Optimal Conductor Selection for Maximum Loading of Distribution Networks

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Abstract - *In this paper, a novel method is proposed for improving the maximum loading of distribution networks for different types of load models without violating the voltage and current constraints. The conductor, which is determined by the proposed method, will maximize the total savings in cost of conducting material and energy losses by maintaining acceptable voltage levels in distribution networks. Minimum voltage of the feeder can also be maintained by allowing the feeders to take load growth up to a specific period of time. The effectiveness of the proposed method is explained with 32 node distribution network.*

Key Words: Optimal conductor, loading, distribution netwok

1. INTRODUCTION

The distribution networks play an important role in any electric power system. In general, the distribution system consists of feeders, distributors and service mains. The conductor size of a feeder is governed by the current carrying capacity, voltage drop, and overall economy. The current carrying capacity of a conductor depends on the conductor losses and surroundings.

The value of conductor size obtained should be checked for overall economy. According to Kelvin's law the most economical cross-section is that which makes the annual value of interest and depreciation of the conductor equal to the annual cost of the energy wasted in the conductor. The maximum current on the feeder is not remains always but it occurs certain times. At all the other time the value of current is less than the maximum value.

In recent years, considerable attention has been focused in planning of distribution systems to reduce the capital investment involved, to reduce energy losses, and to produce better quality of supply to consumers. Recently, improved modeling techniques and certain optimization and programming approaches have been presented to determine the best location, and suitable interconnections between substations, to meet the increasing demands more reliably and economically. In these approaches, the size and type of conductor for each feeder segment is often chosen based on the current carrying capacity of the optimal feeder configuration [1–4]. The work presented in [3] goes one step further, i.e., the conductor type is selected based on the need for feeder voltage support as well as the current carrying capacity requirement. Motivation behind this additional step is that it may be required to use a large conductor size in order to maintain the voltage of the feeder at an acceptable level. This is especially the case of rural feeders in some developing countries, where feeders are often stretching over long distances to serve even very light loads.

Ponnavaikko and Rao [4] presented models to represent substation feed area, feeder voltage drop, feeder load distribution, cost of losses in the feeders and transformers were formulated in terms of the variable system parameters. Based on these models, objective functions were defined which are employed in arriving at optimal substation size, feeder loading limits and conductor sizes. The technique suggested greatly reduced the computational time and effort compared to the other methods. The proposed method was highly promising, since it was very fast, simple and easy to program.

Miu and Chiang [5] are probably the first to propose a solution algorithm for distribution system load capability. They have computed the load capability under different loading conditions for a given load variation pattern. However, they have not proposed any mathematical model for computing the present worth cost of feeder energy loss.

However, the methods of refs [6-9] available in the literature are not based on any load flow techniques which is important for optimizing the branch conductors of radial distribution networks. Also it is very important to consider voltage constraint and maximum current carrying capacity for each type of conductor.

Tram and Wall [12] proposed an algorithm for optimal selection of conductors of radial distribution feeder. Researchers developed a fast algorithm to help the distribution engineer select proper conductors for his feeder expansion plans is presented. The optimal conductor type is determined for each feeder segment to maintain an acceptable voltage profile along the entire feeder, minimizing capital investments and the cost of feeder losses. Lateral branches as well as regulators along the feeder are considered. In this paper, computer implementation of the algorithm is described. Its use in conjunction with an optimization model for configuring feeder networks to derive an overall distribution expansion plan is also discussed.

In the present work, a simple algorithm is proposed for determining the maximum loading of the feeders for different load models without violating the maximum current carrying capacity of branch conductors. In this article, a method is proposed for selecting the optimal size of branch conductor for radial distribution networks. The conductor, which is determined by the proposed method, will satisfy not only the maximum current carrying capacity, but also maintain acceptable voltage levels of the radial distribution systems. In addition, it will give maximum saving in capital cost of conductor and cost of energy loss in radial distribution systems. A predetermined annual load growth is also considered to determine the allowable load growth period without violating the minimum voltage limit of the feeders.

2.LOAD FLOW METHOD

Selecting a method in order to evaluate the performance of a power distribution system and to examine the effectiveness of proposed alterations to a system in the planning stage, it is essential that a load flow analysis of the system is to be carried out. It basically gives the steady state operating point of a distribution system corresponding to a specified loading condition. The repetitive solution of a large set of linear equations in the load flow problem is one of the most time consuming parts of distribution system simulations. Some applications, especially in the fields of optimization of distribution system, need repeated fast load flow solutions.

A. Algorithm for Load Flow Solution of Radial Distribution System

Step 1: Read line and load data of distribution system.

Assume initial node voltages 1 p.u, set $\varepsilon = 0.0001$.

Step 2: Start iteration count, c =1.

Step 3: Calculate load currents at each node.

Step 4: Initialize real power loss and reactive power loss vectors to zero.

Step 5: Using the node currents calculated in Step 3, calculate branch currents.

Step 6: Calculate node voltages, real and reactive power loss of each branch.

Step 7: Check for convergence i.e., $|\Delta V_{max}| \le \varepsilon$ in successive iterations. If it is converged go to next Step otherwise increment iteration number and go to Step 3.

Step 8: Calculate total real power and reactive power losses for all branches.

Step 9: Print voltages at each node, real and reactive power losses and number of iterations.

Step 10: Stop.

3. IMPROVING THE MAXIMUM LOADING OF DISTRIBUTION SYSTEMS BY OPTIMAL CONDUCTOR SELECTION

In any distribution system (DS), it is important to go for optimal choice of the type of conductor in each branch of the system that can minimize the sum of depreciation cost on capital investment and cost of energy losses. This optimal conductor should also be able to maintain acceptable voltage levels at all nodes and should have sufficient current carrying capacity. The problem of choice of the optimal type of conductor for each feeder branch is presented as an optimization problem using branch wise minimization technique

B. Optimal Branch Conductor Selection.

Objective Function

In any distribution system, the optimal choice of the size of conductor in each branch of the system, which minimizes the sum of depreciation on capital investment and cost of energy losses, is important. This optimal size should also be able to maintain acceptable voltage levels at all nodes and should have sufficient current carrying capacity. The problem of choice of the optimal size of conductor for each feeder segment is presented as an optimization problem using branch wise minimization technique.

The objective function for optimal selection of conductor for branch j with k type conductor is:

$$\text{Min } F_{(j,k)} = CL_{(j,k)} + CC_{(j,k)} \tag{1}$$

(i) Cost of energy losses (CL)

The annual cost for the loss in branch j with k type conductor is:

$$CL_{(j,k)} = PLS_{(j,k)} \times K_e \times Lsf \times T \tag{2}$$

Where

PLS = Power loss

Ke = Cost of annual energy loss constant

T = 8,760 hrs in the year

Lsf = loss factor

(ii) Depreciation on capital investment (CC)

The annual depreciation on capital cost for branch j with k type conductor is:

$$CC_{(j,k)} = \alpha \times cst_k \times Ln_j \tag{3}$$

Where α = Interest and depreciation factor

cst_k = cost of *k* type conductor (Rs/km)

Ln_j = length of branch j (km)

Constraints

(i) Feeder voltage

The voltage at every node in the feeder must be above the acceptable voltage level, i.e.

$$V_{min} < \left|V_{(i,k)}\right| < V_{max}$$

for i = 2, 3, . . . , nn.

(ii) Maximum current carrying capacity

Current flowing through branch j with k type conductor should be less than the maximum current carrying capacity of k type conductor, i.e.

$$I_{max(k)} < \left|I_{(j,k)}\right| < I_{max\,(k)}$$

for all branches j = 1, 2, 3, . . . , nb.

C. Algorithm for Optimal Branch Conductor Selection

A radial distribution system has several branches. When these branches are re conductored, it alters the flow of power and changes the resulting kW loss and voltage profile. To compute the modification of reconductoring, the following algorithm is developed.

Step 1: Read the system data.

Step 2: Set branch number j=1

Step 3: Set conductor type k=1

Step 4: Run the load flows, compute the voltage at node i, current and real power loss under peak load condition of branch j with k type conductor.

Step 5: Calculate objective function of branch j with k type conductor using Eqn. (1).

Step 6: If k ≥ no. of conductor types then go to Step 7, else increment k value and go to Step 4.

Step 7: Arrange the objective function values of the different k types of conductors in ascending order.

Step 8: Select minimum cost of conductor for branch j

Step 9: If the voltage and current constraints are not satisfied, select next minimum cost type conductor for branch j.

Step 10: If j ≤ no. of branches then, go to Step 4.

Step 11: Run the load flows by selected conductors and compute the necessary results with optimal type of conductor for each branch.

Step 12: Stop

D. Loading Factor

After running the load flow program for a base $\left|I_{(j)}\right|$ case, for *j* = 1, 2, . . . , nb must be computed. After that,

$$\Delta\delta_{(j)} = \frac{CI_{(j)} - \left|I_{(j)}\right|}{\left|I_{(j)}\right|} \quad \text{for } j = 1, 2, \ldots, nb$$

must be computed .

Now the minimum of all the values of

$\Delta\delta_{(j)}$ for j = 1, 2, . . . , nb must be selected such that maximum current carrying capacity of the branch conductors should not be violated.

Therefore,

$$\Delta\delta_{min(l)} = \min\left\{\ \Delta\delta_{(j)}\right\} \;,j=1,2\ldots,nb \qquad (4)$$

Where *l* is the branch number at which loading factor is minimum.

Update the value of the loading factor

$$\Delta\delta = \Delta\delta + \Delta\delta_{min(l)} \qquad (5)$$

The real and reactive power loads of all the nodes beyond the branch *l* must be increased by a factor $\Delta\delta_{min(l)}$ and the rest of the loads will remain unchanged.

$$P_{(m)} = (1 + \Delta\delta)P_{0(m)} \qquad (6)$$

$$Q_{(m)} = (1+\Delta\delta)Q_{0(m)} \qquad (7)$$

Where $P_{0(m)}$ is the real power load at node i for base system

$Q_{0(m)}$ is the reactive power load at node i for base system

E. Algorithm for Computing the Loading Factor

The following is the algorithm to find out the loading factor

Step 1: Set the initial loading factor as zero

Step 2: Run the load flows

Step 3: Compute the loading factors at each branch using Eqn (5) and select the minimum value of loading factor and corresponding branch.

Step 4: Check the convergence i.e., ε =0.001 for the loading factors, if true go to Step 6.

Step 5: Compute the powers beyond this branch using Eqn (6) and (7) and go to Step2.

Step 6: Print the value of the loading factor.

F. Load Growth

Load growth in an area of study with time as a natural parameter. The growth in feeder load may be due to addition of new loads or due to the incremental addition to the existing loads. A feeder which is designed and constructed on a long-term basis can accept additional loads while satisfying the voltage constraint. Once the load exceeds the feeder capacity, new facilities such as substations or additional feeders need to be created. Till such time, for a given substation feed area and the configuration of the feeder, it is assumed that the feeder load grows at a predetermined annual rate in proportion to the connected loads.

Real and reactive power loads at N th year of the system is given by

$$TPL_{(N)} = TPL_{(0)}\,(1+g)^N \qquad (8)$$

$$TQL_{(N)} = TQL_{(0)}\,(1+g)^N \qquad (9)$$

Where

g = annual load growth rate= 7.5 %(assumed)

$TPL_{(0)}$ = Total real power load in the base year

$TQL_{(0)}$ = Total reactive power load in the base year

$TPL_{(N)}$ = Total real power load in the Nth year

$TQL_{(N)}$ = Total reactive power load in the Nth year

G. Effect of Load Modeling on Maximum Loading

The balanced loads can be represented either as constant power (CP), constant current (CC), constant impedance (CI), exponential (Exp) or composite load. The composite loads are essentially a combination of these base loads on proportion of the type of consumer loads. In this case, the composite loads are taken as 50% CP + 20% CC +20% CI + 10% Exp. At each node of the distribution system, the proposed algorithm is capable of performing load flow calculations considering either one of the above loads or a combination of the above loads.

$$PL_{(i)} = PL_{0(i)}\left(\alpha_0 + \alpha_1 V + \alpha_2 V^2 + \alpha_3 V^{e1}\right) \qquad (10)$$

$$QL_{(i)} = QL_{0(i)}\left(\beta_0 + \beta_1 V + \beta_2 V^2 + \beta_3 V^{e2}\right) \qquad (11)$$

In the algorithm, $e1$ = 1.38 and $e2$ = 3.22 are considered for exponential load.

The first term of Eq. (10) and (11) represents constant power load, the second term represents constant current load, and subsequent terms represent constant impedance and exponential loads, respectively. $PL_{(i)}$ and $QL_{(i)}$ are the total real and reactive power loads at the receiving end node i.

4.ILLUSTRATIVE EXAMPLE

To demonstrate the effectiveness of the proposed method, one system is considered. Presently in India, utilities are using three or four types of conductors for radial distribution systems viz. Rabbit, Raccon, Weasel and Squirrel.

A 32-node, 11kV radial distribution system, whose single line diagram is shown in Figure 1 is considered. The line and load data of this system are given in Table 1 and 2.

The real and reactive power loads of the system are 4402.30 kW and 4490.34 kVAr respectively.

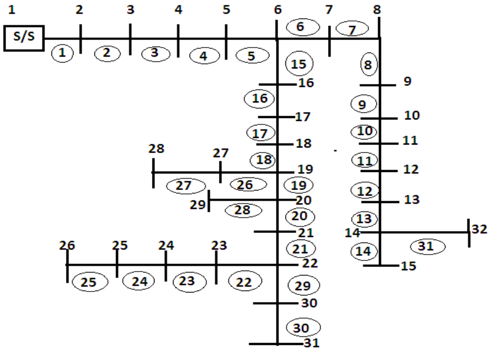

Fig 1: Single line diagram of 32- node RDS

Results of conductor optimization are presented in Table .1. From Table 1, the reconductoring of some of the branches can be seen. Table 2 gives the summary of test results before and after reconductoring Fig.2. Voltage profile of 32-node system before and after conductor selection

Branch number	Before conductor modification	After conductor modification
1 to 13	Rabbit	Raccon
14	Rabbit	Weasel
15 to 21	Rabbit	Raccon
22 to 23	Weasel	Raccon
24	Weasel	Rabbit
26	Weasel	Raccon
27	Weasel	Rabbit
28	Weasel	Squirrel
30	Weasel	Squirrel

TABLE 1: RECONDUCTORING OF VARIOUS BRANCHES OF 32-NODE DS

Parameters	Before Conductor Selection Base Case	After conductor selection	Improvement
Real power loss (kW)	424.36	274.74	149.62
Reactive power loss (kVAr)	285.14	267.78	17.36
Total Power Cost (Rs.)	2230583.36	1444252.44	786330.92
Min.Voltage (p.u)	0.91026	0.93046	

TABLE 2: SUMMARY OF TEST RESULTS OF 32-NODE DS

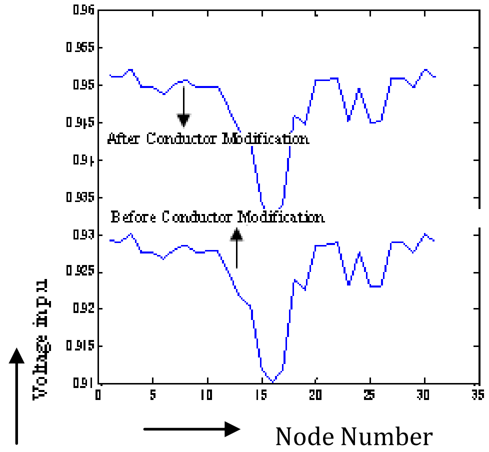

Fig-2: Voltage profile of 32-node system before and after conductor selection

H. Overloading

Now, before and after conductor modification, the system conductors can be overloaded. The Tables 3 show the value of loading factor and maximum allowable load of the feeder for different types of load models without violating the minimum voltages (V_{min} = 0.9 p.u.) and maximum current carrying capacity of branch conductors. From these tables, It can be observed that the maximum loading condition is improved after optimal branch conductor selection.

TABLE 3: LOADING FACTOR AND MAXIMUM FEEDER LOADING AFTER CONDUCTOR SELECTION

Type of load model	Loading factor	After optimal conduction selection Base loads		After optimal conduction selection Max. Loads		N_{max} (years)
		Total real power load (kW)	*Total reactive load (kVAr)*	*Total real power load (kW)*	*Total reactive power load (kVAr)*	
Constant power load (C.P)	0.521	4402.30	4490.34	6696.51	6830.43	5.8
Constant current load	0.683	4165.11	4248.40	7010.79	7150.99	7.2
Constant impedance load (C.I)	0.863	3965.26	4044.56	7385.58	7533.28	8.6
Exponential load (Exp.)	0.903	4099.88	3804.80	7803.81	7242.14	8.9
Composite load	0.647	4228.31	4272.34	6964.42	7036.95	6.9

Load growth

Eqn. (10) or (11) is used to determine the maximum allowable load growth period. From Table, for constant power load, $TPL_{(N=Nmax)}$ = 6696.51 kW and as mentioned earlier real power load at the base year, $TPL_{(0)}$ = 4402.30 kW. Therefore, using Eqn. (10), N_{max} can be obtained as:

$$6696.51 = 4402.30\,(1+0.075)^{N_{max}}$$

Or N_{max} = 5.8 years

Similarly for constant current, constant impedance, exponential and composite loads, N_{max} is obtained as 7.2, 8.6, 8.9 and 6.9 years for after conductor modification respectively.

The load growth of the feeder is allowed as long as the voltage limit is not violated. Tables .4 and 5 show the total loads of the feeder, total power losses and minimum system voltage at the end of each year before and after the conductor modification for different types of load models. From these tables, it can be observed that the number of years is increased after optimal branch selection.

Type of load model	Year	Total active power load (kW)	Total reactive power load (kVAr)	Total active power loss (kW)	Total reactive power loss (kVAr)	Min. voltage (p.u.)
Constant power load (C.P)	0	4402.30	4490.34	424.36	285.14	0.91026
	1	4732.47	4828.09	497.25	334.12	0.90282
Constant current load (C.C)	0	4103.40	4186.31	361.34	242.82	0.91736
	1	4387.02	4475.65	417.57	280.61	0.91116
	2	4688.14	4782.86	482.56	324.28	0.90448
	3	5007.50	5108.68	557.65	374.75	0.89731
Constant impedance load (C.I)	0	3862.80	3940.84	314.92	211.64	0.92299
	1	4113.53	4196.64	360.32	242.16	0.91763
	2	4377.69	4466.14	411.98	276.88	0.91192
	3	4655.59	4749.65	470.70	316.34	0.90586
	4	4947.45	5047.41	537.42	361.19	0.89941
Exponential load (Exp.)	0	4024.83	3645.92	304.26	204.48	0.92348
	1	4298.94	3861.34	347.50	233.54	0.91818
	2	4589.68	4085.33	396.59	266.54	0.91254
	3	4897.79	4317.66	452.29	303.97	0.90655
	4	5223.97	4557.98	515.40	346.39	0.90019
Composite load	0	4183.03	4217.68	372.56	250.36	0.91595
	1	4479.11	4512.50	431.78	290.15	0.90949
	2	4794.64	4826.16	500.59	336.39	0.90252

TABLE 4 : LOAD FLOW RESULT FOR DIFFERENT TYPES OF LOAD MODELS BEFORE CONDUCTOR SELECTION

Type of load model	Year	Total active power load (kW)	Total reactive power load (kVAr)	Total active power loss (kW)	Total reactive power loss (kVAr)	Min. voltage (p.u.)
Constant	0	4402.30	4490.34	274.74	267.78	0.93046

power load (C.P)	1	4732.47	4827.12	320.80	312.67	0.92885
	2	5087.41	5189.15	374.94	365.44	0.92374
	3	5468.96	5578.34	438.70	427.57	0.91709
	4	5879.14	5996.71	513.91	500.87	0.91084
	5	6320.07	6446.46	602.83	587.54	0.90691
	6	6794.08	6929.95	708.37	690.39	0.89883
Constant current load (C.C)	0	4165.11	4248.40	242.68	236.55	0.93574
	1	4458.37	4547.53	280.45	273.36	0.93084
	2	4770.64	4866.05	324.10	315.90	0.92758
	3	5102.90	5204.95	374.54	365.06	0.92192
	4	5456.10	5565.22	432.82	421.87	0.91784
	5	5831.21	5947.82	500.18	487.53	0.91231
	6	6229.13	6353.70	578.02	563.40	0.90828
	7	6650.76	6783.77	667.98	651.08	0.90272
Constant impedance load (C.I)	0	3965.26	4044.56	217.44	211.95	0.93830
	1	4230.41	4315.01	249.27	242.98	0.93494
	2	4510.89	4601.10	285.60	278.39	0.93030
	3	4807.24	4903.38	327.04	318.78	0.92735
	4	5119.98	5222.37	374.24	364.79	0.92009
	5	5449.56	5558.55	427.96	417.16	0.91749
	6	5796.42	5912.34	489.03	476.69	0.91453
	7	6160.90	6284.10	558.38	544.30	0.90921
	8	6543.14	6673.99	637.18	621.12	0.90348
	9	6943.55	7082.42	726.35	708.04	0.89736
Exponential load (Exp.)	0	4099.88	3804.80	211.46	206.12	0.93915
	1	4384.93	4041.99	242.05	235.94	0.93591
	2	4688.16	4290.50	276.90	269.91	0.93240
	3	5010.47	4550.32	316.61	308.62	0.92859
	4	5352.84	4821.54	361.74	352.61	0.92449
	5	5716.21	5104.00	413.02	402.60	0.91706
	6	6101.52	5397.48	471.23	459.35	0.91030
	7	6509.74	5701.67	537.25	523.71	0.91519
	8	6941.79	6016.10	612.05	596.62	0.90772
	9	7398.60	6340.20	696.70	679.14	0.89806
Composite load	0	4228.31	4272.34	248.35	242.06	0.93395
	1	4531.47	4575.59	287.59	280.31	0.92992
	2	4855.20	4898.97	333.11	324.68	0.92550
	3	5200.70	5243.60	385.94	376.17	0.91965
	4	5569.21	5610.61	447.26	435.94	0.91435
	5	5962.02	6001.17	518.48	505.36	0.90954
	6	6380.41	6416.44	601.26	586.04	0.90420
	7	6825.68	6857.58	697.56	679.90	0.89926

TABLE5: LOAD FLOW RESULT FOR DIFFERENT TYPES OF LOAD MODELS AFTER CONDUCTOR SELECTION

5. CONCLUSIONS

In this paper, a novel method has been proposed for improving the maximum loading of the radial distribution feeder by using optimal conductor selection. The algorithm has been presented for optimal conductor selection. This has been carried for different types of load models. Voltage and current constraints have also been satisfied by allowing the feeders to take the load growth up to a specified period of time. The proposed method has been tested on two different systems. It has been found that loading capability is highest for exponential loads, lowest for constant power loads and lie in between for constant current and constant impedance loads. For composite loads, loading capability depends upon the composition of loads.

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