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ANALYSIS OF VOLTAGE IMPROVEMENT TECHNIQUES AND IMPACT OF ZIP LOAD MODEL ON A RADIAL UNBALANCED DISTRIBUTION NETWORK

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Abstract— Distribution networks are not perfectly balanced all time due to the nature of dynamic loads in the system. High energy demand due to variety of loads makes distribution system to be highly unbalanced. Unbalanced distribution systems have fluctuating voltage profile but we need flat voltage profile for smooth operation and loss minimization in our network. There are several techniques which have been proposed to improve the voltage profile of unbalanced distribution system. In this paper, various modelling techniques and their applications have been examined. Also, voltage profile improvement technique for unbalanced distribution system is discussed. Effect of ZIP load model have also been seen on the proposed system. IEEE 13 bus radial distribution system is taken for study purpose.

Keywords— Distribution system; Newton Raphson; Particle swarm optimization (PSO); Voltage control algorithm (VCA); Voltage stability index.

I. INTRODUCTION

Demand for electricity is increasing nowadays as many devices are required to run with electrical energy. The electricity consumption increases during daily or annually peak periods. Aging infrastructures and limitation on power transfer through transmission and distribution networks increase the need for installation of new sources closer to the consumers rather than investment in new centralized power plants or expansion of power networks. Due to increase in demand of electricity, loads are increasing at industrial and commercial level. Therefore, various dynamic loads like power electronics devices (thyristor, BJT, MOSFET etc.) have also come into picture which inject harmonics in system. Harmonic makes disturbance in the system because of their nonlinear and dynamic characteristic [1]**.** These loads are connected from generating power station to consumer point and classified as two types of network - transmission and distributed network [2]. Transmission network is connecting generating power station to electrical substation, in the same way distribution network is also making link between electrical subsystem and consumer. Ring main distribution system and radial distribution system are the two types of distribution system. These are used according to their requirements [3]**.** Distribution systems can be balanced or unbalanced according to their usage. Balanced distribution system can be converted into single phase equivalent system [4]. But it is difficult to convert unbalanced system into a single phase equivalent system because of its exhibiting components. Normally unbalanced distribution system is considered for load modelling because consumers generally use unbalanced load for their residential and commercial purposes

Recently variety of distributed loads has been increased so analysis and configuration [5] of distribution system also has changed. Load flow analysis require configuration of the distribution system. Modelling of distribution system plays a crucial role in analysing load flow calculation. Nowadays modelling is done according to balanced or unbalanced distribution system. Unbalanced distribution system is more crucial because most of the consumer uses unbalanced load. R/X ratio of unbalanced distribution networks is high so it is difficult to implement fast Decoupled method and Newton Raphson method [6]. Newton Raphson and fast Decoupled method require mesh connection and low R/X ratio which is difficult to find in distribution system [4]. So, it can be concluded that it is hard to solve unbalanced distribution system (UDS) by using Gauss Seidel, Newton Raphson and Fast Decoupled Load Flow (FDLF) method. Backward/forward sweep method is one of the suitable methods to provide solution of load flow of unbalanced distribution system. J. A. Michline Rupa [10] has shown in his paper that how backward/forward sweep (BFS) method is implemented in IEEE33 bus system. Power calculation of each branch is done by backward sweep method and voltage at each node is obtained from forward sweep method [10]. A comparison between FDLF and BFS method has also been observed in paper [7]. Use of Fast Decoupled method in distribution system is difficult but Axis Rotation Fast Decoupled Load Flow (ARFDLF) can be used in place of FDLF method for viable solutions. Novel Load Impedance Matrix [LIM] is proposed in paper [8] which gives voltage at the buses in single step. Backward/Forward sweep method involves two steps to obtain voltages whereas conventional methods require more number of iterations to determine the same. But no. of steps in LIM method is less than in comparison to BFS method and gives same nodal voltages. Nodal voltages at any iteration may be calculated directly from the values obtained in the previous iteration by using Load Impedance Matrix. G.K.

Viswanadha Raju [12] proposed a well-defined two stage approach to minimise active power losses in distribution system. In this method, firstly he closed all switches of network for calculating the current obtained by power source and then opened them one by one in sequential manner so that current can be found in each branch. In second stage, branch exchange operation is done for calculation of current in next iteration. There are number of DGs integrated for fast power solutions in distributed load networks at different places.

Further in this paper, various models of distribution system is described in detail in section II. Then, results of various voltage improvement techniques along with the impact of ZIP load model in unbalanced distribution system are analysed in section III. Finally, conclusion of paper is given in brief in section IV.

II. Modelling Of Distribution System

Modelling of distribution system components and their proper placement in the network is key factor of electricity used by consumers. Poor modelling affects power and voltage quality (waveforms) which in turn increases energy losses in the system. So, it would be necessary to properly model the components like line, load, shunt capacitor, and transformer in distribution system.

A. Line Modelling

Lines are one of the important components in distribution system modelling. It can be overhead or underground line. It becomes necessary to determine series and shunt impedance of the line before doing modelling of any distributed system. J. Carson developed several equations for computing self and mutual impedances of unbalance distributed line in his paper. Physical layout of Carson's concept has been shown in Fig. 1.

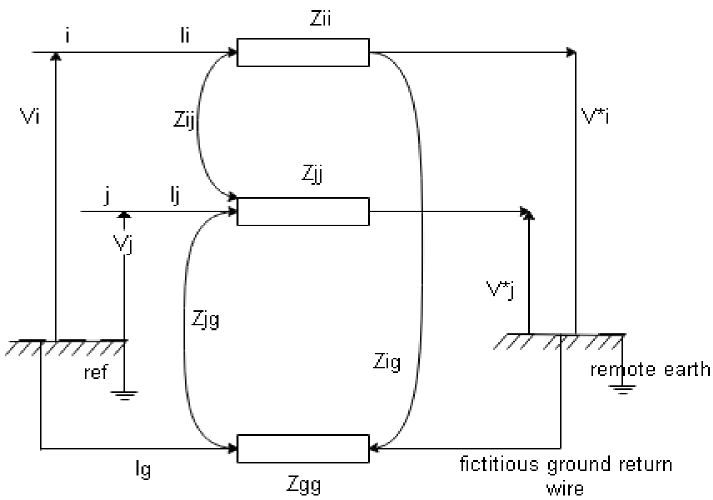

Fig. 1 Physical Layout of Carson's Theory

He represented line with one end of conductor connected to source and other end grounded with earth. Grounded conductor becomes path for returning unbalance currents. It is assumed that earth has uniform surface with constant resistivity therefore any effect from neutral grounding is neglected [9].

If frequency=60 Hz and earth resistivity=100 Ohm per meter. Approximated Carson's self (z_{ii}) and mutual (z_{ij}) impedances are:

$$z_{ii} = r_i + 0.09530 + j0.12134 \left(ln \frac{1}{GMR_i} + 7.93402 \right) \text{ Ohm/mile} \quad (1)$$

$$z_{ij} = 0.09530 + j0.12134 \left(ln \frac{1}{D_{ij}} + 7.93402 \right) \text{ Ohm/mile} \quad (2)$$

Where,

GMR_i = Geometrical mean radius of conductor

D_{ij} = Geometrical mean distance of conductor

After calculating impedances, impedance matrix $[Z_{abc}]$ is designed and with help of this matrix, voltage and current matrices of line are given below.

Voltage matrix at node 'n',

$$[VLG_{ABC}]_n = [a].[VLG_{abc}]_m + [b_t].[I_{abc}]_m L \quad (3)$$

Where,

$$[a] = [U] + \frac{1}{2}[Z_{abc}].[Y_{abc}] \quad (4)$$

$$[b] = [Z_{abc}] \quad (5)$$

Current matrix -

$$[I_{abc}]_n = [c].[VLG_{abc}]_m + [d].[I_{abc}]_m \quad (6)$$

Where,

$$[c] = [Y_{abc}] + \frac{1}{4}[Y_{abc}].[Z_{abc}].[Y_{abc}], \quad (7)$$

$$[d] = [U] + \frac{1}{2}[Z_{abc}].[Y_{abc}] \quad (8)$$

Voltage required at node m is the function of voltage at node n and current at node m.

Voltage matrix at node 'm',

$$[VLN_{abc}]_m = [A_t].[VLN_{ABC}]_n - [B_t].[I_{abc}]_m \quad (9)$$

Where,

$$[A_t] = [a_t]^{-1}, \quad (10)$$

$$[B_t] = [a_t]^{-1}.[b_t] \quad (11)$$

Shunt calculation requires conductance and susceptance. Conductance is neglected when it is compared with susceptance. Susceptance calculation is done in similar way that of inductance in series impedance section.

B. Line Modelling

There are various types of load combination which can be modelled in terms of constant ZIP (impedance, current and power) or different combination of constant ZIP. Current is controlling parameter because it can be controlled in effective and efficient way as compared to any other parameter. Modelling equations in current parameter terms for constant impedance, constant current, and constant power load models are given as-

1). Constant Impedance:

$$Z_{a,b,c} = \frac{|V_{a,b,c}|^2}{S_{a,b,c}^*} = \frac{|V_{a,b,c}|^2}{|S_{a,b,c}|}\angle\theta_{a,b,c} \quad (12)$$

$$= |Z_{a,b,c}|\angle\theta_{a,b,c} \quad (13)$$

$$IL_{a,b,c} = \frac{V_{a,b,c}}{Z_{a,b,c}} = \frac{|V_{a,b,c}|}{|Z_{a,b,c}|}\angle(\delta_{a,b,c} - \theta_{a,b,c}) \quad (14)$$

$$= |IL_{a,b,c}|\angle\alpha_{a,b,c} \quad (15)$$

2). Constant Current:

$$IL_{a,b,c} = |IL_{a,b,c}|\angle(\delta_{a,b,c} - \theta_{a,b,c}) \quad (16)$$

$$= |IL_{a,b,c}|\angle\alpha_{a,b,c} \quad (17)$$

3). Constant Power:

$$|S_{a,b,c}|\angle\theta = P_{a,b,c} + jQ_{a,b,c} \quad (18)$$

$$IL_{a,b,c} = \left(\frac{S^{a,b,c}}{V^{a,b,c}}\right)^* = \frac{|S_{a,b,c}|}{|V_{a,b,c}|}\angle(\delta_{a,b,c} - \alpha_{a,b,c}) \quad (19)$$

$$= |IL_{a,b,c}|\angle(\alpha_{a,b,c}) \quad (20)$$

And

$$V_{a,b,c} = |V_{a,b,c}|\angle\delta_{a,b,c} \quad (21)$$

Where,

$V_{a,b,c}$ is voltage of three phase load, $IL_{a,b,c}$ is line current of three phase load, $S_{a,b,c}$ is complex power of load, $P_{a,b,c}$ is active power, $Q_{a,b,c}$ is reactive power, $\delta_{a,b,c}$ is line-to-neutral voltage angles, $\alpha_{a,b,c}$ is diff. angle between line to neutral and power factor angle, $\theta_{a,b,c}$ is power factor, and $Z_{a,b,c}$ is impedances of load.

All of these load models are included in load file for calculation purpose.

C. Shunt Capacitor Modelling

Shunt capacitor provides reactive power in distribution system to improve voltage levels and to minimise requirement of reactive power demand. Modelling of Wye- Connected Capacitor bank is done by using following equations.

1). Wye- Connected Capacitor:

Susceptance (B_c) for each unit is

$$B_c = \frac{Kvar}{kV_{LN}^2 \cdot 1000} \text{S} \quad (22)$$

And,

$$IC_a = jB_a \cdot V_{an} \quad (23)$$

$$IC_b = jB_b \cdot V_{bn} \quad (24)$$

$$IC_c = jB_c \cdot V_{cn} \quad (25)$$

Where, IC_a, V_{an} are phase current and phase voltage respectively. In our system, Wye connected capacitor bank is considered for load flow solution.

D. Transformer Modelling

Transformers are required to transfer voltage from transmission level to distribution feeder level. These are classified as stepping up, stepping down and phase shifting type transformers. There are different transformers combinations which can be used in radial distribution system as below-

1. D–Grounded Y
2. Open Y–Open D
3. Grounded Y–Grounded Y
4. Ungrounded Y–D
5. D–D

Where,
Y= star, and D= delta.

In our proposed system, type 1 and 3 are used for load flow solution purpose.

Transformer equations of voltage and current matrices are -

$$[VLG_{abc}]_m = [A_t].[VLN_{ABC}]_n - [B_t].[I_{abc}]_m \quad (26)$$

$$[I_{ABC}]_n = [C_t].\ [VLG_{abc}]_m + [D_t].[\ I_{abc}]_m \quad (27)$$

Where, A_t, B_t, C_t, D_t are coefficients and their value depends on type of transformer connections used for calculation purpose [6].

E. ZIP load modelling

The polynomial expression known as the ZIP coefficients model represents the variation (with voltage) of a load as a composition of the three types of constant loads Z, I, and P. Z, I, and P stand for constant impedance, constant current, and constant power loads, respectively. The expressions for active and reactive powers of the ZIP coefficients model are:

$$P = P_0\left[Z_p\left(\frac{V_i}{V_o}\right) + I_p\frac{V_i}{V_o} + P_p\right] \quad (28)$$

$$Q = Q_0\left[Z_q\left(\frac{V_i}{V_o}\right) + I_q\frac{V_i}{V_o} + P_q\right] \quad (29)$$

Where, P and Q are the active and reactive powers at operating voltage (V_i); P_0 and Q_0 are the active and reactive powers at rated voltage (V_0); Z_p, I_p, and P_p are the ZIP coefficients for active power and Z_q, I_q, and P_q are the ZIP coefficients for reactive power.

III. Analysis Of Case Studies And Results

Three phase load flow analysis is done by interfacing MATLAB with Open DSS on IEEE 13 bus radial distribution network. Different case studies have been demonstrated for system voltage improvement and to analyze the impact of ZIP load model on the system. Energy storage device like capacitor of optimal rating is incorporated in the system at suitable locations for enhancing voltage profile of the distribution network. Their locations in the system are decided by iterative method for optimal results.

A. *Case 1 : Voltage Enhancement with Capacitor Placement*

Firstly, three phase load flow results are obtained for IEEE 13 bus distribution system. The voltage profile for base case is shown in Fig. 2. Then for further analysis purpose, phase 1 voltage profile is taken and comparisons with different voltage improvement techniques are shown.

TABLE I
Improvement Of Voltage With Capacitors

Capacitor	**Bus No.**	**Size (kVAR)**	**System Loss (kW)**	**Loss Reduction (%)**
Base Case	-	-	110.5	
One cap	8	600	101	8.59
Two cap	4,8	600,600	97.3	11.94

Table 1 shows that the system losses were 110.5 kW without any improvement technique. Then with 1 capacitor installation % loss reduction is 8.59 % and with 2 capacitor employment in the system % loss reduction increases to 11.94% and there is improvement in voltage profile of the system as we can see from Fig. 3,4 for optimal rating and suitable placement of capacitor in the system. An iterative method was taken for determining location of capacitor. Blue line is for base case and red line is for 1, 2 capacitor employment in the system respectively.

Where, 8^{th} bus number = 671 bus in IEEE 13 bus system,
4^{th} bus number = 633 bus in IEEE 13 bus system.

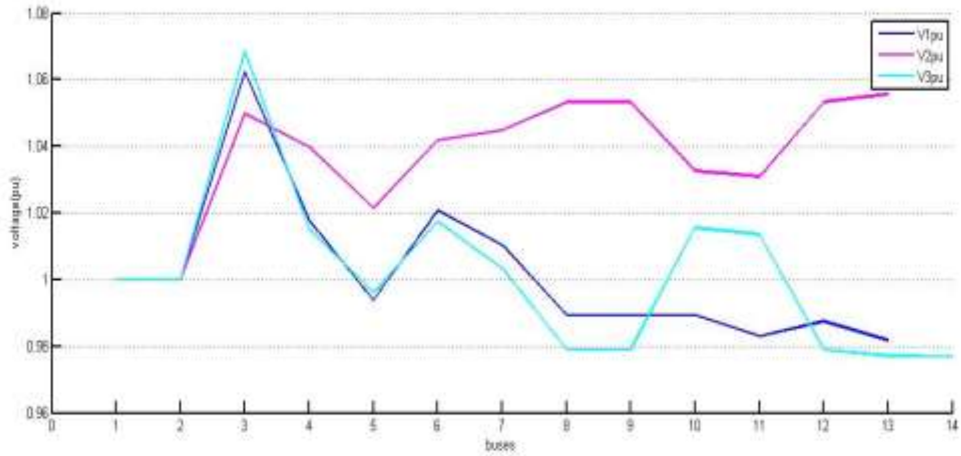

Fig. 2. Voltage Profile of Base System

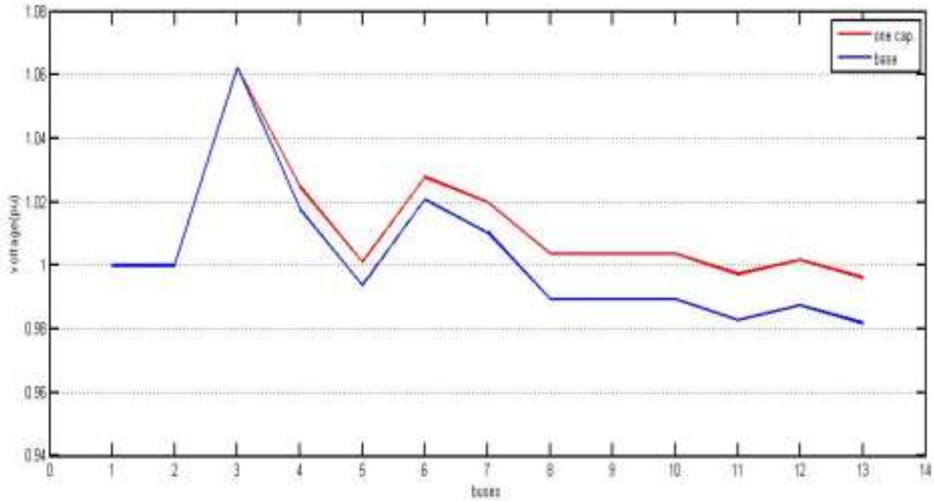

Fig. 3. Comparison of Voltage Profile With One Capacitor

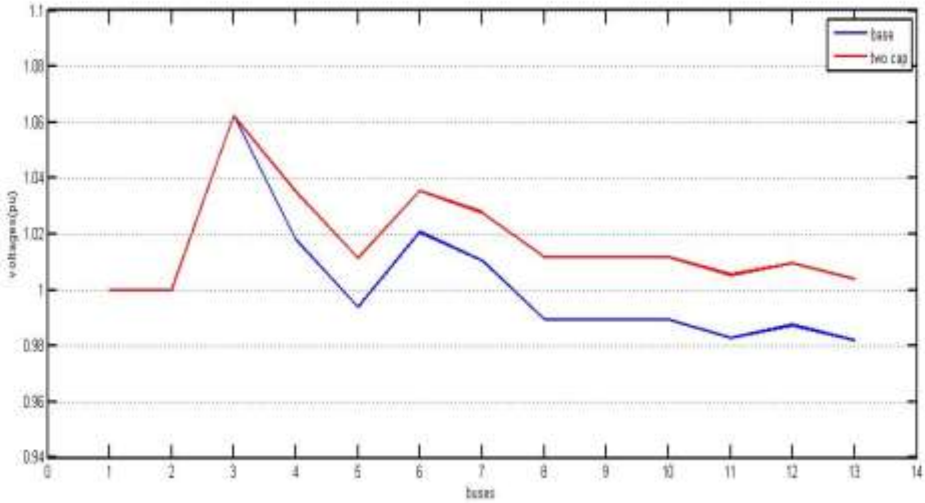

Fig. 4. Comparison of Voltage Profile With Two Capacitors

B. *Case 2 : Impact of ZIP Load Model on Proposed system*

Here, impact of ZIP load model is seen on the proposed system in terms of power flow and losses calculated. Values of ZIP parameters for half of the load is [0.3,0.4,0.3,0.3,0.4,0.3,0.87] and for rest half load is [1,0,0,1,0,0,0.87]. Power flow is determined in terms of active and reactive power for each case as given below.

1) Power flow Through Transformers:

There are three transformers used in 13 bus system at source bus, 650 and 632 bus numbers. One transformer is connected at substation end which gives interconnection between substation and tested feeder. So, from Table 2, it can be seen that power flow at source bus is higher than other bus because it takes power directly from substation end whereas transformer connected at bus number 632 draws power lesser than other transformer due to far end loads. It can be observed from Table 2 that power flows get rescheduled when ZIP load modelling is used in the system. In comparison to base system, power flows in transformers with ZIP load model have been reduced, which shows the impact of voltage dependent load modelling (ZIP) on the proposed system.

TABLE II
ACTIVE AND REACTIVE POWER FLOW IN TRANSFORMER

Element	Terminal	Active and Reactive Power (Base Case)		Active and Reactive Power (ZIP Load)	
		P (kW)	Q (kVAR)	P (kW)	Q (kVAR)
Transformer. SUB	1	3577.9	1722.5	3564.5	1711.3
Transformer.REG1	1	1251.8	681.4	1237.2	668.5
Transformer.REG2	1	978.3	374	995.7	386.8
Transformer.REG3	1	1347.8	666.9	1331.6	655.7
Transformer.XFM1	1	405.4	299.9	406.8	301.0

2) Power flow Through Line Terminal:

Active and reactive power flows between two nodes i.e. between two line terminals is shown in Table 3. Node 650 is connected at substation end so it draws maximum power from source bus and power reduces as we move towards far end from node 650. Node 670 is resultant node between node 671 and 680 so power flow between 671 to 680 is zero as shown in Table 3 because there is no direct path available between node 671 and node 680. So, it can be observed that power flow between nodes 650 to 632 is maximum (closest bus) and power flow between bus no. 671.692 is minimum (farthest bus). In Table 3, power flow at spot load has been shown, it can be observed that power flow at nodes where spot loads are connected is same as power given in IEEE data sheet. Injected load shows variation of power at 52 different nodes. Distributed loads are connected between node 671 and node 680, therefore at bus number 671 magnitude of spot loads is maximum. A comparison in power flows is shown between base system and with ZIP load model on the proposed system. Power flows get rescheduled according to change in load modeling in the system. In most of the lines, power flows found to be reduced in ZIP load model in comparison to base system.

TABLE III
ACTIVE AND REACTIVE POWER FLOW IN LINES

Line Terminal 1	Line Terminal 2	Active and Reactive Power (Base Case)		Active and Reactive Power (ZIP Load)	
		P (kW)	Q (kVAR)	P (kW)	Q (kVAR)
650	632	3577.5	1721.9	3564.1	1710.7
632	670	2697.6	962.4	2683.8	952.3
670	671	2484.9	805.8	2463.7	792.2
671	680	0	0	0	0
632	633	406.2	300.9	407.7	302.1
632	645	413.9	265.9	414.0	266.8
645	646	241.2	138.5	235.7	135.4
692	675	847.9	-141.8	821.5	-156.6
671	684	291.2	67.0	288.3	65.1
684	611	166.3	-16.8	163.1	-18.8
684	652	124.4	83.0	124.6	83.4
671	692	1016.4	-7.8	990.1	-6.8

3) Power Flow Through Injected Loads:

Active and reactive power flows in injected loads of the system are shown in Table 4. Power flows found to be rescheduled for ZIP load model in comparison to base case. It shows the impact of ZIP load modeling on the proposed system.

TABLE IV
ACTIVE AND REACTIVE POWER FLOW IN LOADS

Injected Load	Active and Reactive Power (Base Case)		Active and Reactive Power (ZIP Load)	
	P (kW)	Q (kVAR)	P (kW)	Q (kVAR)
"Load.671"	1155.0	660.0	1163.6	665.0
"Load.634A"	160.0	110.0	159.2	109.4
"Load.634B"	120.0	90.0	122.4	91.8
"Load.634C"	120.0	90.0	119.8	89.8
"Load.645"	170.0	125.0	175.4	129.0
"Load.646"	240.6	138.1	235.2	135.0
"Load.692"	168.5	149.6	168.6	149.8
"Load.675A"	485.0	190.0	470.3	184.2
"Load.675B"	68.8	60.7	68.5	60.4
"Load.675C"	290.0	212.0	278.9	203.9
"Load.611"	165.9	78.1	162.8	76.6
"Load.652"	123.6	83.0	123.8	83.2
"Load.670A"	17.0	10.0	17.4	10.2
"Load.670B"	66.0	38.0	71.9	41.4
"Load.670C"	117.0	68.0	118.4	68.8

4) Comparison in System Loss of different Configurations:

Losses and minimum bus voltages of the system have also been calculated for base case and with ZIP load model in the proposed system. Minimum bus voltage found to be improved i.e. 0.9778 p.u. with ZIP load model in comparison to base case voltage i.e. 0.975 p.u. System and % circuit losses also found to be reduced for ZIP load model case in comparison to base case as shown in Table 5.

TABLE V
COMPARISON IN SYSTEM LOSS OF DIFFERENT CONFIGURATIONS

Configuration	Minimum Bus Voltage (p.u.)	System Loss (kW)	% Circuit Loss
Base Case	0.975 (611)	110.5	3.19
ZIP Load	0.9778 (611)	108.3	3.13

IV. CONCLUSIONS

In this paper, various voltage improvement techniques and impact of ZIP load model have been examined on the proposed system. From comparative analysis of different cases, it is found that better results are obtained for two capacitor placement in the system during peak load condition. If number of units of capacitors are increased according to their requirements then it can give better result. Improvement of voltage profile also depends on location and size of the capacitors. Inaccurate location of capacitor can lead towards huge losses in distribution network. Impact of ZIP load model have also been seen on the system when power flows get rescheduled which shows that load models are voltage dependent. Some renewable energy sources which are eco-friendly can be used to meet desirable voltage profile in the network. Wind, solar power, and photovoltaic cell are some distributed generations which can be further used according to their requirement and availability in the proposed systems.

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