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Capacitor Siting and Sizing using Cost Minimization & Monty Carlo Simulations for RDS

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Abstract*: *Capacitors are widely used in distribution networks for energy loss reduction, reactive power compensation, voltage regulation, and for system capacity release. However, it's important that the system is designed initially, and capacitors are applied in correct magnitude and at right node to achieve best results. The most important task for distribution engineer is to efficiently simulate the system at design stage and later apply optimum capacitance injection. The work presented in this paper proposes a cost minimization algorithm using a unique mathematical model along with Monty carlo simulation to choose optimal value of capacitors, both fixed and switching based on total minimum cost algorithm.

Keywords*: RDS (Radial Distribution System), *Branch Voltage (V), Stability Index (SI), Load flow, Radial Power Distribution (RDS), Power Loss Index (PLI), Candidate Node.

I. INTRODUCTION

As discussed in the reference paper by author [1], [6], designing and operating distribution networks with low losses has great significance. Review of research paper available have indicated that at distribution level, as much as 13% of total power generated is wasted in the form of losses [3], [4], [6] and is a significant contributor in making the system inefficient. One of the methods for reduction in power loss is to place capacitor at effective node. Capacitors are widely used in the distribution networks for energy loss reduction, reactive power compensation, voltage regulation, and for system capacity release. These are typically installed on distribution primary feeders. Addition of capacitors introduces kVAr at the point of installation. These can be permanently connected or can be switched on and off. Switching can be manual or automatic and can be controlled either by time clocks or in response to voltage or reactive-power requirements. When they are placed in parallel to the load having a lagging power factor, they become the source of reactive power for the load and thus reduce the line current necessary to supply the load and in turn reduce the voltage drop and also improve the power factor.

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The extent improvement & benefits depends upon how the capacitors are placed on the system, i.e.

(i) The location and number,
(ii) The type (fixed or switched),
(iii) The size
(iv) The control scheme of the capacitors.

Therefore, it is important for a capacitor placement algorithm to determine optimum location, number, type, size, and control scheme of capacitors to be installed.

The key objective for distribution system designer while designing the capacitor sizing and placing, is to have minimized power loss for a given load profile and have minimum fixed and running costs of the capacitors.

The work presented in this paper proposes a cost minimization algorithm using a unique mathematical model along with Monty Carlo simulation to choose optimal value of capacitors, both fixed and switching. The algorithm selects the optimal value of capacitors, and places them at the best possible nodes with the goal of maximizing the net savings while ensuring the node voltages and stability index are within the permissible range. For achieving the same, algorithm uses an evaluation parameter 'Node vulnerability index' for which details are presented in paper [3]. The presented work also considers potential variation to the connected loads and proposes a use of Monte Carlo simulation for selecting the split between fixed and switching capacitor. The proposed algorithm utilizes the load flow as defined in the paper [1], [6] and further expands the same to include the capacitor sizing and placement for cost optimization.

II. METHODOLOGY

The work presented in the paper is a continuation of the work author has performed on the Radial Distribution System as part of the reseach work and continue expanding the same to achieve the objective identified in previous section. Below is the bulleted road map to achieve the objective, with clearly defining reference to the previous research work.

Step 1:

Define the computationally fast 'Load Flow' algorithm along with 'Stability Index' and develop computation formulas & algorithm & integrate Monte-Carlo simulation principle and probabilistic model to the algorithm. This work is presented by author in [3], [4].

Step 2:

Power Loss Index and finding candidate nodes. This work is presented by author in [6].

Step 3:
Formulation of cost minimization objective function which includes the energy cost, capacitor installation cost and the purchase cost while ensuring the node voltages and stability index are within the permissible range. This work is presented in this paper.
Step 4:
Variations in the connected loads and accordingly choose Fixed and Switching Capacitor. This work is presented in this paper.

III. COST MINIMIZATION OBJECTIVE FUNCTION

This section presents formulation of cost minimization objective function which includes the energy cost, capacitor installation cost and the purchase cost.

A. Mathematical Formulation

Cost optimization formulation objective is to maximize savings, keeping distribution system performance constraints within acceptable range. Savings are calculated by finding the benefit due to released demand, released feeder capacity, savings in energy and subtracting the cost of installation of capacitor.

The formulation can be represented as:

Max S = KP + KF + KE – KC --- (1)

Where:
S = Net Savings (US$)
KP = Benefit due to released demand (US$)
KF = Benefit due to released feeder capacity (US$)
KE = Benefit due to savings in energy (US$)
KC = Cost of installation of capacitor (US$)

However following distribution system constraints needed to be met during optimization.

1. V & SI $\geq$ Range (address the voltage changes) [3]
2. $Q_i^c = \sum_i^n (Q_{Li})$(address injected value less than reactive load at any node) [6]
3. Capacitor suitable for load variations (address connected load variations) [6]
4. VI $\geq$ Acceptable range [3]

Benefit due to released demand (kW) can be defined as;

KP = Δ KP x CKP x IKP --- (2)

Where:
Δ KP = Reduced demand kW.
CKP = Cost of generation (taken as $200 /kW)
IKP = Annual deprecation cost assumed as 0.2

Benefit due to released feeder Capacity (kVA) can be defined as;

KF= Δ KF x CKF x IKF --- (3)

Where:
Δ KF = Released feeder capacity kVA.
CKF = Cost of feeder (taken as $3.43 / kVA)
IKF = Annual deprecation cost assumed as 0.2

Benefit due to Benefit due to savings in Energy (kWh) can be defined as;

KE = Δ KE x r --- (4)

Where:
Δ KE = Saving in Energy
r = Rate of energy taken as $ 0.06 / kWh

Cost of installation of Capacitor

KC = Qc x ICKC x IKC + ICF x N x IKC --- (5)

Where:
Qc = Total kVAR
ICKC= Cost of capacitors (taken as $4 /kVAR)
IKC = Annual deprecation cost assumed as 20%
ICF = Capacitor fixed installation cost per location (taken as $1000 / location)
N = Nos of nodes where capacitors are installed.

B. Cost Optimization Algorithm

Algorithm used for cost optimization is shown below.

ALGORITHM STEPS

1. Run PLI algorithm and find candidate nodes [6]
2. Select nodes with PLI cut-off level (Pcutlevel= 0.9) [6].
3. Calculate kVAr at that node for each phase [6].
4. Choose the minimum kVAr value amongst each phase for algorithm QLkVAr [6].
5. It assumed that available capacitors are integer multiple of smallest size i.e. 30 kVAr.
6. Inject Qc at the candidate nodes with value as multiple integer of 30 kVAR but less than QLkVAr.
7. Check whether the voltage and 'SI' values are within acceptable limits [3], [6].
8. Calculate the savings.
9. Select nodes with PLI cut-off level (Pcutlevel = 0.9 - 0.1), i.e. 0.8, 0.7…….1.
10. Repeat step 1 to 9 till savings are less than the previous step.
11. Plot the result and choose maximum saving via converged solution (Refer Fig. 1).

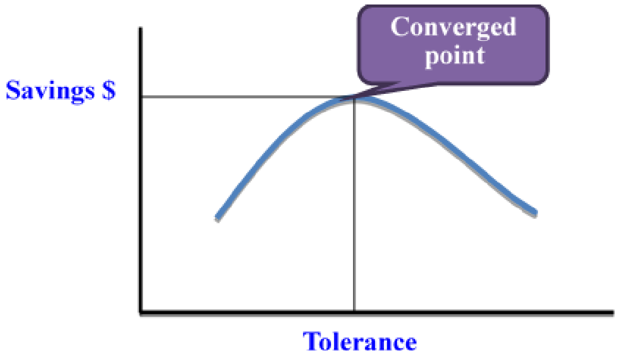


Fig. 1. Plot between savings & tolerance

C. Impact due to variations in the Connected Load

For a typical power system, the connected load varies with the time and capacitor placement plan needs to address the same. One way of addressing this is to have a combination of fixed and switching capacitor, which can address all operating scenarios.

The method proposed in this work is based on Monte Carlo simulation, where each connected load has been assumed varying based on the certain predefined distribution shape as defined in Table III. Monte Carlo method relies on repeated random sampling to obtain results.

IV. RESULT AND DISCUSSION

This simulation is run on a typical 19 bus distribution system from the D. Thukram, H. M W. Banda and J. Jerome [11] and same is replicated in the Appendix.

A) Cost Optimization Algorithm Results

Fig. 2 shows the net savings calculated as a result of optimization simulation run. The same results are also reflected in Table I, which also includes value of released demand, released feeder capacity, savings in energy and cost of installation of capacitor

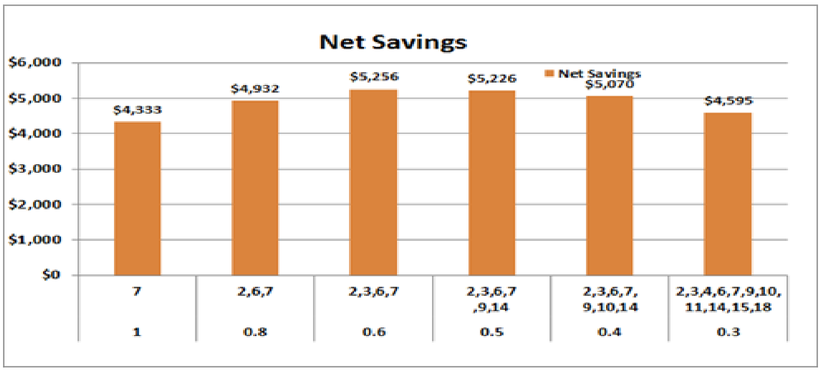


Fig. 2. Plot between savings & tolerance for 25 bus system

Table- I: Net Savings Table Index

Tolerance	*Total Injected Qc kVAr*	*Nodes*	*Nos*	*KP*	*KF*	*KE*	*KC*	*Net Savings*
1	990	7	1	$352	$355	$4,619	$992	$4,333
0.8	2340	2,6,7	3	$484	$561	$6,359	$2,472	$4,932
0.6	2340	2,3,6,7	4	$521	$561	$6,846	$2,672	$5,256
0.5	2340	2,3,6,7,9,14	6	$547	$562	$7,189	$3,072	$5,226
0.4	2340	2,3,6,7,9,10,14	7	$550	$562	$7,230	$3,272	$5,070
0.3	2340	2,3,4,6,7,9,10,11,14,15,18	11	$573	$562	$7,532	$4,072	$4,595

Table- II: Net Savings Table Index

Tolerance	*Unit*	*Before Compensation*	*After Compensations*
Total load real power	kW	3240	3240
Total load reactive power	kVAr	2393	53
Total feeder real power	kW	3313	3300
Total feeder reactive power	kVAr	2447	63
Total feeder real power loss	kW	73	60
Total feeder reactive power loss	kVAr	54	10
Total feeder power	kVA	4119	3300
Loss Reduction			18%
Qc Required	kVAr	0	2340

Minimum Voltage	0.971	0.976
Minimum SI	0.927	0.942
Savings		$5256

From the Fig. 2 & Table I, we can note that solution is converged at tolerance value of 0.6 and provides the maximum savings.

The simulation also checks the improvements in the node voltages, before and after installing capacitors. This check is done to meet the constraints as defined in the optimization algorithm. Fig.3, Fig.4, and Fig.5 are the plot of node voltage improvement before and after installation of capacitors for phase A, phase B and phase C. A clear improvement in the voltage can be seen.

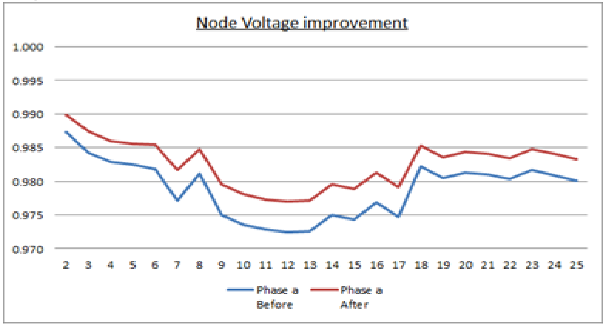


Fig. 3. Node voltage improvements for phase A

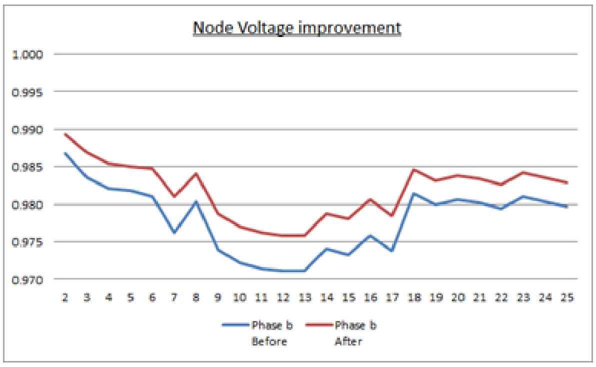


Fig. 4. Node voltage improvements for phase B

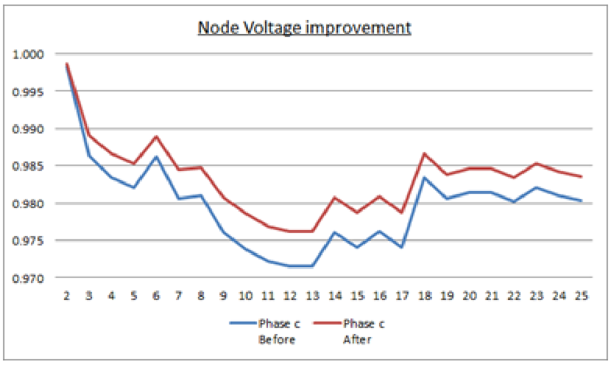


Fig. 5. Node voltage improvements for phase B

Similarly, Fig.6, Fig.7 & Fig.8 shows the improvement in the 'Node Stability Index' before and after installing capacitors.

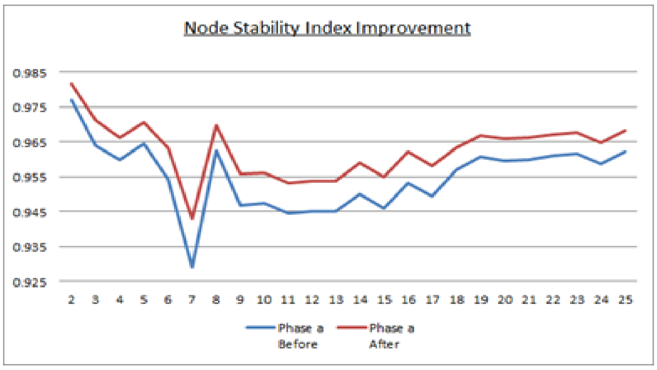


Fig. 6. Node stability index improvements for phase A

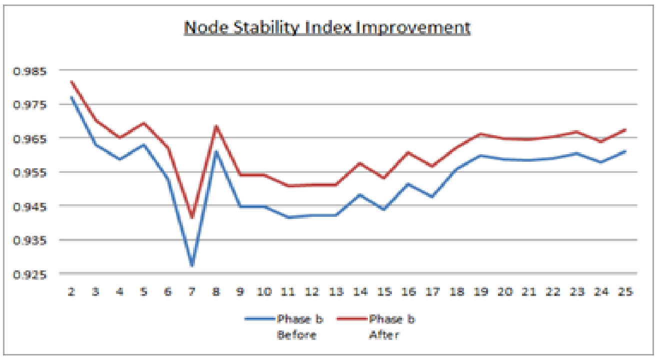


Fig. 7. Node stability index improvements for phase B

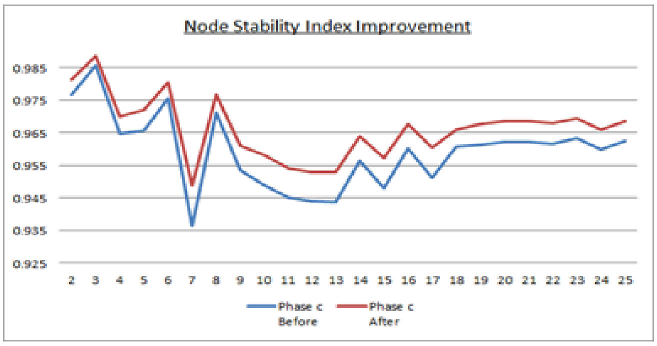


Fig. 8 Node stability index improvements for phase C

The improvement in the Vulnerability index (VI) is also checked. Fig. 9 shows the scatterplot of VI before and after placing capacitors.

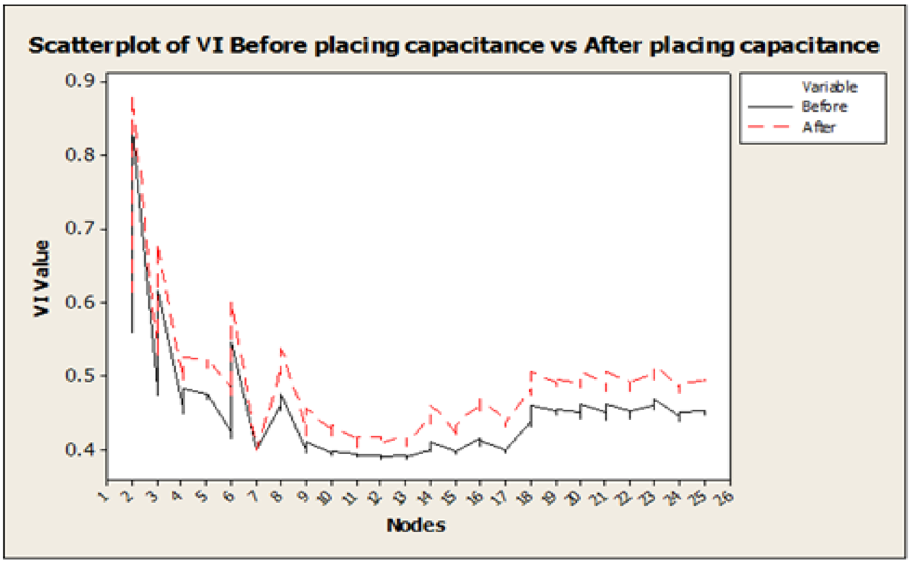
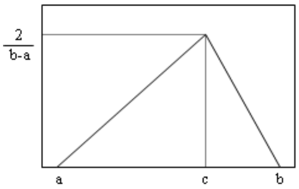
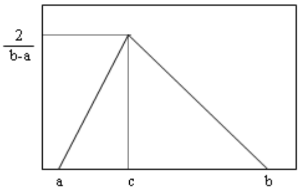
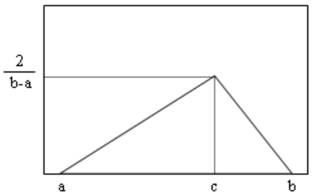
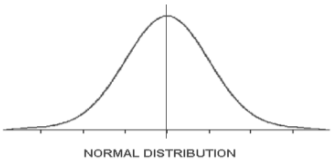


Fig. 9 Scatterplot of VI before placing capacitor vs after placing capacitor

B) Variation in Connected Load simulation Result.

For a typical power system, the connected load varies with the time and capacitor placement plan needs to address the same. One way of addressing this is to have a combination of fixed and switching capacitor, which can address all operating scenarios. For obtaining optimum results, it is important to select the correct split between fixed and switching capacitor. The method proposed in this section is based on Monte Carlo simulation, where each connected load has been assumed varying based on the certain predefined distribution shape as defined in Table III. Monte Carlo method relies on repeated random sampling to obtain results. Mote Carlo method is often used in physical and mathematical problems when it is impossible to obtain a closed-form expression or a deterministic algorithm. They are used to model phenomena with significant uncertainty in inputs.

Table- III: Probability Distribution for Connected Load

Nodes	Probability Distribution shape	
	Shape	Data
2, 7, 13, 18,19		a = 20% b = 100% c = 130%
4, 10, 16		a = 90% b = 100% c = 140%
5, 12, 15		a = 15% b = 100% c = 105%
20,21, 22,23,24,25	No Variation	
3, 6, 8, 9, 11, 14, 17		Mean = 1.0 SD = 0.1

The simulation is run for 500 times and each time input data is randomly selected from predefined distribution shape. The result provides the distribution of injected kVAr values that is used to decide fixed vs switching capacitor requirement.

The Fig 10. shows the results of 500 trails and shows the spread of injected kVAr values at defined node. The lower level of kVAr can be taken as a fixed capacitor and variation can be addressed as switching capacitors.

The Fig. 11 is the bar chart showing the variation in injected kVAr values and shows minimum required and switching kVAr and kVAr range per node. The minimum value of kVAr amongst the 500 trails is used as fixed capacitor and difference between maximum & minimum value as switching capacitor

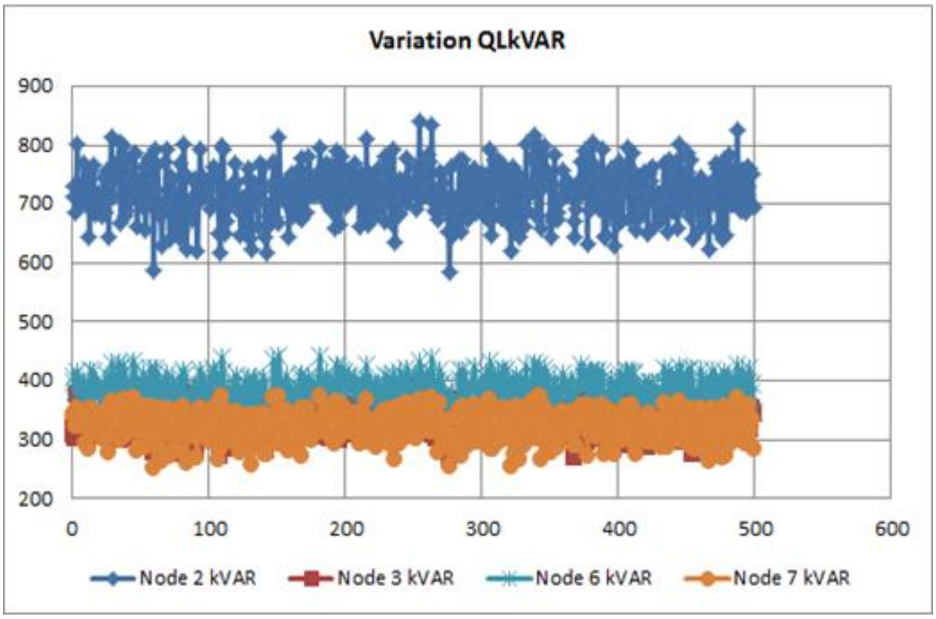


Fig. 10. Variation in injected kVAr values for 500 trails

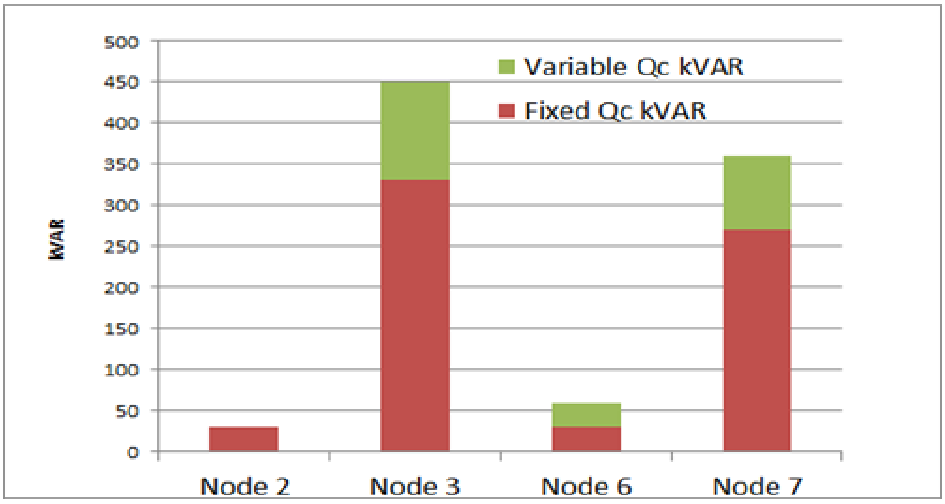


Fig. 11. Bar chart of variation in injected kVAr values for 500 trails

V. CONCLUSION

The work presented in this paper defines a cost minimization algorithm along and Monty Carlo simulation to choose optimal value of capacitors, both fixed and switching. The model selects the optimal value of capacitors, and places them at the best possible nodes with the goal of maximizing the net savings while ensuring the node voltages and stability index are within the permissible range. Power Loss Index calculation (PLI) is used as input for cost optimization algorithm and the proposed method was tested on a reference 25 bus system [1]. The Power loss index determines the candidate location of the nodes and rank them based on PLI cut-off values. The location and capacitor values are further optimized by running the cost optimization algorithm which also provides the optimum capacitor values.

The split between fixed and switching capacitor is calculated based on Monte-Carlo simulation, where each connected load has been assumed varying based on the certain predefined distribution shape. The minimum value of injected kVAr is used as fixed capacitor and spread range is used as switching capacitor.

This method places the capacitors only where required with optimum size and offers much net annual saving in initial investment.

APPENDIX

Input connected load data for the feeder are given in Table IV, V, Conductor data for the feeders are given in Table VI and Fig. 12 shows sample 19 Bus Distribution Feeder used for the modeling and simulation purpose.

Table- IV: Input Load data

Node	Phase Load in kVA		
	A	B	C
2	64	32	64
3	68	32	60
4	25	35	40
5	40	32	28
6	26	19	18
7	60	50	50
8	46	33	21
9	76	92	82
10	21	26	16
11	46	46	68
12	60	50	50
13	27	33	40
14	19	19	25
15	27	30	43
16	48	64	48
17	40	30	30
18	33	33	34
19	54	62	44

Table- V: Conductor Data

Conductor type	Resistance PU/Km	Reactance PU/Km
1	0.008600	0.003700
2	0.012950	0.003680

Table- VI: Conductor Code & Distances

Sending End Node(IR)	Receiving End Node(IR)	Conductor Code	Distance in Km
1	2	1	3
2	3	2	5
2	4	1	1.5
4	5	2	1.5
4	6	1	1
6	7	2	2
6	8	1	2.5
8	9	1	3
9	10	1	5
10	11	1	1.5
10	12	1	1
11	13	2	5
11	14	1	3.5
12	15	1	4
12	16	2	1.5
14	17	1	6
14	18	2	5
15	19	1	4

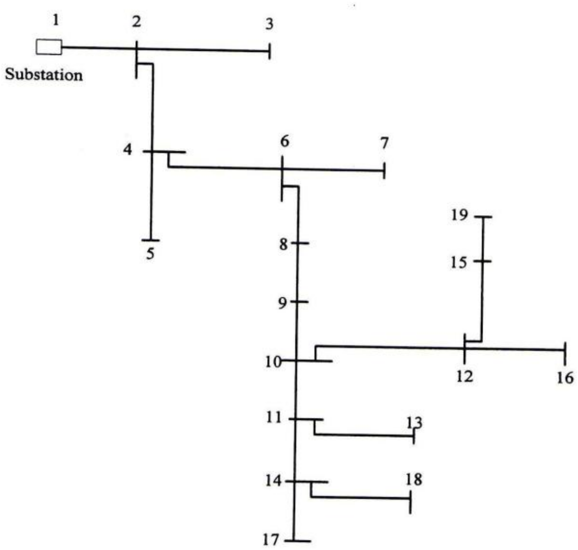


Fig. 12. Shows a practical 19 Bus Distribution Feeder used for the modeling and simulation purpose.

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