (I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S} + I_{S_{m}}^{S}) \]

All current flow of demand node will be calculated according to \( I_{T} \).

The voltage drop of the particular is
\[ V_{S_{m}}^{m} = \sum \left( V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} + V_{S_{m}}^{m} \right) \]

The individual node voltage drop of the sequence node set
\[ V_{S_{mn}}^{m} = \sqrt{3} I_{T} R_{m} \cos \theta + \sqrt{3} I_{T} R_{m} \sin \theta \]
The power loss of joint node feeder and all associated sequence node feeder

\[ p^{JN}_m = \sum (p^{Se}_{m1} + p^{Se}_{m2} + p^{Se}_{m3} + \ldots + p^{Se}_{m(n-1)} + p^{Se}_{mn} + p^{De}_{m1} + p^{De}_{m2} + \ldots + p^{De}_{m(n-1)} + p^{De}_{mn}) \]

The power flow of nth joint node of the sequence joint node set for mth joint node if all connecting nodes are demand nodes

\[ p^{Se}_{mn} = \sum (p^{De}_{m1} + p^{De}_{m2} + \ldots + p^{De}_{m(n-1)} + p^{De}_{mn}) \]

The power loss of the nth node of the sequence node set for mth node

\[ p^{Se}_{mn} = 3(r^{Se}_{mn})^2 R^{N_i}_m D^{N_i}_l \]

Total power losses is

\[ P_{PL} = \left( \sum_{i=1}^{n} p^{HN}_{i1} \right) + p^{HN}_{ss} + F_{loss} \left( \sum_{i=1}^{n} p^{HN}_{i1} + p^{HN}_{ss} + p^{JN}_m \right) \]

In this case demand loss is same for all possible complete routes of the feeders. For this reason demand loss is ignored. All fixed cost are also ignored.

Cable cost of jth feeder segment of the feeder branch of nth load substation route is

\[ C_{ij} = D_i C_{ij} (1 + IR/100.0) \text{ PNL} \]

Total cable cost of the network is

\[ C_{CJO} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} \]

Cable installation cost of jth feeder segment of the feeder branch of nth load substation is

\[ C_{i,j} = D_i C_{i,j} (1 + IR/100.0) \text{ PNL} \]

Total cable cost of the network is

\[ C_{CJO} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{i,j} \]

Total power loss cost is

\[ C_{PDF} = 8760L_{pdf} p^{HN}_{pdf} C_{loss} L_{ref} \]

Total variable cost of the network is

\[ T_{res} = C_{CJO} + C_{PDF} + C_{pdf} \]

The type and size of cable depend on voltage level and required current flow and current density in the feeder. The type and size of cable are selected from table of standard cable according to the input voltage level of the feeder and current flow of the feeder. Current flow of ith feeder is I_i and I_{ref} is current of standard cable, C_i, C_{ref} is also equal or nearly greater than I_i, compare to other rated current of standard cable.

The cable size and type of ith feeder will be C_i as primary selection.

Economical cable size and type are selected after primary selection of cable size of all feeder routes. Total number of feeder type and size are considered in the following way:

If N_{ref} is the total number of standard cable size and type of data bank and N_{ref} is the number of primary selection of jth feeder of the feeder branch of nth load substation then the difference between N_{ref} and N_{ref} will be

\[ D_{i,j} = N_{ref} - N_{ref} \]

The final selection of cable size and type will be selected between N_{ref} and N_{ref}. Maximum voltage drop of the feeder route of load substations have to be determined after primary selection of cable size and types of all feeder branches. According to descending order of voltage drop of feeder route of load substations the cable size and type of each feeder segment of feeder route of load substations are determined.

Cable size and type of all feeder segments are selected which are economic after justification of all feeder type and size of feeder segment of all branches.

3.1 Notations

- D_{jk} is the distance from jth node to kth node that is the distance of ith branch of feeders.
- x_j y_k are geographical horizontal co-ordinates of jth node and kth node respectively.
- y_j y_k are geographical vertical co-ordinates of jth node and kth node respectively.
- C^{NN} indicates calculated node number of the calculation module.
- A^{NN} indicates actual node number that is designed by the planners.
- CD^{NN} indicates calculated demand node number of the calculation modules.
- ACD^{NN} indicates actual demand node number that is designed by the planners.
- VD^A indicates the allowable voltage drop that will be maintained each segment.
- VD^I indicates the limitation indication of voltage drop that is assigned by planners of the proposed network.
- VL Voltage level of the network.
- IR indicates the interest rate of total investment.
- PNL Planners proposed network life.
\[ P_{2(n-1)} \] indicates the position of the second node of the sequence of node selection.

\[ N_{sl} \] indicates the position of the first node of the sequence of node selection.

\[ N_{tr} \] indicates the second node of the sequence of node selection.

\[ ATR\tau \] indicates the approximate transformer rating for the \( i \)th node point of demand node.

\[ DL_{1} \] indicates demand load of \( i \)th node.

\[ AEF_{x} \] indicates the approximate efficiency of the transformer.

\[ p_{t} \] is the actual efficiency of the \( i \)th load node transformer.

\[ p_{a} \] is the actual copper loss of the \( i \)th load node transformer.

\[ p_{m} \] is the actual transformer rating of the \( i \)th demand node.

\[ R_{t} \] is the required transformer rating of the \( i \)th load node.

\[ DL_{2} \] is the demand load of the \( i \)th demand node.

\[ RT_{s} \] is the required transformer rating of the source substation.

\[ p_{a} \] is the actual iron loss of the source substation transformer.

\[ p_{c} \] is the actual copper loss of the source substation transformer.

\[ AT_{s} \] is the actual transformer rating of the source substation.

\[ T_{n} \] is the position of the internal database of the \( n \)th transformer rating.

\[ T_{s} \] is the position of the internal database of the iron loss of the \( n \)th transformer rating.

\[ p_{a} \] is the position of the internal database of the copper loss of the \( n \)th transformer rating.

\[ p_{c} \] is the position of the input source of the \( n \)th transformer rating.

\[ p_{a} \] is the position of the internal database of the loss of the \( n \)th transformer rating.

\[ p_{c} \] is the position of the internal database of the copper loss of the \( n \)th transformer rating.

\[ I_{n} \] is the current rating of the \( i \)th demand node.

\[ V_{n} \] is the voltage of the \( i \)th demand node.

\[ S_{n} \] is the node sequence indicator for the \( n \)th node.

\[ S_{n}^{(n-1)} \] is the node sequence set for the \( n \)th node.

\[ S_{n}^{(n-1)} \] is the \((n-1)\)th node of the sequence node set for the \( n \)th node.

\[ J_{n}^{(n-1)} \] is the joint node seq. indicator for the \((n-1)\)th joint node.

\[ J_{n} \] is the sequence joint node set for the \( n \)th joint node.

\[ J_{n}^{(n-1)} \] is the \((n-1)\)th node of the sequence joint node set for the \( n \)th joint node.

\[ D_{n} \] is the \((n-1)\)th node of the sequence of demand node set for the \( n \)th demand node.

\[ D_{n}^{(n-1)} \] is the \((n-1)\)th node of the sequence of demand node set for the \( n \)th demand node.

\[ D_{n}^{(n-1)} \] is the \((n-1)\)th node of the sequence of demand node set for the \( n \)th demand node.

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\[ D_{n}^{(n-1)} \] is the \((n-1)\)th node of the sequence of demand node set for the \( n \)th demand node.

\[ D_{n} \] is the sequence demand node set for the \( n \)th demand node.
is resistance \( i \) no. of hidden node of \( m \)th node of the eq. node set for \( m \)th node in ohm/km

- \( P_{\text{load, } a} \) is loss factor & total no. of load substation
- \( C_{\text{ij}}^{\text{sh}} \) is cable cost per km of \( j \)th feeder segment of \( i \)th demand load substation route.
- \( C_{\text{ij}}^{\text{hd}} \) is cable installation cost per km of \( j \)th feeder segment of \( i \)th load substation route.
- \( C_{\text{sh}, L_{\text{ch}}} \) is cost per kWh, the desired life of networks and load factor of the network

4. PROGRAMMING STRUCTURE AND RESULTS

The programming structure of the optimal network planning is as below:

- Maximum Demand Node Number, Maximum Transformer Number, Maximum branch node number, Maximum obstacle clearing
- Maximum node selection no., Maximum Node Node Number, Maximum Cable size number, Maximum obstacle rectangular, Maximum obstacle
- Demand Load
- User Input Node Connection, Transformer Parameters
- Rectangular obstacles location, Cable Specifications
- Circular obstacles location, Source substation location

Figure 4.1: Programming Structure of Optimal Planning Solution of Distribution Networks

An example of distribution network is considered. In this case 57 nodes are used in which 35 nodes are load substation nodes and 21 nodes are joint nodes and one is source substation node. The output screen is generated 24x32. The maximum area is considered 23.333x30 square km. The ratio factor is considered 1.5. The source substation rating is 17.5MVA. The limitation of voltage drop is considered 4%. The mapping of the network is the output of the solution programming which is shown as below:

Figure 4.2: Mapping of distribution networks

The optimal the cable size is as below:

Figure 4.3: Cable Size of Design

The KVA rating of transformers are 250,300,200,500, 500,1500,500,600,500,630,300,200,250,500,250,200,150,200,200,500,300,500,200,250,630,630,500,630,63 0,200,1500,500,630,250,630 sequentially.

5. CONCLUSION

All feeder voltage must be maintained used defined voltage drop to select optimal cable size and type in the entire networks by considering proper calculation of user defined load. Minimal capital investment was the key role to select optimal cable selection.

6. REFERENCES
