ORIGINAL ARTICLE

# Distribution Feeder Loss Optimization: A Case Study

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**Received:** 15th March 2023
**Revised:** 1st June 2023
**Accepted:** 6st June 2023

OPEN ACCESS

**Abstract:** The feeder reconfiguration is a process of shifting the system load from one feeder to another feeder for loss minimization in distribution system or for maintenance purpose. The present paper proposes an effective approach for feeder reconfiguration and capacitor allocation for power loss optimization and voltages profile improvement in the existing Ratnagiri city electricity distribution system of Maharashtra State, India. A scheme of feeder reconfiguration is presented with respect to existing feeders for power loss optimization. The presented paper also proposes a method to find suitable location and size of capacitors to reduce power loss due to reactive component of branch current. A sequential searching method is used to find the locations for all capacitors in distribution system and the size of capacitor at each location is evaluated by optimizing the loss saving equation. The performance of the proposed method has been investigated on the existing Maharashtra State Electricity Distribution System of Ratnagiri city and it is found that proposed method reduces power loss in existing system significantly. The proposed method enables us to obtain a near-optimal solution with the capacitor selected and proposed reconfiguration. If more switches are provided for the reconfiguration process, the results obtained can be improved still further.

**Keywords:** Distribution network; feeder reconfiguration; power loss; sectionalizing switches; tie switches.

## Introduction

The present need to increase overall efficiency of power system forced supply utility to focus on improvement in efficiency of distribution system. Now a days it is possible by using smart and intelligent technology to forecast the causes of loses and suggest technology to improve overall efficiency. However, the solution for loss minimization and efficiency improvement must be cost effective and should not violate any operational constraints of power system. The cost effective solution for power loss minimization is possible by feeder reconfiguration and optimal placement as well as setting of capacitors in distribution system. The distribution feeders can be reconfigured by changing the positions of the normally open and normally closed switches to increase network reliability, reduce line losses and to perform scheduled maintenance. The reconfigured system should satisfy all load requirements and should remain radial for effective coordination of protection scheme used. Capacitors are used in distribution systems to compensate reactive power drown by the lines due to inductive loads, enhance voltage profile, reduce the line loss and reduce line burden. Continuous research have been conducted in last few decades to solve the distribution system capacitor placement and sizing problem. Capacitor allocation is more effective for distribution system, which has randomly distributed concentrated loads and any number of laterals. Numbers of papers are available in the literature for distribution feeder reconfiguration, optimum capacitor allocation and both feeder reconfiguration and capacitor allocation for loss minimization. In [1], an efficient algorithm is used for feeder reconfiguration. Alternating current power flow model is used for analysis. A combination of feeder reconfiguration and placement of distributed generators are used for loss reduction is presented in [2]. Distributed generators are used to compensate for reactive power. A growth simulation algorithm is proposed for generator allocation and power loss minimization. A feeder reconfiguration and distributed generator allocation are proposed using the Hyper Cube-Ant Colony Optimization algorithm [3]. For the optimum location of DGs, loss sensitivity analysis is used. In [4], a genetic algorithm is used for feeder reconfiguration. The objective is formulated as a multiple constraint optimization problems. An optimal capacitor placement method is used for power loss minimization and system voltage enhancement [5]. A multi-objective genetic algorithm is used to find suitable locations for capacitors. In [6], a review of various methods for capacitor placement in the distribution network is presented. A capacitor allocation in an unbalanced network is presented in [7]. A fuzzy-based genetic algorithm is used to find the optimal location for capacitors. A novel capacitor allocation and control method in an unbalanced distributed network is proposed using a differential evaluation algorithm [8]. Allocation of both fixed and switched capacitor is presented. In [9], capacitor placement and sizing for different types of load models are presented. A combination of GA and BSW optimization algorithm is used to formulate the objective function. A modified honeybee mating optimization approach is used for feeder reconfiguration [10]. The presented method is simulated on 32 bus systems and considerable loss reduction on the distribution system shown. In [11], an optimal capacitor placement method is presented for an unbalanced distributed network. The presented algorithm has a lot of limitations.

Most of the research papers in literature give incite for feeder reconfiguration and capacitor placement in distribution networks using various types of algorithms for standard theoretical bus systems. The present paper proposes a case study for distribution system loss minimization by feeder reconfiguration and optimal capacitor allocation in existing Electricity Distribution Company.

## Power Loss Determination

To determine power loss in the distribution system there is a need to use a set of power flow equations which must be simple but gives more accurate solution [12-13]. To use these equations, consider a radial network as shown in Figure 1.

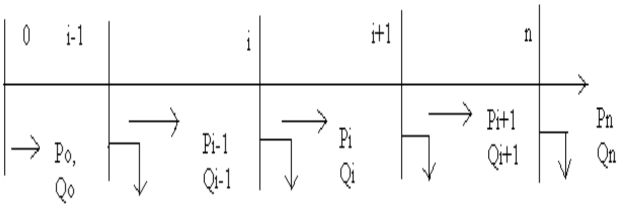

**Figure 1.** Single line diagram of a radial network

Let,

$Z_l = r_l + jx_l$ (Line impedances for $l$ number of lines)

$S_L = P_L + jQ_L$ (Load a constant power sink for $l$ number of lines)

$P_k$ : Active power at sending end of line

$Q_k$ : Reactive power at the sending end of line

$V_k$ : Voltage at the sending end of line

Distribution system branch power flow equations can be used to determine power flow in radial distribution network. The same equations can be used to find active power, reactive power and voltage at the receiving end as follows,

$$P_{k+1} = P_k - r_k \frac{P_k^2 + Q_k^2}{V_k^2} - P_{Lk+1} \tag{1}$$

$$Q_{k+1} = Q_k - x_k \frac{P_k^2 + Q_k^2}{Q_k^2} - Q_{Lk+1} \tag{2}$$

$$V_{k+1}^2 = V_k^2 - 2(r_k P_k + x_k Q_k) + (r_k^2 + x_k^2)\frac{P_k^2 + Q_k^2}{V_k^2} \tag{3}$$

If active power, reactive power and voltage at the first node of the network are evaluated, then by using above equations successively, it is possible to determine these quantities at any other node in a network.

If you consider $P_k$ ,$Q_k$ and $V_k$ as a quantities at receiving end, then it is possible to determine these quantities at the sending end also by using following recursive equations,

$$P_{k+1} = P_k - r_k \frac{P_k^{'2} + Q_k^{'2}}{V_k^2} - P_{Lk+1} \tag{4}$$

$$Q_{k+1} = Q_k - x_k \frac{P_k^{'2} + Q_k^{'2}}{V_k^2} - Q_{Lk+1} \tag{5}$$

$$V_{k+1}^2 = V_k^2 - 2(r_k P_k + x_k Q_k) + (r_k^2 + x_k^2)\frac{P_k^{'2} + Q_k^{'2}}{V_k^2} \tag{6}$$

where,

$$P_k^{'} = P_k + P_{Lk}^{'} \tag{7}$$

$$Q_k^{'} = Q_k + Q_{Lk}^{'} \qquad (8)$$

Having a network model, it is possible to express the power loss and measure the load balance in the system in terms of system variables [13-15]. Here for power loss minimization, the objective is to minimize the total i$^2$r losses in the system, which can be calculated as follows,

$$C_p = \sum_{k=0}^{n-1} r_k \frac{P_k^2 + Q_k^2}{V_k^2} \text{ p.u.} \qquad (9)$$

Where, $C_p$ is the objective function for network reconfiguration and power loss minimization.
Here to determine load balancing, the ratio of complex power at the sending end of a branch $S_k$, over its kVA capacity $S_k^{max}$ is used as a measure of how much that branch is loaded. The branch can be transformer, a tie line with a sectionalizing switch or a line section. Here load balanced index is given by,

$$C_b = \sum \left( \frac{S_k}{S_k^{\max}} \right)^2 = \sum \frac{P_k^2 + Q_k^2}{S_k^{\max 2}} \qquad (10)$$

Where, $C_b$ is the objective function for load balancing.

## Determination of Location and Optimum Size of the Capacitor

There are various methods and algorithms available to find location and optimum size of capacitor [16-18]. Here a different approach is used to find capacitor location and size. Considering a radial distribution system with *n* branches and excited by single source. Considering the capacitor *C* is located at the bus b and β be the set of branches associated with the source and the capacitor buses. In Figure 2, if the capacitor is located at bus 15 (*b*=15), the set β consist of branches 1, 2, 3, 4, and 14. The capacitor draws a reactive current $I_c$, and for a radial network it changes only the reactive component of current of branch set β. The current of the branches (⍰β) is not affected by the present location of the capacitor. Hence, the new reactive component $I_{ri}^{x}$ of k$^{th}$ branch can be expressed as,

$$I_{rk}^{x} = I_{rk} + A_k I_c \qquad (11)$$

where,
$A_k = 1$; if the branch $k \in \beta$
$A_k = 0$; otherwise.

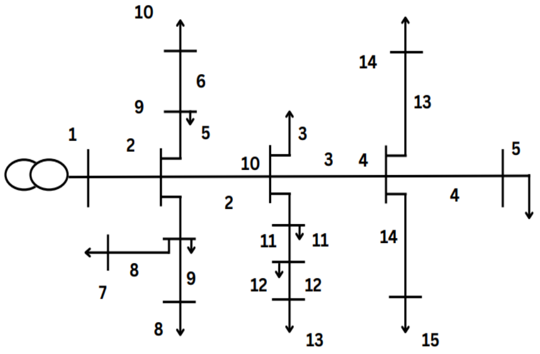

**Figure 2.** System line diagram

Here, $I_{rk}$ is the reactive component of the current of the k$^{th}$ branch. In the compensated network, the loss related to the reactive component of the branch current is given by,

$$P_{Lr}^{com} = \sum_{k=1}^{n} (I_{rk} + A_k I_c)^2 R_k \qquad (12)$$

The loss saving *S* is given by,

$$S = P_{Lr} + P_{Lr}^{com} \qquad (13)$$

$$= -\sum_{k=1}^{n} (2 A_k I_{rk} I_c + A_k I_c^2)\ R_k \qquad (14)$$

Where,
$P_{Lr}$ is power loss without capacitor addition.
The system equation which gives maximum loss saving associated with capacitor current $I_c$ is given by,

$$\frac{\partial S}{\partial I_c} = -2 \sum_{k=1}^{n} (A_k I_{rk} + A_k I_c^2) R_k \qquad (15)$$

From the above equation, the capacitor current $I_c$ is given by,

$$I_c = \frac{\sum_{k=1}^{n} A_k I_{rk} R_k}{\sum_{k=1}^{n} A_k R_k} = -\frac{\sum_{k \varepsilon \alpha} I_{rk} R_k}{\sum_{k \varepsilon \alpha} R_k} \qquad (16)$$

The corresponding capacitor size is given by,

$$Q_C = V_b I_c \qquad (17)$$

Where, $V_b$ is the capacitor voltage at bus *b*.

To get highest loss saving with respect to allocation of single capacitor, the procedure is need to be repeated for all buses in the network.

The above process can be repeated for all buses to get the highest possible loss saving for a single capacitor located in a system. The presented technique will provide only the locations for the capacitor placement and optimal size for singly located capacitor and may not be more useful when multiple capacitors are placed in a system.

## Problem Formulation

Here, the network reconfiguration problem is formulated as a single objective optimization problem with equality and inequality constraints.

Let,

*s* :- A set of possible configurations of given network.

*y* :- One configuration belongs to *s* whose operating state is specified by *x.*

*Find y, to minimize f (x, y), where* $y \varepsilon s$

*such that,*

$0 < I < I_{max}$ *and*

$V^2_{min} < V^2 < V^2_{max}$

Where,

*I*:- Feeder current.

$I_{max}$:- Maximum feeder current decided by feeder size.

*V* :- Load bus voltage.

$V_{min}$:- Lowest value of load bus voltage.

$V_{max}$ :- Highest value of load bus voltage.

## System Analysis

The system under consideration is an actual power system network of Maharashtra State Electricity Distribution Company Limited (MSEDCL) as shown in Figure 3 (single line diagram). In order to minimize the losses in the system, the strategy of feeder reconfiguration is adopted. An objective program, with justified assumptions and practical constraints, is designed with the help of MATLAB software. The results obtained through the proposed simulated system have been compared with the existing practical system performance so as to compare the merit and demerits of the proposed method.

The distribution network under consideration has following specifications:

*Voltage Level: 110/33/11kV*

*Number ofFeeders: 3*

*Number of Buses: 55*

*Number of Tie Switches: 4*

*Number of Sectionalizing Switches: 4*

Consider an ACSR (weasel), dia-30 sqr. mm, impedance of (0.977+j0.328) ohm/km.

The bus distribution on three feeders is as below:

*Feeder 1 - MIDC - Bus no. 1 to 22 i.e. 22 buses.*

*Feeder 2 - Shivajinagar - Bus no. 23 to 39 i.e. 17 buses.*

*Feeder 3 - Khedshi - Bus no. 40 to 55 i.e. 16 buses.*

Tie Switch locations:

*TS1 – Bus no 7 to 35.*

*TS2 – Bus no 12 to 55.*

*TS23– Bus no 30 to 49.*

*TS4 – Bus no 39 to 50.*

The placement of all types of switches in the network needs a careful study of the load curve, losses and regulation. The exhaustive actual data as supplied by MSEDCL is available with author.

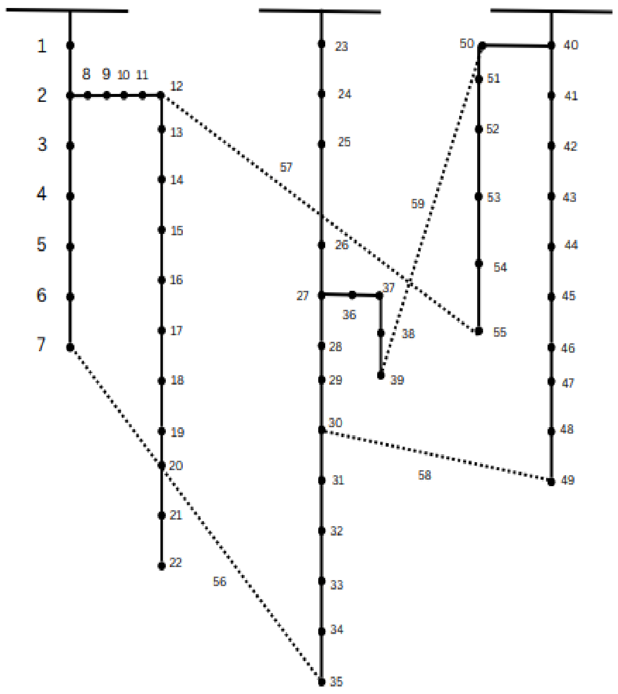

**Figure 3.** Substation Distribution Network.

## Assumptions and Justification for Feeder Reconfiguration

Loads on the system considered as constant PQ devices (Time invariants): As the system load changes according to the hours of the day, it may require the configuration to change according to load. Simulation of the system with varying load duration curve requires a controller in the system which senses a change in load and reconfigures the system according to the load duration curve [19]. The discussion presented here is restricted to a constant peak load duration curve.

Reconfiguration is restricted to present available switching options only : A general power distribution network may consist of a large number of switching options. The discussion presented here is restricted to practical Maharashtra State Electricity Distribution Company Ltd. Ratnagiri where only four switching options are available for reconfiguration.

Supply disturbance due to switching is neglected: Instantaneous automatic switching for reconfiguration is possible using an automatic controller, which avoids supply disturbance to the load [20-21]. However, the discussion presented here is restricted to manual switching which may cause supply disturbance to the load during reconfiguration and therefore it is neglected.

## Assumptions and Justification for Capacitor Allocation

Loads on the system are considered as constant PQ devices. (Time invariants): Varying load duration curve changes the size and location of the capacitors. Simulation of such a system requires an automatic system, which senses load variation and changes capacitor size and location accordingly. The discussion presented here is restricted to constant peak load duration curve and therefore size and location of the capacitors once decided need not be changed.

Effect of harmonics due to capacitor switching is neglected: Capacitors are considered to be constant VAR source and therefore the effect of harmonics due to capacitor switching is neglected.

## Simulation Model Development

MATLAB Simulink with power system block set is used for simulation of the system. The system is modeled into following subsystems.

### *Feeder Section and Load Subsystem Model*

Each feeder consists of number of feeder sections, which terminates at a bus where the load is connected. Each feeder section along with the bus and load is modeled into a subsystem. The feeder current is measured by the current measurement block, which is used to find power loss ($I^2R$) after converting into its RMS value. The voltage measurement block is used to measure bus voltage. The bus voltage, feeder current and power loss are sending to workspace for display purpose. A subsystem of load and feeder section is shown in Figure 4.

The power loss calculation subsystem consists of a product block and a constant block. The constant block represents the feeder section resistance. Total power loss in a system is a sum of power losses taking place in each feeder section.

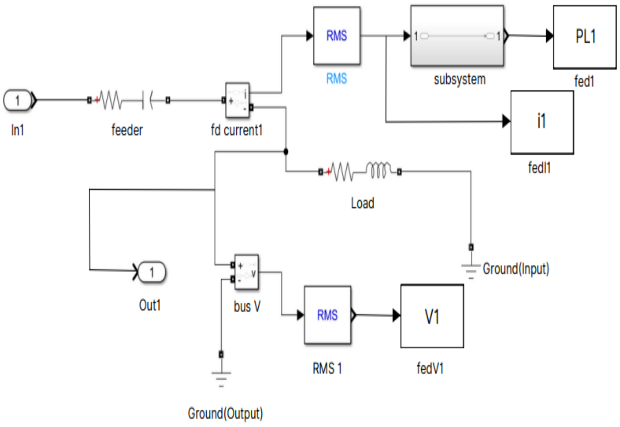

**Figure 4.** Subsystem of load and feeder section model

The power loss calculation subsystem consists of a product block and a constant block. The constant block represents the feeder section resistance. Total power loss in a system is a sum of power losses taking place in each feeder section.

### *Algorithm for Reconfiguration*

- Consider a given system configuration
- Simulate to find total power loss in the system
- Using available switching options, form all possible trees of a given configuration
- Simulate for each configuration and find out total power loss
- Check for constraints violation
- Select the configuration which gives the minimum loss in the system without violating any constraints.

### *Capacitor Bank Model*

The capacitor bank is modeled into a subsystem that finds out the capacitor reactive current, which is used to find optimum capacitor size. A subsystem of the capacitor bank is shown in Figure 5.

Following algorithm is used to find optimum size and location of capacitors.

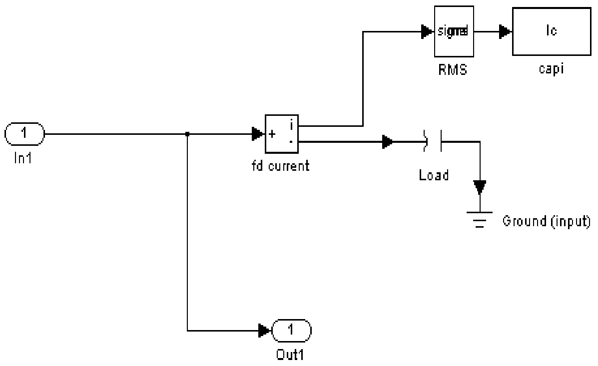

**Figure 5.** Subsystem of Capacitor Bank Model

## Algorithm for Capacitor Allocation and Sizing

- Consider a given system configuration.
- Run a simulation to find total power loss in the system.
- Connect a capacitor at a bus; vary its size in both directions till maximum loss saving obtained.
- Repeat the above steps for all buses in the system.
- The bus which gives maximum loss saving is the optimum location.
- The product of capacitive current and bus voltage gives the optimum size of the capacitor.

## Result and Discussion

The single line diagram of 11kV, 55-bus system is shown in Figure 3. The data of the system is obtained from original configuration. This system has total load of (1864.66 + j724) kVA per phase and total loss of the distribution feeder is 121.73 kW.

Following four cases are considered for loss reduction,
Case1: Feeder reconfiguration only.
Case2: Capacitor allocation only.
Case3: Fist capacitor placement and then reconfiguration
Case4: First reconfiguration and then capacitor placement

**Table 1.** Optimization Results

| Main Item | Original Configuration | Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|---|---|
| Switches status | - | (12,55) | - | (12,55) | (12,55) |
| Max bus Voltage(kV) | 11 | 11 | 11 | 11 | 11 |
| Min bus Voltage(kV) | 10.53 | 10.56 | 10.57 | 10.62 | 10.61 |
| Capacitor (kVAR) | | | | | |
| Feeder1 | - | - | 740 | 740 | 420 |
| Feeder2 | - | - | 500 | 500 | 500 |
| Feeder3 | - | - | 120 | 120 | 560 |
| Total power loss (KW) | 121.71 | 112.27 | 108.46 | 103.35 | 101.16 |
| Power loss reduction | - | 7.75 % | 10.88% | 15.08 % | 16.88 % |

Simulation results of the four cases considered above are summarized in a Table1.

For original system, the variation of bus voltage with respect to the number of buses and variation of feeder section loss with respect to feeder sections are shown in Figure 6(A) and 6(B). For the reconfigured system with feeder reconfiguration only; the variation of bus voltage with respect to the number of buses and variation of feeder section loss with respect to feeder sections are shown in Figure 7(A) and 7(B). For the original system with optimal capacitor allocation only; the variation of bus voltage with respect to the number of buses and variation of feeder section loss with respect to feeder sections are shown in Figure 8(A) and 8(B). For the reconfigured system with optimal capacitor allocation and then feeder reconfiguration; the variation of bus voltage with respect to the number of buses and variation of feeder section loss with respect to feeder sections are shown in Figure 9(A) and 9(B). For the reconfigured system with feeder reconfiguration first and then optimal capacitor allocation; the variation of bus voltage with respect to the number of buses and variation of feeder section loss with respect to feeder sections are shown in Figure 10(A) and 10(B). In each case with respect to original system the feeder loss found to be decrease whereas the bus voltage profile found to be improved. For capacitor allocation, using presented technique, first the location of the capacitor is determined and then optimal size of a singly located capacitor is evaluated for optimal loss saving without violating any constraint. The Figure 11, Figure 12 and Figure 13 represent the loss saving associated with the allocation of capacitors for all buses in the base system except the source bus. It can be realized from the graphs that the highest loss saving of 13.27 kW can be achieved by placing a capacitor of 246.66, 166.66, 40 kVAR for feeder1, feeder2 and feeder3 respectively.

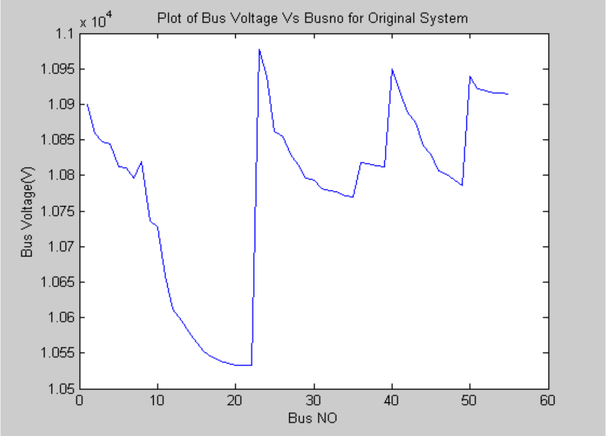

**Figure 6(A).** Variation of bus voltage with buses (Orig.)

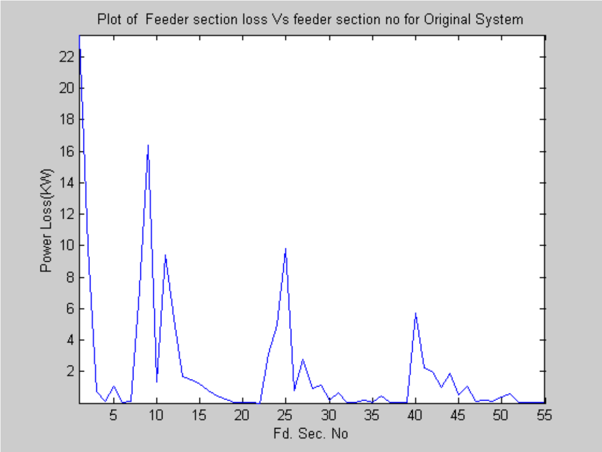

**Figure 6(B).** Variation of loss with feeder sections (Orig.)

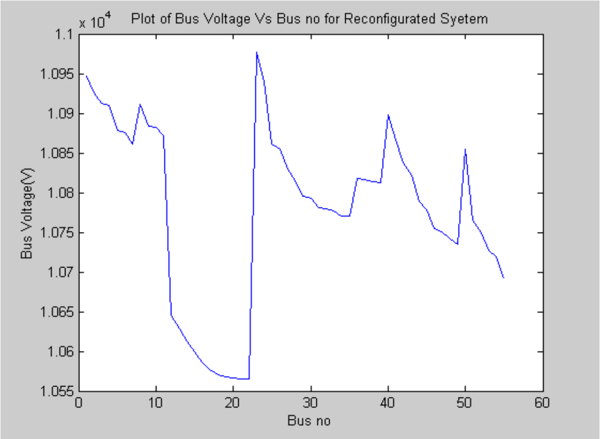

**Figure 7(A).** Variation of bus voltage with buses (Case 1)

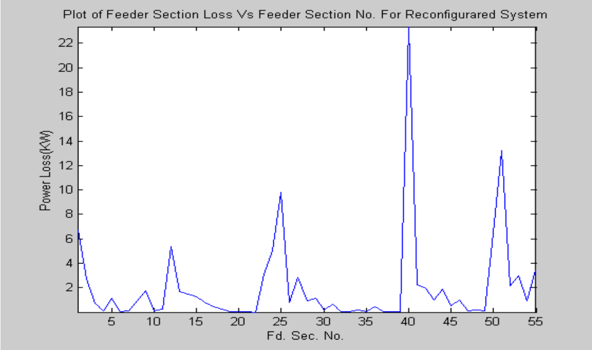

**Figure 7(B).** Variation of loss with feeder sections (Case 1)

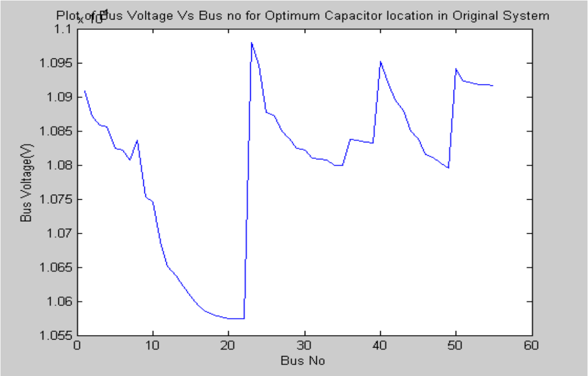

**Figure 8(A).** Variation of bus voltage with buses (Case 2)

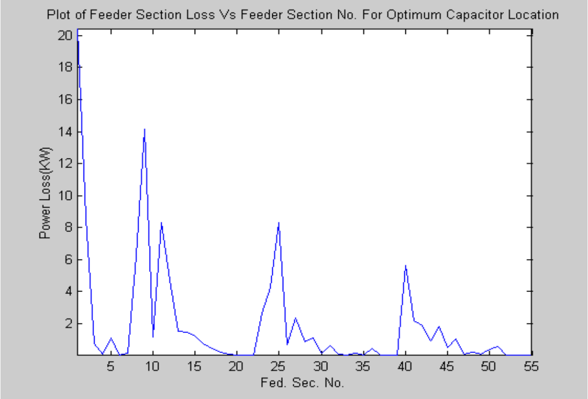

**Figure 8(B).** Variation of loss with feeder sections (Case 2)

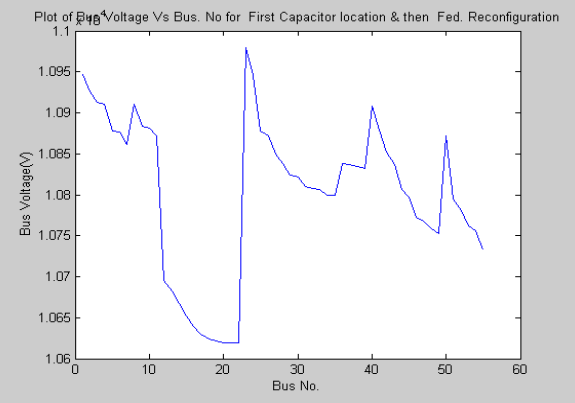

**Figure 9(A).** Variation of bus voltage with buses (Case 3)

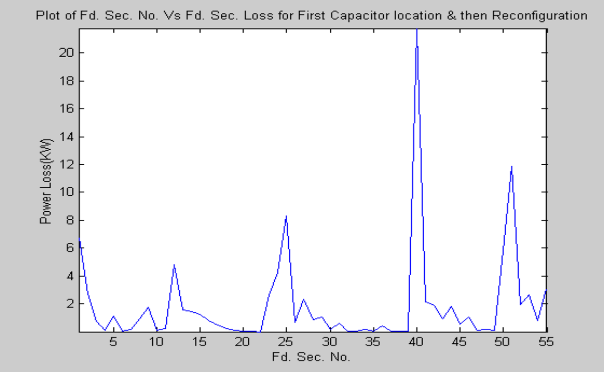

**Figure 9(B).** Variation of loss with feeder sections (Case 3)

**Figure 10(A).** Variation of bus voltage with buses (Case 4)

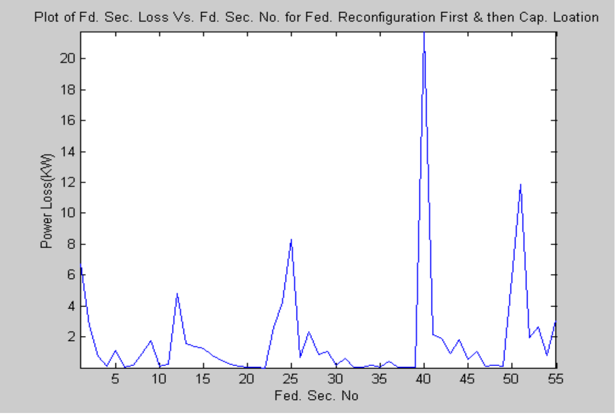

**Figure 10(B).** Variation of loss with feeder sections (Case 4)

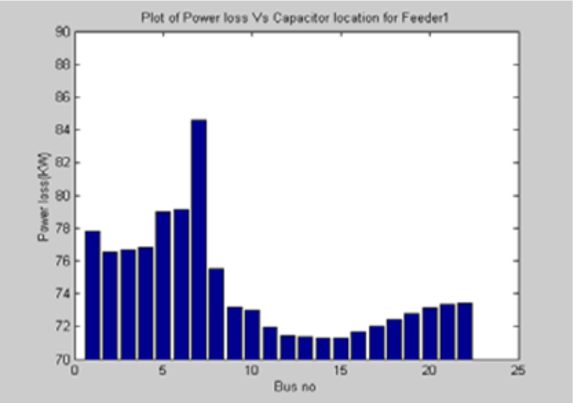

**Figure11.** Optimum Capacitor Location for Feeder1

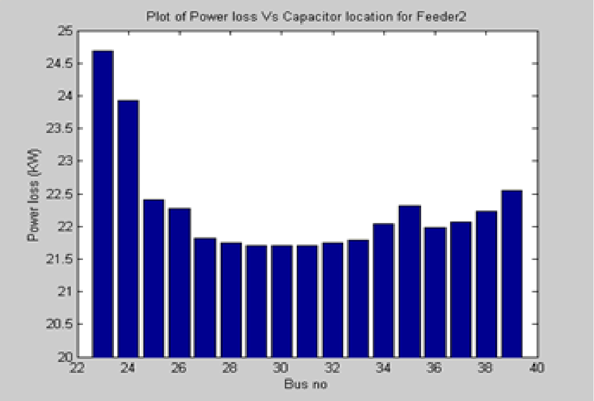

**Figure 12.** Optimum Capacitor Location for Feeder2

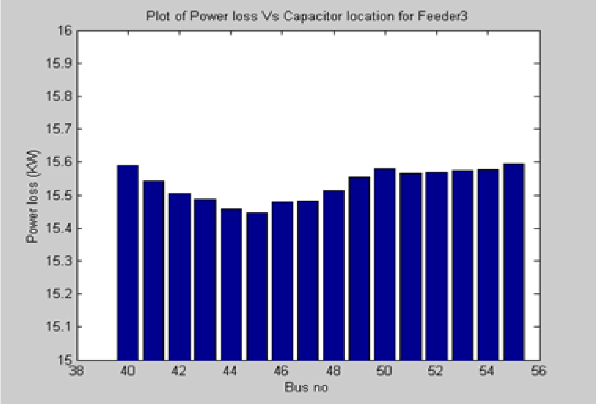

**Figure 13.** Optimum Capacitor Location for Feeder3

## *Energy and Cost Saving*

Loss reduction = Losses in original configuration– Losses in Case 4

= 121.71 – 101.16

= 20.55 kW

Annual Energy Saved = 20.55 * 8760 (hours of year)

= 180018 Units.

Consider per unit cost of Electrical Energy =Rs. 5.00

Total Rs. Saved per annual = 180018 * 5

= Rs. 900090

Total Rs. Saved per month

= Rs. 75007.50

Consider total initial cost for installation of capacitors (420 kVAR, 500 kVAR and 560 kVAR) = Rs. 120000.00

Assuming maintenance cost per annum of capacitors = Rs.25000.00

*The total payback period is less than two months and after that the saving of approximately Rs. 75000.00 per month will be achieved.*

# Conclusion

The presented work provides a technique to develop an algorithm which can be implemented in MATLAB or in any other software. This technique is highly useful to make an effective decision regarding the feeder configuration and capacitor allocation. From simulation studies, following few important conclusions are presented:

The power loss in distribution system can be greatly reduced by systematically reconfiguring the existing feeders in distribution network and by selecting proper location and size of capacitors. The total effect is depends on structure and size of distribution network.

The power loss reduction in a system is depends on number of switching operations perform for reconfiguration. Loss reduction rate increases with switching operations.

The formulated feeder reconfiguration and capacitor allocation problem does not violate any constraint. The voltage profile of the reconfigured network is found to be better as compared to original system.

The proposed method provided not only accurate and reliable but also it can calculate the price of kWh for the consumer service in case of budgetary reason.

The proposed method save lot of energy and it is highly recommended for distribution networks.

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**Publisher:** Chinese Institute of Automation Engineers (CIAE)

**ISSN:** 2223-9766 (Online)