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Power Loss Reduction in Radial Distribution Systems by Placing Optimal Capacitor Banks

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ABSTRACT: Decreasesthe power loss in distribution network by placing shunt capacitors, other advantages as improves the voltage and power factor. The power loss is more in distribution systems because it takes placeat totalconductors of distribution systems i.e., 30 % of the total power generation. The I^2R power loss in a radial distribution network, one method islessening thetotal network resistant path. It is difficult to reduce the length of the conductors because the distance from electrical substation to consumer loadis constant. This paperproposed a method is decrease the branch current, it comes from the source. It is achieved by placing the shunt capacitors in radial distribution network by compensate reactive power in the loads.This paper proposed a perspectiveto reduce the power lossin distribution systems by placing optimal capacitor banks. The location of capacitor banks are considering in shunt with the load.For estimating the profits Net Present Value (N.P.V) principle is used.Mixed integer programming model (MIP) is constructed for find out the optimal placement of capacitors. Maximises the Net Present Valueby considering the conditions those are voltage, reactive power and cost.The proposed method is used for IEEE-15 bus network. From the results of MATLAB simulation the proposing method is efficient, the power loss is minimized and a positive Net Present Value is obtained.

KEYWORDS: Power loss reduction, Reactive component of current, Capacitor banks, Net Present Value Criterion, Optimal Capacitor Banks placement by Maximizing the Net Present Value, Voltage Control by automatic switching of VAR to capacitor banks.

I.INTRODUCTION

Introduction: Thepower loss is in part with the distribution network. The power loss occurring at the conductors in a network [1] and it is 30% in total power generation. The power loss in line sections are 26% inthe transmission and distribution loss, 41% in distribution and sub transmission loss [8], the distribution networkoccupies 55% in totalpower loss.

Previous works: In terms of objective function, previous proposal for voltage limits exceeds [7]. Some methods are considering the investment in the project basis. Some methods on solution algorithms such asfuzzy &genetic algorithm [7], Benders decomposition [2],heuristic search [5],and tabu search [6].

Proposed method: The power loss is decreased by decreasing the current flown to the load side, because it decreases the branch current comesfrom the source.This paper proposed a method is placing the capacitor banks in shunt with the load. The estimating the profits by the capacitor placement, the Net Present Value (NPV) principle is used [8]. The aim is maximizing the Net Present Value (it includes capacitor purchasing, installing cost and operation and maintaining cost). The voltage limits is satisfied by an iterative process. The proposed method is analysed for IEEE-15 bus. The MATLAB simulation is given a better result.

II.DIRECT CALCULATION OF POWER LOSS IN RADIAL NETWORKS

2.1 Introduction to the power loss caused by the real and reactive currents

A line or branch in distribution network is electrically modelled as Fig.2.1,

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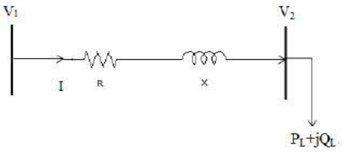

Fig. 2.1 single line diagram of distribution line

Where, I is the current flowing of the line, resistance R, resistance X, V_1 and V_2 voltages at sending and receiving ends of line. The power loss is splitting into two parts i.e., real part of current I_R and reactive or imaginary part of the currentI_X. Therefore, the power loss is

$$P_{Loss} = \left(I_R^2 + I_X^2\right)\cdot R$$

$$= I_R^2 \cdot R + I_X^2 \cdot R = P_{Loss,R} + P_{Loss,X} \qquad (1)$$

The power loss for distribution line (Fig. 2.1) is

$$P_{Loss} = P_{Loss,R}\left(i,i+1\right) + P_{Loss,X}\left(i,i+1\right)$$

$$= \left(\frac{P_i}{V_i}\right)^2 \cdot R_{i,i+1} + \left(\frac{Q_i}{V_i}\right)^2 \cdot R_{i,i+1} \qquad (2)$$

Equation (2),the power loss in line section is nothing but the summation of power loss due real part of current and power loss caused by the reactive current. The capacitor banks are directly compensating the reactive power demand and therefore the power loss is decreased.

2.2 Derivation for power loss caused by real and reactive currents

This paper, the network is assuming that, 3-phase balanced and absent incurrent harmonics.

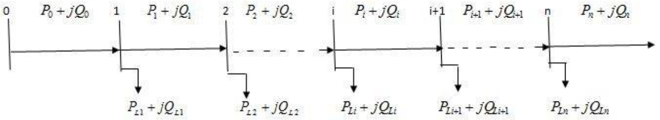

Fig.2.2 one line diagram for feeder in distributing system

From Fig.2.2,$P_{Loss,R}$ is power loss due to real part of current, $P_{Loss,X}$ is the power loss caused by reactive part of current and are as follows.

$$P_{Loss,R}\left(i,i+1\right) = \left(\frac{P_i}{V_i}\right)^2 \cdot R_{i,i+1} \qquad (3)$$

$$P_{Loss,X}\left(i,i+1\right) = \left(\frac{Q_i}{V_i}\right)^2 \cdot R_{i,i+1} \qquad (4)$$

Where, resistance of line $R_{i,i+1}$ between bus i and bus i+1, voltage V_i for busi, total real powers P_i flowsthrough node i and total reactive powers Q_i flows through node i and it is calculated as

$$P_i = \sum_{n=i+1}^{N} P_{Ln} \qquad (5)$$

$$Q_i = \sum_{n=i+1}^{N} Q_{Ln} \qquad (6)$$

Where, P_{Ln}, Q_{Ln} are active power andimaginary powersof the load at bus n. The total real power loss due to realpower load is

$$P_{\substack{Loss,R\\Total}} = \sum_{i=0}^{N-1} P_{Loss,R}(i,i+1) = \sum_{i=0}^{N-1} \left(\frac{\sum_{n=i+1}^{N} P_{Ln}}{V_i} \right)^2 \cdot R_{i,i+1} \tag{7}$$

The total active power loss due to reactive power demandis

$$P_{\substack{Loss,X\\Total}} = \sum_{i=0}^{N-1} P_{Loss,X}(i,i+1) = \sum_{i=0}^{N-1} \left(\frac{\sum_{n=i+1}^{N} Q_{Ln}}{V_i} \right)^2 \cdot R_{i,i+1} \tag{8}$$

Where, P_{Ln}, Q_{Ln} andV_i are determined by running load flow study. In this project, the newton raphson method of load flow study is conducted. The total active power loss $P_{\substack{Loss\\Total}}$ caused by real part of current and reactive part of current can be calculated as

$$P_{\substack{Loss\\Total}} = P_{\substack{Loss,R\\Total}} + P_{\substack{Loss,X\\Total}} \tag{9}$$

Therefore, the total active power loss $P_{\substack{Loss\\Total}}$ is the sum of total active power loss due to real part of the current $P_{\substack{Loss,R\\Total}}$ and total active power loss due to the reactive part of current $P_{\substack{Loss,X\\Total}}$ .The annualcost (rupees) due to the total active power loss is

$$C_t = P_{\substack{Loss\\Total}} \cdot F_{Loss} \cdot K_E \times 8760 \tag{10}$$

Where, unit energy pricesK_E (rupees/kWh) and the power loss factor F_{Loss} which is the ratio of the average power loss and the peak power loss.

$$F_{Loss} = \frac{\bar{P}_{Loss,X}}{\hat{P}_{Loss,X}} \tag{11}$$

The power loss at each time point is analysed by running power flow. $\hat{P}_{Loss,X}$ is the peak power loss at the peak load point and $\bar{P}_{Loss,X}$ is the average power loss of all of the time points [8].

2.3 Derivation for Power loss caused by real and reactive currents with capacitor placement

Fig. 2.3 has shown the capacitor banksare installingat the receiving end node and in shunt with the load, the active power flowing out the node did not reduced by the capacitor placement. The active power loss caused by real part of current with capacitor placing is same as the active power loss due to real part of current before compensation.

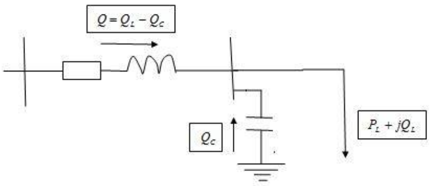

Fig. 2.3 Reactive power balance for after capacitor placement at the bus

The active power loss due to real component of current after capacitor bank installation becomes $P'_{\underset{Total}{Loss,R}}$.

$$P'_{\underset{Total}{Loss,R}} = \sum_{i=0}^{N-1}\left(\frac{\sum_{n=i+1}^{N} P_{Ln}}{V_i}\right)\cdot R_{i,i+1} = P_{\underset{Total}{Loss,R}} \tag{12}$$

When the capacitor banks are installed at receiving end node and in shunt with the load, the reactive power flowing through the node is reducing by placing the capacitors. The active power loss due to reactive part of the current after capacitor bank installation becomes $P'_{\underset{Total}{Loss,X}}$.

$$P'_{\underset{Total}{Loss,X}} = \sum_{i=0}^{N-1}\left(\frac{\sum_{n=i+1}^{N}\left(Q_{Ln} - L_i \cdot Q_C \cdot X_i\right)}{V_i}\right)\cdot R_{i,i+1} \tag{13}$$

Where, Q_C is the capacitor capacity per unit size, L_i is integer variable denotes the number of the capacitor modules in a capacitor banks and X_i is the binary indication variable indicating whether to installing the capacitor bank at node i(1:yes;0:no). The product of L_i, Q_C, and X_i is reactive power compensation capacity at the node.

$$P'_{\underset{Total}{Loss}} = P'_{\underset{Total}{Loss,R}} + P'_{\underset{Total}{Loss,X}} \tag{14}$$

Therefore, the totalactive power loss for after capacitors installation $P'_{\underset{Total}{Loss}}$ is equals to the sum of the total active power loss due to real part of currents $P'_{\underset{Total}{Loss,R}}$ and the total active power loss due to reactive part of the currents $P'_{\underset{Total}{Loss,X}}$.

III. MODEL FORMULATION

3.1 Net Present Value (NPV) Analysis

After the capacitor banks installed, the total real power loss $P'_{\underset{Total}{Loss}}$ cost in rupees per annum is

$$C'_t = P'_{\underset{Total}{Loss}} \cdot F_{Loss} \cdot K_E \times 8760 \tag{15}$$

The annual savings after capacitors placement is

$$b_t = C_t - C'_t \tag{16}$$

Therefore the Operating and Maintenance costs OM_t of the capacitor banks are considered, the net annual profit

$$B_t = b_t - OM_t \tag{17}$$

The annual operating and maintenance cost of capacitors for the distribution network, OM_t is calculated as

$$OM_t = \sum_{i=1}^{N} X_i \cdot K_o \tag{18}$$

Where, K_O is the annual operating and maintenance cost (rupees) of capacitors of each bus. Therefore the Net Present Value is calculated as

$$NPV = \sum_{t=1}^{T}\frac{B_t}{(1+d)^t} - IO \tag{19}$$

$$IO = IC + PC \tag{20}$$

Where, IC is the installation cost of capacitors for given distribution network, PC is the purchase cost of capacitors for given radialdistribution network. The installation cost of capacitors for given distribution network is

$$IC = \sum_{i=1}^{N} X_i \cdot K_I \tag{21}$$

Where, K_I is installation cost of capacitor banks for each bus in radial distribution network.

3.2 Capacitor cost function

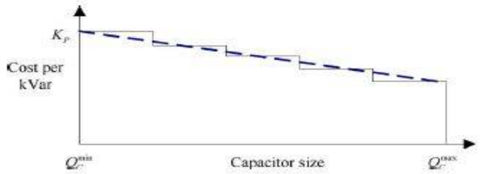

Fig. 3.1 Capacitor cost function

The purchasing cost of capacitors for given distribution network, can be ca1culated as

$$PC = \sum_{i=1}^{N} L_i \cdot X_i \cdot \left(K_P - \gamma \cdot L_i\right) \tag{22}$$

To considering the varying purchasing cost of capacitors depending on the capacitors unit size, the capacitors purchasing cost function isapproximately a linear dash line shown in Fig.3.1. The other parameters of equation (22) are given in table I.

3.3 Model formulation and solution

For maximizing the Net Present Value subjected to certain conditions to obtaining the maximum profits in terms of initial investment and the profits. The representation of model is

$$\text{Max } NPV = \sum_{t=1}^{T} \frac{\left(C_t - C_t^{'}\right) - OM_t}{\left(1+d\right)^t} - \left(PC + IC\right) \tag{23}$$

Subjected to following conditions,

- For size of the capacitor is fixed:

$$0 \le L_i \cdot Q_C \cdot X_i \le Q_{Li}^{\min} \tag{24}$$

- For size of the capacitor is controlled:

$$Q_{Li}^{\min} \le L_i \cdot Q_C \cdot X_i \le Q_{Li}^{\max} \tag{25}$$

The constraint (24) means, if size of the capacitor is fixed, the capacity of capacitor must be less than the minimum reactive power load at the bus i and (25) means, if size of the capacitor is controlled.

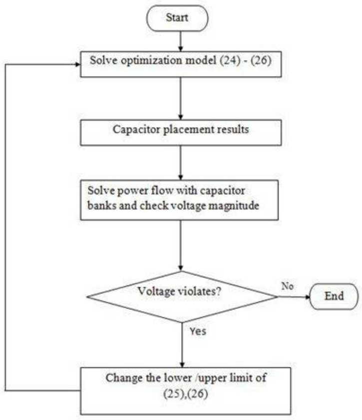

Fig. 3.2 Flow chart for satisfying the voltage limits

We have rewritten the model to a Mixed Integer Quadratic Programmingmodel formulation (MIQP);it iseasier to solving the model. Then the binary decision variable in (13) and (22) is eliminated and constraints (24) and (25) have rewritten as

$$0 \le L_i \cdot Q_C \le Q_{Li}^{\min} \cdot X_i \tag{26}$$

$$Q_{Li}^{\min} \cdot X_i \le L_i \cdot Q_C \le Q_{Li}^{\max} \cdot X_i \tag{27}$$

Therefore, the model becomes a MIQP. It must be noticed to the voltage limits are not strightly including in the problem. But, the limits of voltage magnitudes are satisfied by an iterative method showed in Fig. 3.2. Generally, the voltage boosting is rather limited because the size of capacitor is constrained by (24) and (25). From Fig. 3.2,once the optimizing results are obtaining, then the load flow simulations are performed for examining if the overvoltage occurs. If the voltage limit is exceeded, then the voltage magnitude is regulating to normal voltage level by adjusting during the capacitor installing time. The voltage is regulated and thenit is necessary to changes constraints (24) and (25) by a smaller or upper limit and then resolve the optimizing model. This approach iterates until all of the voltage limits are satisfied.

3.4 Operational control of capacitor banks

The installing of capacitors to the radial distribution network is simplefor operational controlfor the capacitors. The controlling of the capacitor banks is to maximizing the power loss reduction by switching the capacitors as for the reactive power demand sensed by controller [2]. An easyswitching strategy is shown in Fig.3.2.

Operation1 control ru1e

- **For $Q_{Ci} < Q_{Li}$**

Switch up to a tap that minimizes $|Q_{Ci} - Q_{Li}|$.

- **For $Q_{Ci} > Q_{Li}$**

Switch down to a tap that minimizes $|Q_{Li} - Q_{Ci}|$.

Here, Q_{Li} is the reactive power load at bus i, sensed by the controller, and Q_{Ci} is the reactive for of the capacitor bank. This control strategy is minimizing the reactive current of each bus,isalmost minimizes the reactive component of currents of line and loads.

IV. SIMULATION RESULTS

The proposed method is applied for power loss decrement of IEEE-15 bus. The simulation is conducted in a 64 bit PC with 2.50 GHz CPU, 4 GB RAM with MATLAB software is used to solve the optimization model. The base capacity is 100 MW and base voltage of 1l kV for IEEE-15 bus radial distribution network. At bus 1 the voltage is 1.000 p.u., the parameters are considered in this model are given in Table I. The parameters of Table I does not reflecting ground reality of the IEEE-15 bus distributing network.

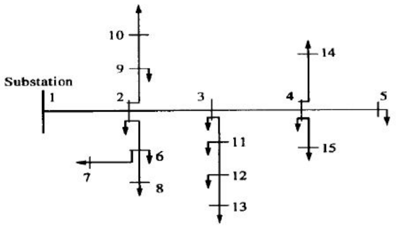

Fig. 4.1 Single line diagram of IEEE-15 bus radial distribution system

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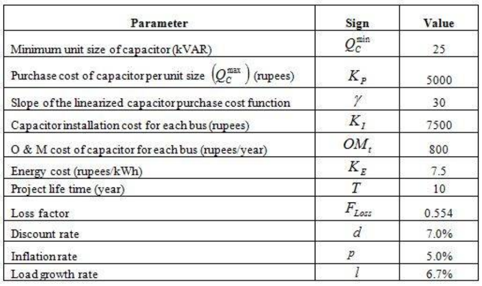
TABLE I
PARAMETERS IN CALCULATION



Parameter	Sign	Value
Minimum unit size of capacitor (kVAR)	Q_C^{min}	25
Purchase cost of capacitor per unit size $\left(Q_C^{max}\right)$ (rupees)	K_P	5000
Slope of the linearized capacitor purchase cost function	γ	30
Capacitor installation cost for each bus (rupees)	K_I	7500
O & M cost of capacitor for each bus (rupees/year)	OM_t	800
Energy cost (rupees/kWh)	K_E	7.5
Project life time (year)	T	10
Loss factor	F_{Loss}	0.554
Discount rate	d	7.0%
Inflation rate	p	5.0%
Load growth rate	l	6.7%

From TABLE II, the lowest voltage is at bus 13 is 0.94438 p.u for before compensation and 0.96098 p.u for after capacitor placement. The network improves the voltage profile with the capacitor banks, overvoltage is does not occurred. The power factor is 0.7001 lagging for before compensation and is 0.8735 lag for after compensation. Therefore, the power factor for the IEEE-15 bus network is improved and the total active power loss due to reactive part of current for before compensation is 31.4312 kW and after compensation it is 4.8454 kW. So the total real power loss is 61.7855 kW and 33.7281 kW for before and after compensation respectively. Therefore, 28.0574 kW of power loss is reduced with the compensation by total injecting the capacity of 725 kVARis used to installing with 7-buses with minimum rating of capacitor capacity is 25 kVAR.

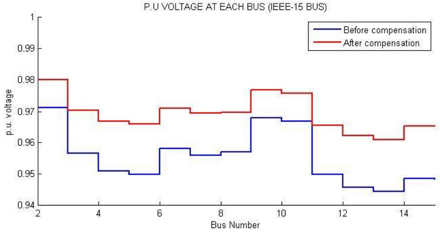


Fig. 4.2 Voltage magnitudes variation for each bus in IEEE-15 bus network

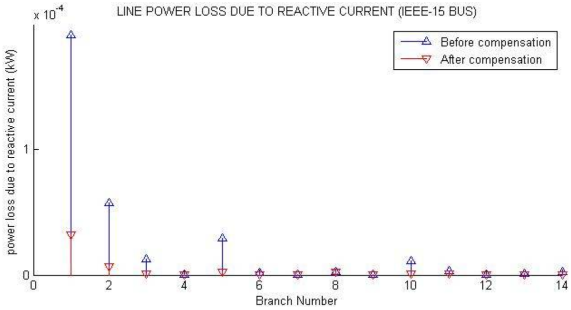


Fig. 4.3 Line active power loss due to reactive component of currentfor IEEE-15 bus network in each bus

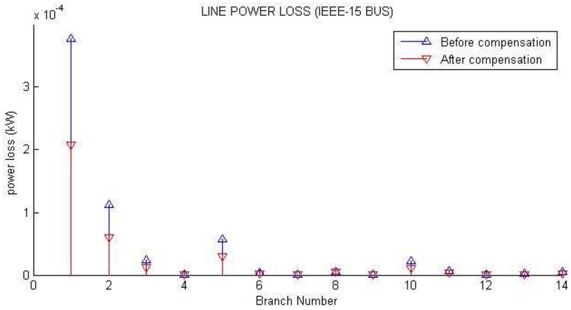
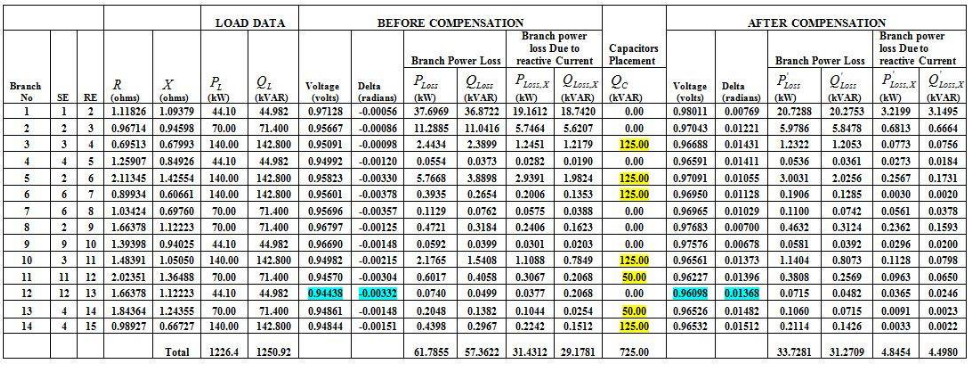


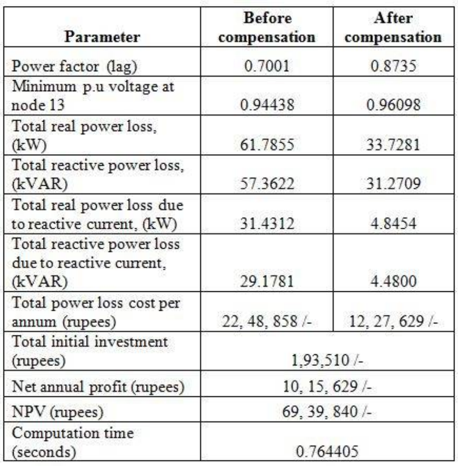
Fig. 4.4 Line active power loss for IEEE-15 bus network in each bus

TABLE II
Load Flow analysis for IEEE-15 bus Network



					LOAD DATA		BEFORE COMPENSATION							AFTER COMPENSATION						
									Branch Power Loss		Branch power loss Due to reactive Current		Capacitors Placement			Branch Power Loss		Branch power loss Due to reactive Current	
Branch No	SE	RE	R (ohms)	X (ohms)	P_L (kW)	Q_L (kVAR)	Voltage (volts)	Delta (radians)	P_{Loss} (kW)	Q_{Loss} (kVAR)	$P_{Loss,X}$ (kW)	$Q_{Loss,X}$ (kVAR)	Q_C (kVAR)	Voltage (volts)	Delta (radians)	P'_{Loss} (kW)	Q'_{Loss} (kVAR)	$P'_{Loss,X}$ (kW)	$Q'_{Loss,X}$ (kVAR)
1	1	2	1.11826	1.09379	44.10	44.982	0.97128	-0.00056	37.6969	36.8722	19.1612	18.7420	0.00	0.98011	0.00769	20.7288	20.2753	3.2199	3.1495
2	2	3	0.96714	0.94598	70.00	71.400	0.95667	-0.00086	11.2885	11.0416	5.7464	5.6207	0.00	0.97043	0.01221	5.9786	5.8478	0.6813	0.6664
3	3	4	0.69513	0.67993	140.00	142.800	0.95091	-0.00098	2.4434	2.3899	1.2451	1.2179	125.00	0.96688	0.01431	1.2322	1.2053	0.0773	0.0756
4	4	5	1.25907	0.84926	44.10	44.982	0.94992	-0.00120	0.0554	0.0373	0.0282	0.0190	0.00	0.96591	0.01411	0.0536	0.0361	0.0273	0.0184
5	2	6	2.11345	1.42554	140.00	142.800	0.95823	-0.00330	5.7668	3.8898	2.9391	1.9824	125.00	0.97091	0.01055	3.0031	2.0256	0.2567	0.1731
6	6	7	0.89934	0.60661	140.00	142.800	0.95601	-0.00378	0.3935	0.2654	0.2006	0.1353	125.00	0.96950	0.01128	0.1906	0.1285	0.0030	0.0020
7	6	8	1.03424	0.69760	70.00	71.400	0.95696	-0.00357	0.1129	0.0762	0.0575	0.0388	0.00	0.96965	0.01029	0.1100	0.0742	0.0561	0.0378
8	2	9	1.66378	1.12223	70.00	71.400	0.96797	-0.00125	0.4721	0.3184	0.2406	0.1623	0.00	0.97683	0.00700	0.4632	0.3124	0.2362	0.1593
9	9	10	1.39398	0.94025	44.10	44.982	0.96690	-0.00148	0.0592	0.0399	0.0301	0.0203	0.00	0.97576	0.00678	0.0581	0.0392	0.0296	0.0200
10	3	11	1.48391	1.05050	140.00	142.800	0.94982	-0.00215	2.1765	1.5408	1.1088	0.7849	125.00	0.96561	0.01373	1.1404	0.8073	0.1128	0.0798
11	11	12	2.02351	1.36488	70.00	71.400	0.94570	-0.00304	0.6017	0.4058	0.3067	0.2068	50.00	0.96227	0.01396	0.3808	0.2569	0.0963	0.0650
12	12	13	1.66378	1.12223	44.10	44.982	0.94438	-0.00332	0.0740	0.0499	0.0377	0.2068	0.00	0.96098	0.01368	0.0715	0.0482	0.0365	0.0246
13	4	14	1.84364	1.24355	70.00	71.400	0.94861	-0.00148	0.2048	0.1382	0.1044	0.0254	50.00	0.96526	0.01482	0.1060	0.0715	0.0091	0.0023
14	4	15	0.98927	0.66727	140.00	142.800	0.94844	-0.00151	0.4398	0.2967	0.2242	0.1512	125.00	0.96532	0.01512	0.2114	0.1426	0.0033	0.0022
				Total	1226.4	1250.92			61.7855	57.3622	31.4312	29.1781	725.00			33.7281	31.2709	4.8454	4.4980

TABLE III
Summary of Optimization Results for IEEE-15 busRadial Distribution Network



Parameter	Before compensation	After compensation
Power factor (lag)	0.7001	0.8735
Minimum p.u voltage at node 13	0.94438	0.96098
Total real power loss, (kW)	61.7855	33.7281
Total reactive power loss, (kVAR)	57.3622	31.2709
Total real power loss due to reactive current, (kW)	31.4312	4.8454
Total reactive power loss due to reactive current, (kVAR)	29.1781	4.4800
Total power loss cost per annum (rupees)	22, 48, 858 /-	12, 27, 629 /-
Total initial investment (rupees)	1,93,510 /-	
Net annual profit (rupees)	10, 15, 629 /-	
NPV (rupees)	69, 39, 840 /-	
Computation time (seconds)	0.764405	

TABLE III summarizes the optimization results. From the economic view, the investment to the project is1,93, 510 /- rupees, the net profit is 10, 15, 629 /- rupees per year, the Net Present Valueis 69, 39, 840 /- rupees per period of the project, so the project is adding a net value of 69, 39, 840 /- rupees to the utility for the period of ten years. And also, the proposing method is good for computationally, as the time taken to solve for themodel is 0.764405 seconds only in MATLAB simulation.

V. CONCLUSIONS

For reducing the power loss, the proposed method given best result. The problem is maximizing the Net Present Value subjected to certain constraints i.e., voltage, reactive power and cost and is formulatingthe Mixed Integer Programming modelfor directly analysing the power loss for given IEEE-15 bus network. The model is solving by using MATLAB software for more efficiently. The simulation results given that the power loss of the network is effectively reduced and obtains the Net Present Value is positive and largeand is adding to the utilitywith this method and also the voltage and power factor are improved.

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