METHODOLOGY TO FIND THE LOAD PATTERN OF A LV DISTRIBUTION FEEDER AND OPTIMAL CAPACITOR PLACEMENT

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Abstract: The problem of capacitor placement for loss reduction in distribution system has been researched well in the past. In this paper a concept has been developed to determine the load pattern of a distribution feeder. Then a simple methodology has been illustrated to select the optimal size and location of capacitors to be placed in LV distribution network. The objectives were to minimize peak power loss and to improve voltage profile. The concept was extended to maximize the monetary savings while reducing the power loss in the network.

Keywords: Load pattern, Capacitor, Power loss, Distribution network

1. Introduction

In a Low voltage (LV) distribution system, power or energy loss and voltage drop along the feeder are common problems, which are encountered by power distribution networks across the country. This condition creates financial loss to industrial and domestic users as well as the power companies. Therefore this condition has to be improved in order to minimise the power loss and to assure the quality of power supply to the customers. There are many strategies including phase balancing, network reconfiguration widely used in the industry. However shunt capacitors installation method is generally adopted to minimise the power loss and voltage drop [1, 2].

Various methods [2] are used to install shunt capacitors at appropriate locations in the LV distribution systems to reduce power loss and to improve voltage profile along the feeder. Most of the early studies on this subject used different techniques [2 - 13]. Such methods had complexities in their approaches. Grainer and Lee [3, 4], developed computer-based optimization techniques. This is to determine the net monetary savings associated with the reduction of power loss through placement of shunt capacitors on distribution feeders. Further on to these analytical optimization techniques, heuristic search strategies have been developed recently [5]. The purpose of developing heuristic search strategies is to reduce the complexities of analytical optimization [6 - 13] whilst keeping the result at an optimal value. However, the short comings of these methods; such as complexity, time consuming and use of computer-based techniques caused chaotic results in implementation in the distribution network consisting a large number of customer data (Appendix B). On the other hand, distribution network is usually radial so that the analyses can be easily carried out with line parameters and customer loads.

This paper presents a simple and smart method to resolve the complications encountered in above mentioned techniques. The method has been developed using one excel spreadsheet. This is incorporated with line parameters (line resistance, reactance and distance) and customer loads which are connected to each pole of the distribution network. This study is carried out in order to achieve an overall power loss reduction in the system with maximum savings.

Although this method resolves most of the issues associated with power loss and voltage drop, it can only be used for fixed capacitor placements. Cost analysis has been carried using optimum number of capacitor banks and

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corresponding location, which indicates that this method can optimally use the capital cost and bring economical benefits during the life cycle. Also, the method has been developed considering the improvement of system voltage.

2. Theory

Usually capacitors are installed to the feeders to improve the power factor of the distribution system. By placing capacitors, the reactive power of the system is reduced and accordingly the apparent power is reduced. The active power remains the same other than the loss reduction. Figure 1 illustrates this effect. Fig 1 is a daily load pattern measured in Mavilmada distribution substation (in Kandy area) with and without capacitors. More details of the site are described in section 3. The measured maximum apparent power S (without the capacitor placement) was 215.2 kVA. It reduced to 211.5 kVA after the capacitor placement.

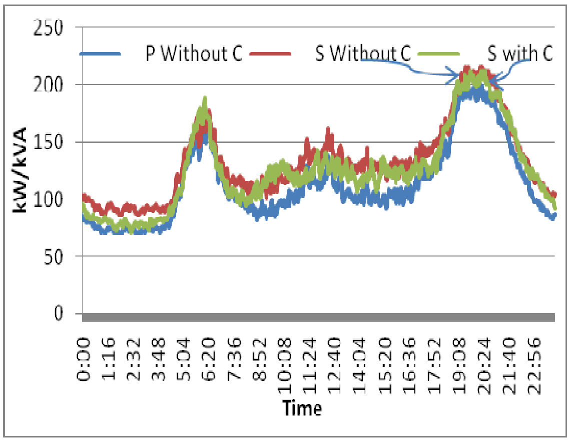

Figure 1 - Daily Load Pattern for MAV Substation.

Since the system voltage is 400 V (line to line), the active (P), reactive (Q) and apparent (S) power values are directly proportional to their relevant currents.

The power loss and voltage drop of the distribution line can be written as

$$P_{line} = I_S^2 R_{line} \quad (1)$$

$$V_{drop} \approx (X_{line} \operatorname{Sin} \emptyset + R_{line} \operatorname{Cos} \emptyset) I_S \quad (2)$$

Where I_S is the line current and
$\emptyset$ is the phase angle

For calculating power loss and voltage drop, I_S can be calculated from customer energy consumption data as follows:
From the electricity bills up to eight months, if the energy consumption E is in kWh, the average active power is given by

$$P_{av} = {}^{E}/_{(8 \times 24 \times 30)} \text{ in } kW \quad (3)$$

The line current $I_{av} = {}^{P_{av}}/_{(\sqrt{3} \times 400 \times pf)}$ (4)

Where pf is the power factor.

The money saving in the maximum demand is given by

$$M_{sav} = (S_{initial} - S_{final}) \times (charge\ per\ kVA) \quad (5)$$

If the installation and other costs for the capacitors are C, then the payback period can be given as

$$Payback\ period = {}^{C}/_{M_{sav}} \quad (6)$$

3. Site Selection

Recently the CEB has installed shunt capacitors to some of their selected distribution substations located in central province. Two substations, located in Kandy area, were selected for the study. They were Siyambalagastenna (SIY) substation and Mavilmada (MAV) substation. The SIY substation was selected for preliminary studies whereas the MAV substation was chosen for detailed analyses.

The SIY substation had a 400 kVA, 11/0.4 kV, 3p transformer consisting 521 customers in 5 feeders. Three 20.8 kVAr capacitors have been installed in 2nd 3rd and 5th feeders. The MAV substation had a 400 kVA, 11/0.4 kV, 3p transformer consisting 491 customers in 3 feeders. These three feeders are named as A, B and C as shown in Figure 3. A single 20.8 kVAr capacitor has been installed at feeder A in MAV substation as shown in Figure 2. The cost of this capacitor was Rs.15,150 and the breaker was Rs.3,520. Expected life time of this breaker switched capacitor is about 5 years.

Figure 2 - Installed Capacitor at MAV Substation.

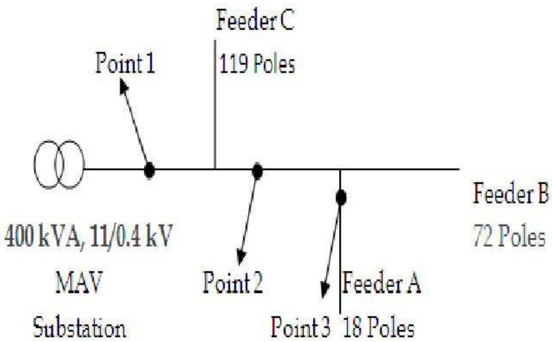

Figure 3 - Feeder Diagram for MAV Substation.

4. Methodology

Preliminary investigations were done at SIY substation by measuring the power factors. The purpose was to check the effectiveness of the capacitor installation. The daily load pattern of the SIY substation was obtained using power measurements. A Fluke 1735 data logger was used to record the power measurements. The active, reactive, apparent powers, power factor, voltages and current values were recorded in every minute continuously for 24 hours. The measurements were repeated with and without capacitors, which were 20.8 kVAr each and already installed at 2nd, 3rd and 5th feeders of SIY substation.

On the other hand, a detailed study was conducted at MAV substation in four steps, namely:

1. Measurement and verification of power and power factor in the substation
2. Development of the feeder data in an excel sheet based on line parameters and customer electricity bill data
3. Calculation of power loss and their reduction by capacitor placement to the feeder using the developed excel sheet
4. Cost analyses including payback period of the selected cases

In the first step, similar to SIY substation, daily load pattern was obtained in MAV substation with and without capacitor placements at the transformer LV side. To get a better picture on the daily load pattern, weekly load measurements were recorded at point 2 (see Figure 3). Accordingly average daily load pattern was obtained. In addition, two sets of readings at peak points of load pattern were taken at the exact feeder that we considered (feeder A, see Figure 3). The whole load pattern of feeder A was not obtained due to some practical problems. The first set of measurements covered power flow to feeders A, B and C whereas the second set of measurements covered feeders A and B. By mapping both patterns, the relevant factors were obtained to plot the load pattern of feeder A. To discuss the design approach, feeder A was selected due to simplicity. Figure 4 shows a photograph of the power measurement.

Figure 4 - Data Logger is connected to the Bus-bar for Load Measurements

As the first step, in the feeder A, R and L line parameters (Appendix A) were collected while current dara was measured. The line parameter values (R and L) were obtained from data sheets and distances between poles were measured. In the second step, line parameters and consumers' electricity bill data were collected. In the consumer data, account numbers of the feeder A were collected and from the account data the energy consumption (for eight months) were obtained. By visiting the location (feeder A), the pole location for each consumer was obtained. Accordingly, the total load connected to each pole was obtained. According to equations 3 and 4, pole currents were obtained. The power factor was selected as the average value of the measured values. All calculations were inserted in the excel spreadsheet.

In the third step, variation of power loss with respect to the time was calculated according to the equation 1. Then the variation of power loss with respect to pole location by considering three specific times (1) morning peak, (2) night peak and (3) during light load period, was obtained. By covering 24 hours measurements average power loss curve was obtained. Afterwards, the power losses were calculated and compared with the measured values. It was found that the power losses based on measured values were significantly higher than those of calculated. The difference should most probably be due to exclusion of non-technical losses in calculation and therefore the measured data were considered as accurate over the others. Thus the capacitor location was found according to the measured data.

Two cases of capacitor location were considered. One was a single capacitor connected to a pole having highest load i.e. a branch to the feeder. The second was additional capacitors in other poles to compensate more reactive power. Cost analysis was carried out and payback period was calculated for both cases. Finally optimal case was suggested based on power loss reduction, voltage drop improvement and the lower payback period.

In addition, a third case was analysed by single capacitor placement at the first pole to compensate the minimum reactive power.

5. Results and Discussion

Figure 5 shows the daily load pattern for MAV substation without capacitor placement. According to Figure 1, the average power factor without and with capacitors were 0.84 and 0.9 respectively. The reactive power has been reduced by 28.04% due the 20.8 kVAr capacitor placement, which is a significant reduction.

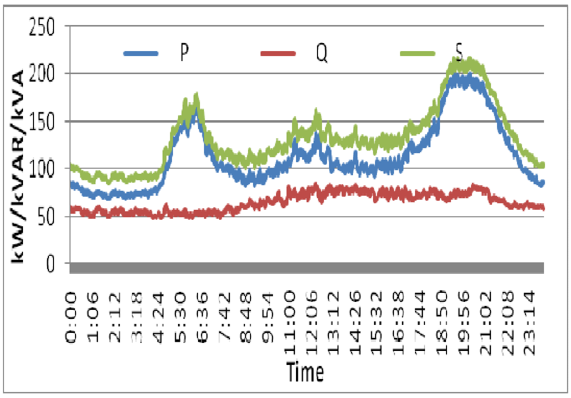

Figure 5 - Daily Load Pattern of MAV Substation without Capacitor

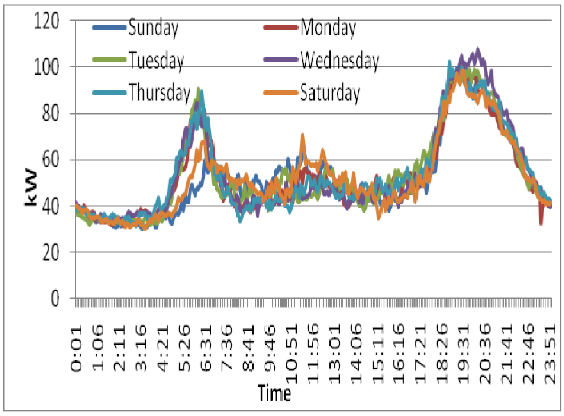

Figure 6 - Weekly Load Data (from measurement)

Figure 6 shows the weekly load pattern recorded at point 2 (See figure 3). It indicates that weekend load pattern differs from that of weekdays. It is clear that the day peak significantly reduced during weekend due to low power consumption during early morning. The average load pattern, of the measured six days (Monday, Tuesday, Wednesday, Thursday, Saturday and Sunday) data, was calculated and plotted in Figure 7.

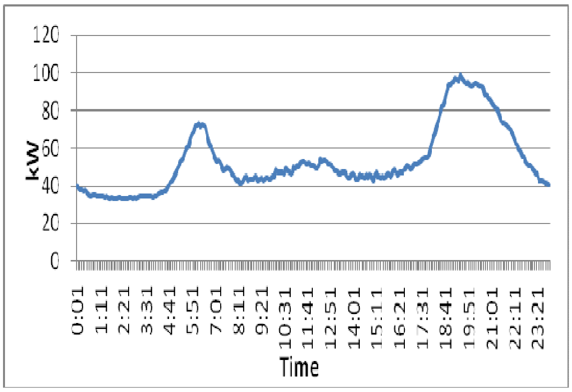

Figure 7 - Average of the Weekly Load Data (average of the measured six days load data)

The load pattern for feeder A was obtained using the measured data taken at points 1, 2 and 3 (See figure 3). A comparison of load patterns at points 1, 2 and 3 are shown in figure 8. The factors betweeen each load pattern were obtained using the ratio between them. The factors between P1/P2 and P1/P3 were approximately 2.5 and 5 respectively. According to thse calculated factors, the daily load pattern for feeder A was obtained and shown in figure 9.

As this paper describes the methodology for optimal capacitor placement, a simple feeder is selected for easy explanation. Therefore further investigations were conducted on the data of feeder A and results are reported below sections.

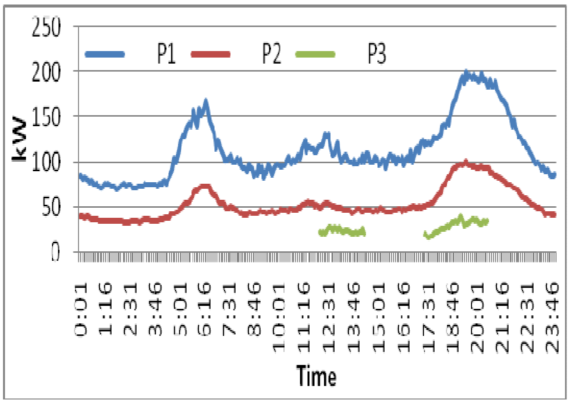

Figure 8 - Comparison of Real Powers of Total Substation and the Feeder A

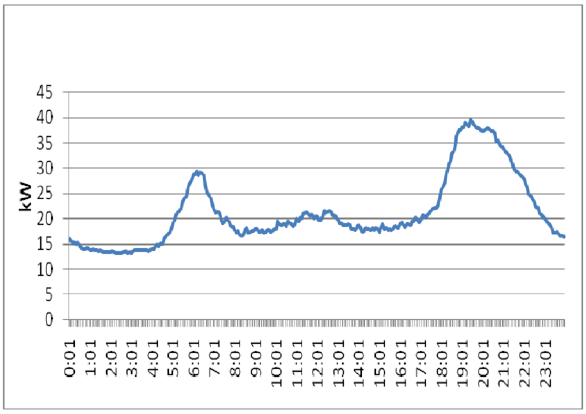

Figure 9 – Estimated Daily Load Pattern of Feeder A, from the data obtained using Figure 8

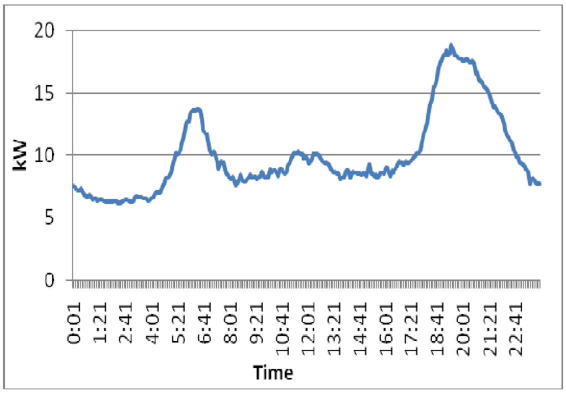

Figure 10 - Estimated Daily load Pattern of Feeder A, from calculation

Figure 10 shows the estimated daily load pattern of feeder A according to the calculated data. From consumers' electricity bills, the average energy consumption per day in kWh was calculated. That was 239.2 kWhs. Then, the total energy consumptions in each day were calculated using measured weekly load data obtained from point 2 (See figure 3). The ratios between calculated (electricity bills) and measured every day's energy consumptions were found. The load patterns of feeder A for all six days were obtained by mapping the weekly measured load data using the ratios obtained. Finally the average curve was obtained using derived curves for all six days.

According to figures 9 and 10, significant difference between measured and calculated power was observed. It has to be noted that non-technical losses (i.e. illicit tapping) were not taken into account for the calculated power.

According to the measured data and calculated data from monthly electrical energy consumption, power losses with respect to pole location were calculated. Figure 11 shows the comparison of measured and calculated power losses.

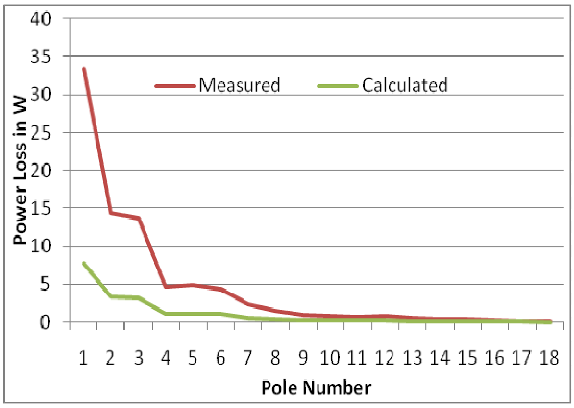

Figure 11 Comparison of average power losses, at each pole of feeder A, obtained based on measured and calculated data

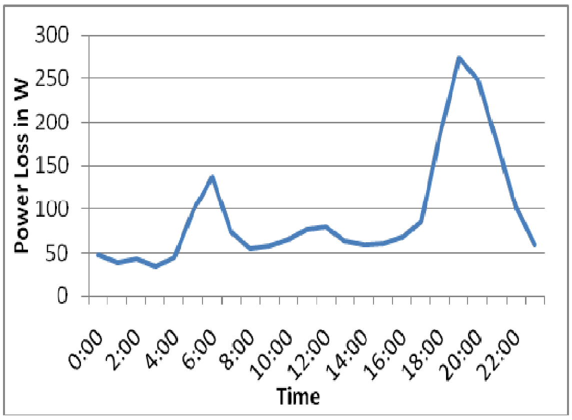

Figure 12 Total Power Loss Variations with the Time of Feeder A

Figure 12 shows the variation of total power loss of the deefer A with respect to the time. It can be seen that the variation is very similar to the power curve as loss is related to the load current.

Fgure 13 shows the variation of power loss along the Feeder A with respect to the pole number. The power loss along the feeder (with respect to pole number) was obtained for every hour. Three instances were selected to compare the differences. The morning peak, light load and night peak were plotted in the same graph (See the figure 13). The average power loss of every hour variation, for the period of 24 hours, was also plotted in the same figure.

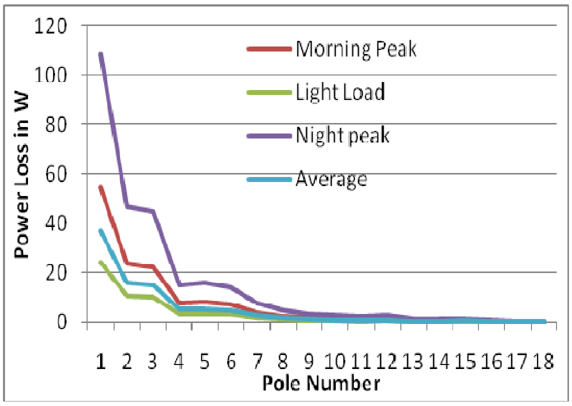

Figure 13 Power Loss Variation with Poles for major loading conditions

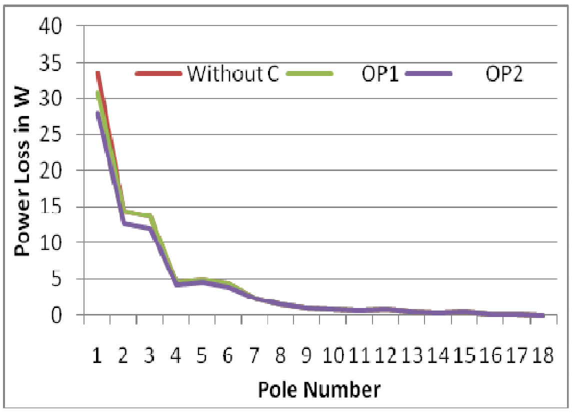

Figure 14 - Average Power Loss along the Feeder A for three different casses

Two cases were selected for the application of the design approach. Those cases were,
Case 1 (OP1) – 3 kVAr capacitor was placed at the first pole.
Case 2 (OP2) – 3 kVAr, 2 kVAr and 1.4 kVAr capacitors were placed at 1st, 3rd and 6th pole respectively.
Figure 14 shows average power loss along the feeder A (i) without capacitor, (ii) in case 1(OP1) and (iii) in case 2 (OP2). It shows the difference in power losses in OP1 and OP2. The calculated power losses in percentage for OP1 and OP2 were 96.89% and 87.91% with respect to the base case of without capacitor. In addition, figure 15 shows voltage drop along the feeder for all three cases. The voltage drops in percentage at the feeder end were 99.16 for OP1 and 94.77 OP2 with respect to the base case of without capacitor. As a result the Option II shows better performance of 12.09% reduction in power loss while improving the voltage drop by 5.23% with respect to its base case.

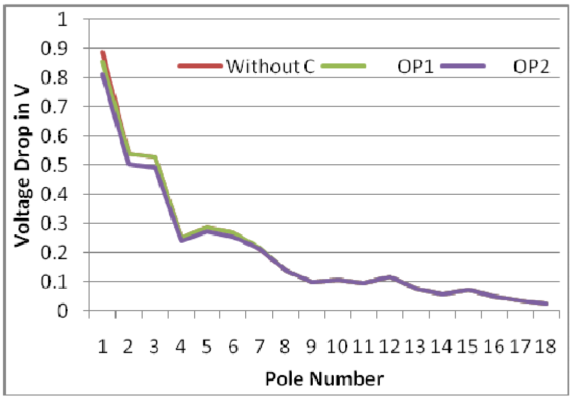

Figure 15 Voltage Drop along the feeder A for three different cases

With commercially available capacitors, the capacitos for two cases were selected as follows: Here it has to be noted that the capacitors were selected to inject only minimum reactive power consumed at that pole.
OP1 –
3 kVAr was built up using a 47 μF and a 22 μF.

OP2 –
3 kVAR was built up using a 47 μF and a 22 μF.
2kVAR was built up using a 47 μF.
1.4 kVAR was built up using a 27 μF.

6. Cost Analysis

Cost analyses for each cases were done seperately. Four possibilities of monetary saving were found.

1. Savings from kVA reductions
2. Savings from kWh reductions (line losses)
3. Savings that could be earned bysupplying the saved kW reductions (as listed in 1) to new customers
4. Savings due to power loss reduction in the upstream of the network

Firstly, the reduction in kVA were calculated and then savings were calculated using the equation 5. The charge per kVA was taken as Rs.850.

Case 1
S initial = 30.15 kVA
S final = 28.95 kVA
Reduction in kVA = 1.2 kVA
Saving = Rs. (1.2*850)

= Rs.1020

Case 2

S initial = 30.15 kVA

S final = 27.58 kVA

Reduction in kVA = 2.57 kVA

Saving = Rs. (2.57*850)

= Rs.2184.50

Seconly, the reductions in kWh were calculated. The price of one unit of kWh was taken as Rs.15.

kWh loss per day,

without capacitor = 2.24 kWh/day

case 1 = 2.044 kWh/day

case 2 = 1.857 kWh/day

Case 1

Reduction in kWh/day = 0.196

Savings /month = 0.196*15*30

= Rs.88.20

Case 2

Reduction in kWh/day = 0.383

Savings /month = 0.383*15*30

= Rs.172.35

Thirdly, the kW saved from the capacitor placement was calculated. The average energy consumption of the feerder A was 600 kWh with the peak load of 40 kW.

Case 1

According to the power consumption with and without capacitor, the kW reduction = 0.0082

kWh saved/day = (600/40)*0.0082

Savings/month = 0.123*30*15

= Rs.55.35

Case 2

kW reduction = 0.016

kWh saved/day= (600/40)*0.016

Savings/month = 0.24*30*15

= Rs.108

Finally, the total savings were calculated for the two cases.

Case 1

Savings = Rs.1020 + Rs.88.20+ Rs.55.35

= Rs.1163.55

Case 2

Savings = Rs.2184.50+ Rs.172.35+ Rs.108

= Rs.2464.85

Then the total cost including capital and installation costs were calculated for the above two cases. Finally the payback period was calculated using equation (6).

Total cost = Capacitor cost + Breaker cost + Installation cost

Case 1

Total cost = Rs.8750

Payback period = Rs.8750/(Rs.1163.55/ month)

= 7.52 months

Case 2

Total cost = Rs.21450

Payback period = Rs.21450/(Rs.2464.85/ month)

= 8.70 months

7. Feeder based minimum reactive power compensation

As case 3, feeder based minimum reactive power compensation is studeied. Here the minimum reactive power of the feeder is compensated at pole 1 as lumped. The power loss in the down stream is same as discussed in case 2. In the feeeder based minimum reactive power compensation method (case 3), a 10.2 kVAr capacitor was placed at the first pole. The kVA reductions due to the placement of capacitor, was calculated.

Case 3

S initial = 30.15 kVA

S final = 27.00 kVA

Reduction in kVA = 3.15 kVA

Saving = Rs. (3.15*850)

= Rs.2677.50

Further the reductions in kWh were calculated for the case 3. The price of one unit of kWh was taken as Rs.15.

kWh loss per day,

without capacitor = 2.24 kWh/day

with capacitor as in case 3 = 1.78 kWh/day

Reduction in kWh/day = 0.46

Savings /month = 0.46*15*30

= Rs.207

The total savings were calculated for the case 3.

Savings = Rs. 2677.50 + Rs. 207

= Rs.2884.50

Then the total cost including capital and installation costs were calculated. Finally the payback period was calculated using equation (6).

Total cost = Rs.19050
Payback period =Rs.19050/(Rs.2884.50/month)
= 6.60 months

Considering the payback period of all three cases, capacitor allocation made for the case 3, shown quick recovery of expenditures.

8. Effects on upstream network

The savings that can be earned from the loss reduction in upstream network must also be considered in the total savings. This will further reduce the payback period. Fault level at the upstream network was measured as indicated in figure 16. The measured fault level was 6.379 kA at the specified point (From the CEB data).

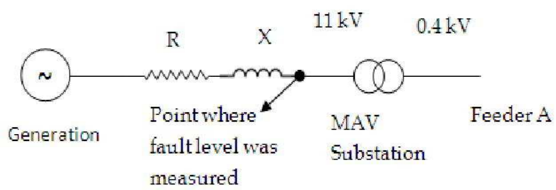

Figure 16 - Fault Level Location

The impedance of the upstream network was calculated. It was taken that,

$$\frac{X}{R} \approx 2 \quad (7)$$

Where X and R are the lumped reactance and resistance of the upstream network respectively. From the fault level measurement,

$$|X + jR| = \frac{V}{I} \quad (8)$$

$$\sqrt{X^2 + R^2} = \frac{11/\sqrt{3}}{6.379}$$

Table 1 - Calculation of Savings in Upstream Network

Cases	I_{Total}/A	P_{Loss}/ kW	Reduction in P_{Loss} / W	Savings/ Rs.
Without C	535	127.9		
Case 1	533.3	127.1	811.8	5479
Case 2	531.3	126.2	1763.6	11904
Case 3	530.5	125.8	2143.3	14467

From the equations (7) and (8), the R was found to be 0.447 Ω. Then the loss in the upstream network for every case was calculated. The loss reduction was also calculated for all three cases.

Table 1 lists the current, power loss, reduction in power loss and saving for all three cases. Finally, the new savings were found and the new payback periods were calculated.

Case 1
Payback period = Rs.8750/ (Rs.1163.55+ Rs. 5479)
= 1.32 months

Case 2
Payback period = Rs.21450/ (Rs.2464.85+ Rs. 11904)
= 1.49 months

Case 3
Payback period = Rs.19050/ (Rs.2884.5+ Rs. 14467)
= 1.10 months

9. Conclusions

A simple method has been discussed in this paper to determine the load pattern of a feeder and to make an optimal capacitor placement. A user friendly excel spreadsheet was developed to analyse this method. In this design approach, three topologies of placing capacitors were analysed and four types of monetary savings were considered. The proposed approach determines the compensation level from the condition of maximizing the net savings. Generalization of the method can be done to other feeders and substations for sectional analysis, which covers the selected feeders and branches. This localised study will help specially distribution planning engineers of the utility.

This research paper adds a contribution to researchers and practicing engineers by delivering a methodology to find the optimal capacitor placement in a radial networks with branches.

Next part of this study is finding the optimum point based on placing the switched capacitor, where it switched dynamically with varying reactive power requirement.

10. Acknowledgement

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12. Appendix

A. Line Parameters

Poles	Distance between poles (m)	Line Resistance (Ω)	Line Reactance(Ω)
tf - 1	35	0.017675	0.01029
1 - 2	30	0.01515	0.00882
2 - 3	30	0.01515	0.00882
3 -4	20	0.0101	0.00588
4 - 5	25	0.012625	0.00735
5 - 6	25	0.012625	0.00735
6 - 7	30	0.01515	0.00882
7 - 8	20	0.0101	0.00588
8 - 9	15	0.007575	0.00441
9 - 10	20	0.0101	0.00588
10 - 11	20	0.0101	0.00588
11 - 12	25	0.012625	0.00735
12 - 13	20	0.0101	0.00588
13 - 14	15	0.007575	0.00441
14 - 15	20	0.0101	0.00588
15 - 16	20	0.0101	0.00588
16 - 17	20	0.0101	0.00588
17 - 18	30	0.01515	0.00882

B. Consumer Data

Pole Number	Number of consumers	Total connected load (W)
1	17	2902.8
2	1	166.7
3	8	2006.4
4	1	401.9
5	2	262.3
6	11	1413
7	1	66
8	3	131.9
9	2	534.5
10	1	234.7
11	0	0
12	2	345.4
13	0	0
14	1	49.8
15	2	45.8
16	2	29.9
17	3	38.8
18	3	30.5