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ARTIFICIAL BEE COLONY ALGORITHM BASED APPROACH FOR OPTIMAL SIZING AND LOCATION OF SHUNT CAPACITORS IN RADIAL DISTRIBUTION SYSTEMS WITH COMPOSITE AND EXPONENTIAL LOADS

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ABSTRACT

This work aims to minimizing the power loss in radial distribution system by placing optimally sized shunt capacitors at appropriate locations. The power flow solution of the proposed radial distribution network with different types of load models is obtained using Backward/forward sweep based load flow methodology. The sensitive nodes which are prone to voltage collapse are identified by the computation of voltage stability index for the installation of shunt capacitors. A nature inspired meta-heuristic search technique namely artificial bee colony algorithm which mimics the foraging behavior of the honey bee swarm is utilized to identify the optimal size of the shunt capacitors to be placed to achieve the loss minimization. The rigidness of the proposed optimization approach searching towards the optimal solution is tested on IEEE 69 bus radial test distribution system with different load models such as constant power, constant current, constant impedance, composite and exponential loads.

Keywords: Radial distribution system (RDS), Artificial bee colony algorithm (ABC), Capacitor placement, Voltage stability index (VSI), Backward /forward sweep (BFS) based power flow technique, Constant power load (CP), Constant current load (CI), Constant impedance load (CZ.).

Nomenclature

R_k	K th branch resistance of RDS
X_k	K th branch reactance of RDS
V_{min}	Lower limit of bus voltage
V_{max}	Upper limit of bus voltage
I_{bmax}	Maximum current carrying limit of feeder line
I_{bpk}	Real part of kth branch current
I_{bqk}	Reactive part of k th branch current
$\lvert I_{bk} \rvert$	Magnitude of k th branch current
Q_c	Rating of shunt capacitor
Q_d	Total reactive power demand of RDS
nb	Total number of branches
n	Total number of nodes in the RDS
nc	Total number of capacitors
objfun	Objective function

1. INTRODUCTION

Power loss in the radial distribution system is comparatively higher than the transmission system because of its higher R/X ratio and untransposed lengthy lines with unbalanced loads. The presence of higher resistance in the distribution network give rise to more power loss in the feeder lines and its sub laterals and it makes the distribution system less efficient for supplying quality power to the tail end consumers. There is a need for improving the efficiency in the system by reducing the power loss in different possible ways. One such way of reducing the power loss is by installing shunt capacitors in the system at required locations to inject reactive power partially. Installation of shunt capacitor enhances the feeder capacity, reduces power loss, and improves voltage regulation of the RDS to the desired level. The objective of reducing power loss within the bounded constraints can be achieved by optimally sizing the capacitor banks and placing them in optimal locations. If the place and sizing is not appropriate it may result in over compensation during light load condition. A power flow method for calculating the bus voltages, line currents and subsequently power loss in the system has been proposed by Tinney, W.F and Hart, C.E in [1]. A modified newton method which eliminates the use of jacobian matrix has been proposed by F. Zhang and C. S. Cheng in [2]. B. Stott and O. Alsac has proposed a Fast decoupled load flow method which has higher convergence speed and can even be used for contingency cases in [3]. A decoupled load flow methodology for solving the distribution systems load flow which employs the decoupling of the jacobian matrix into two sub-Jacobian matrix has been proposed in [4] by Whei-Min Lin and Jen Hao Teng. Thukaram, D *et al*., in [5] proposed the Backward/forward sweep based load flow technique for effectively solving the radial distribution networks power flow problems. T. Gozel *et al*., in [6] proposed a tool for finding out the voltage stability in the radial distribution system which gives information about the nodes which are weak and prone to voltage collapse. A different type of voltage stability index to identify the weaker nodes in the system has been proposed by M. Chakravorty and D. Das in [7]. U. Eminoglu and M.H. Hocaoglu addressed the comparison of the different voltage stability indices in [8].K.Muthukumar and S.Jayalalitha proposed the Harmony Search Algorithm based capacitor sizing in unbalanced radial distribution system for power loss minimization in [9]. A new heuristic optimization tool called Artificial Bee Colony Algorithm (ABC) has been proposed by D. Karaboga in [10]. A Survey on bee colony optimization and its application in the fields of engineering has been proposed in [11] by Dr. Arvinder Kaur and Shivangi Goyal. Optimal allocation and sizing of shunt capacitors using ABC algorithm has been proposed in [12] by Attia, A *et al*. In [13] Abu-Mouti, F.S. and El-Hawary, M.E. made a comparative study of available heuristic algorithms, along with the detailed analyze of ABC Algorithm performance.

2. PROBLEM FORMULATION

The power loss in the distribution systems has to be taken care as it creates certain power quality issues and reduces system efficiency. The objective of the proposed work is to minimize the power loss in the test system by placing shunt capacitors at appropriate locations with optimally sizes. The proposed objective function is mathematically stated as,

Minimize

$$\mathbf{Ploss} = \sum_{k=1}^{nb} \mathbf{Ploss_k} = \sum_{k=1}^{nb} |\mathbf{I_{bk}}|^2 . \mathbf{R_k} \qquad \mathbf{(1)}$$

k = 1, 2, 3… nb

The total system loss amounts to the summation of power losses related with the real and reactive part of branch current magnitude in all the branches of the RDS with “nb” number of branches as indicated in Eq.(2). This study aims to minimize the real power loss by reducing the reactive part of branch currents by injecting reactive power with the aid of shunt capacitors of suitable ratings placed at appropriate locations

$$\mathbf{Ploss} = \sum_{k=1}^{nb} \left(|\mathbf{I_{bpk}}|^2 \mathbf{R_k} + |\mathbf{I_{bqk}}|^2 \mathbf{R_k} \right) \qquad \mathbf{(2)}$$

k = 1, 2, 3… nb

Along with the above mentioned objective function, the following constraints are to be satisfied.

2.1. Bus voltage magnitudes

The magnitude of bus voltage must be within the specified tolerance limits i.e. it should be between the upper and lower bounds of ±5 % of the nominal bus voltage.

$$V_{min} < V_k < V_{max} \quad k = 1, 2….n \qquad (3)$$

2.2. Thermal loading limit of the feeder lines

The current flowing in the branches should be less than the maximum current carrying capacity of the line as in Eq.(4).

$$I_{bk} < I_{bkmax} \quad k = 1, 2….nb \qquad (4)$$

2.3. Maximum Reactive power compensation limit

The total reactive power supplied by the installed capacitors should not exceed the total reactive power demand of the RDS to avoid over compensation.

$$\sum_{j=1}^{nc} Q_{cj} \leq Q_d \qquad (5)$$

where j =1, 2…, nc

3. POWER FLOW SOLUTION

Different load flow solutions were proposed in literature to get the power flow solution of RDS. The Backward/Forward sweep based method (BFS) which employs Kirchhoff’s current and voltage laws is found to be more robust in solving the power flow issues of RDS. This methodology finds out the node currents and corresponding branch currents in backward sweep mode from leaf nodes towards the source node and magnitude of voltage at every node are calculated in the forward sweep from the source end towards the leaf nodes. For the sample radial distribution system shown in Fig.1, the current in each branch and voltage at every node is calculated by using BFS based load flow technique. In backward sweep mode, the load current injection of every node is calculated using Eq. (6).

$$I_i = \frac{S_i^*}{V_i^*} \ \mathbf{where\ i} = 2,3,….,n \qquad (6)$$

Where S_i^* is the conjugate of complex power of i^{th} node, V_i^* is the conjugate of i^{th} node voltage and n is the total number of nodes.

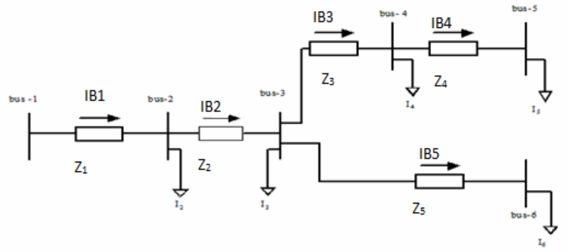

Fig.1. Sample radial distribution network.

3.1. Formulation of BIBC matrix

After the calculation of node currents, the branch currents are obtained by adding the current of up- stream node as,

$IB_5= I_6$
$IB_4= I_5$
$IB_3= I_4+I_5$
$IB_2= I_6+I_5+I_4+I_3$
$IB_1= I_6+ I_5+I_4+I_3+I_2$

Where I_2, $I_{3\ldots}I_6$ are the equivalent injected load currents at their respective nodes. The Bus injection to Branch current (BIBC) matrix of the sample RDS system is a connectivity matrix relating the bus currents and the branch currents and it can be written in matrix format as,

$$\begin{bmatrix} IB_1 \\ IB_2 \\ IB_3 \\ IB_4 \\ IB_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \tag{7}$$

The above equation can hence forth be written in a précised manner as,

$$[BC]=[BIBC][I] \tag{8}$$

3.2. Formation of BCBV (Bus current to Branch Current) matrix

BCBV is a connectivity matrix for branch current to bus voltage constituted for calculation of the node voltages in the forward sweep mode. The node voltages are calculated starting from the root node and ending up with the leaf node. The BCBV matrix can be formulated as shown in Eq.(9),

$$[BCBV]= [BIBC]^T [Z_D] \tag{9}$$

Where T stands for transpose of the BIBC Matrix and $[Z_D]$ is the impedance matrix with the impedance values arranged in diagonal format as per their branch numbering as in Eq.(10)

$$[Z_D]=\begin{vmatrix} Z_1 & 0 & 0 & 0 & 0 \\ 0 & Z_2 & 0 & 0 & 0 \\ 0 & 0 & Z_3 & 0 & 0 \\ 0 & 0 & 0 & Z_4 & 0 \\ 0 & 0 & 0 & 0 & Z_5 \end{vmatrix} \tag{10}$$

Where Z_1, Z_2, Z_3, Z_4, Z_5 are the impedance values of the respective branches in the sample distribution system. The impedance values are arranged in an orderly manner based on the branch numbering of the RDS. The BCBV matrix can be obtained by multiplying the transposed BIBC matrix and impedance matrix as shown,

$$[BCBV]=\begin{bmatrix} Z_1 & 0 & 0 & 0 & 0 \\ Z_1 & Z_2 & 0 & 0 & 0 \\ Z_1 & Z_2 & Z_3 & 0 & 0 \\ Z_1 & Z_2 & Z_3 & Z_4 & 0 \\ Z_1 & Z_2 & 0 & 0 & Z_5 \end{bmatrix} \tag{11}$$

The node voltages of the sample system can be estimated by using BCBV matrix and branch current matrix [IB] as in the Eq. (12).

$$\begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} Z_1 & 0 & 0 & 0 & 0 \\ Z_1 & Z_2 & 0 & 0 & 0 \\ Z_1 & Z_2 & Z_3 & 0 & 0 \\ Z_1 & Z_2 & Z_3 & Z_4 & 0 \\ Z_1 & Z_2 & 0 & 0 & Z_5 \end{bmatrix} \begin{bmatrix} IB_1 \\ IB_2 \\ IB_3 \\ IB_4 \\ IB_5 \end{bmatrix} \tag{12}$$

Where, V_1 is the sub-station bus voltage assumed to be 1 p.u. A flat start is assumed in the first iteration of backward sweep with an assumption of all node voltages as 1 p.u and the bus current and branch currents are computed in backward sweep mode from end nodes. In forward sweep mode, starting from source node towards the leaf nodes the bus voltages are updated with branch currents computed in the preceding backward sweep iteration. The iterative process of above said backward/forward sweep stops when certain convergence criterion is met. Once after the convergence of the solution is met, the estimated branch current flowing in the system and respective branch impedances are considered for the calculation of the real and reactive power loss in the system.

4. LOAD MODELING

In distribution system planning, to be aware of the actual system performance it is essential to model the different types of loads which play a vital role in power flow studies. Distribution system consists of loads with different categories such as residential, commercial and industrial loads. Such loads are to be modeled as voltage dependent loads as their active and reactive power depends on the system voltage which varies with changes in the load. In practical distribution systems the loads can be a mixture of all types of loads. Therefore the voltage dependent load models can be represented as exponential and polynomial models which represent the voltage magnitude and power as a polynomial equation and can be expressed as in Eq.13,14. The Eq.13 and Eq.14 represents the general expression of different types of load models such as constant power, constant current, constant impedance, composite and exponential loads.

$$P = P_0[(a]_0 + a_1V + a_2V^2 + a_3V^{e1}) \tag{13}$$

$$Q = Q_0[(b]_0 + b_1V + b_2V^2 + b_3V^{e2}) \tag{14}$$

For all such loads, the Eq.(13) and Eq.(14) are constrained as,

$$\llbracket(a]_0 + a_1 + a_2 + a_3) = 1.0 \qquad (15)$$

$$\llbracket(b]_0 + b_1 + b_2 + b_3) = 1.0 \qquad (16)$$

Where P_0 and Q_0 stand for nominal real power and reactive power loads respectively and V is the nominal bus voltage magnitude. For constant power load (CP), $a_0=b_0=1$ and $a_j=b_j=0$ for j=1, 2, 3. For Constant Current (CI) load, $a_1=b_1=1$ and $a_j=b_j=0$ for j=0, 2, 3. For Constant Impedance (CZ) load, $a_2=b_2=1$ and $a_j=b_j=0$ for j=0, 1, 3. Composite load modeling is the combination of CP, CI, and CZ where it is modeled with 40%, 30% and 30% of CP, CI and CZ, respectively [14]. For exponential load modeling, $a_3=b_3=1$ and $a_j=b_j= 0$ for j=0, 1, 2 and e1 and e2 are 1.38 and 3.22, respectively [15].

5. VOLTAGE STABILITY INDEX

To identify the candidate location of shunt capacitors to be placed to accomplish the proposed objective function minimization, the computation of voltage stability index of all nodes of the RDS is necessary. As the loads in the distribution systems are increasing, the system is operating at the verge of its stability limits. In order to improve the voltage profile of the radial distribution test system along with power loss minimization, shunt capacitors are to be placed at the nodes which are operating close to the stability limit. In literature, several methods are proposed for determining the stability index of the radial distribution networks. The stability index proposed in [7] is utilized in this work. The voltage stability index of each node of the test system is calculated using Eq.(17).

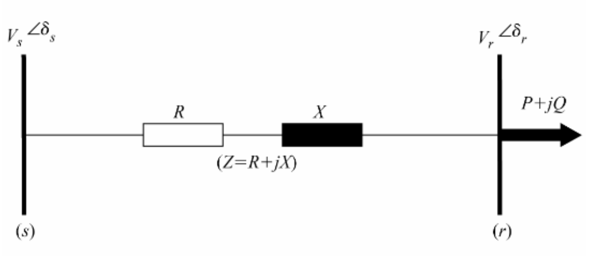

Fig.2. Branch of radial distribution network.

$$VSI\ (r) = (V_s)^4 - 4(PX-QR)^2 - 4(V_s)^2(PR+QX) \qquad (17)$$

Where "r" indicates the succeeding node, V_s is the magnitude of the bus voltage of the preceding node "s". P and Q are the real and reactive power loads which are lumped at the succeeding node, R and X are the effective resistance and reactance of the bus section. The nodes with the lowest value of stability index are identified as the weak nodes and such nodes are considered for shunt capacitor placement.

6. ABC OPTIMIZATION TECHNIQUE

ABC optimization algorithm is a meta-heuristic technique introduced in 2005 by Karaboga which has the capability to solve constrained optimization problems [10]. The intelligent foraging food search behavioral pattern of honey bee approach is used to get a solution for constrained optimization problems. The ABC approach consist of three steps namely employee, onlookers and scout bee phase [10]. In the initial phase, employee bees start exploring randomly within the search space to discover the food sources (employee bee phase). The employee bee's shares the information about the food source to the onlooker bees based on nectar amount (quality of solution) by dancing. The employed bees dancing duration indicates the quality of the food source that it has found. Based on the probabilistic selection, the onlooker bee exploits the food source positions in the neighborhood of the best solution provided by the employed bee phase. In scout bee phase, the solutions that are not having any improvement during search process are abandoned and a scout bee is allowed to explore randomly within the search space to get entirely new food source.

6.1. Procedure for implementing the ABC algorithm

Step-1: Determine the initial population size (SN) and its random values. Y_{jk}, j = 1, 2… SN and estimate the corresponding objective function. Computation of the fitness function (fit) using the formula

$$fit_j = (1/\,(1+objfun_j)) \qquad (18)$$

Step-2: Initiate cycle number = 1

Step-3: Employed bee phase:

Create the new food source position` X_{jk}^{new} in the neighborhood of Y_{jk} using the following expression

$$X_{jk}^{new} = Y_{jk}^{old} + u\,(Yjk^{old} - Ynk) \qquad (19)$$

and evaluate them, where n Є (2,3….,SN) and k Є {1,2,…. D} are indices chosen randomly; D is the number of optimization parameters (dimension of the problem); n ≠ j; 'u' represent a random number within [-1,1].

Step-4: Apply Greedy selection mechanism between Y_{jk}^{old} and Xjk^{new}

Step-5: Compute the probability (P) values for the solutions Y_{jk} using their fitness values as,

$$\mathbf{P_j} = \frac{\mathbf{fit_j}}{\sum_{j=1}^{SN} \mathbf{fit_j}} \qquad (20)$$

The fit $_j$ is the fitness value of solution j; the fitness values of the solutions are calculated as,

$fit_j = (1/ (1+Ploss_j))$

$Ploss_j$ is computed for each individual j th solution using Eq. (2)

Step-6: Onlooker Bee Phase:

Generate the new populations Xjk using Eq. (19) for the onlookers based on the P_j (Eq.(20)) and evaluate them.

Step-7: Apply Greedy selection mechanism

Step-8: Scout Bee Phase:

Replace the abandoned solution with a newly generated random solution Y_{jk} for the scout bee using the following expression.

$$Y_{jk}= \{Y_k^{min} + rand\ (0, 1)*(Y_k^{max} - Y_k^{min})\} \quad (21)$$

Step-9: Store the best solution achieved so for

Step-10: Increment the cycle number.

Step-11: Repeat steps 3 to step 9 until the optimal solution is obtained and stop the iterative process, if cycle number is equal to the predetermined number of cycles.

7. RESULTS AND DISCUSSIONS

To verify the performance of the ABC algorithm for optimal capacitor sizing problem, it has been implemented on the IEEE 69 bus radial distribution test system. The total real and reactive power demand of the test system is 3801.89 K.W and 2694.10 KVAr respectively with the nominal bus voltage of 12.66 KV with base MVA of 100. The detailed line and bus data is taken from [16].

The simulation result presented in Table-1 shows the performance of the ABC approach in optimal shunt capacitor sizing problem to realize the objective function minimization of the test system with different load models. The bus voltage profile of the test system before and after shunt capacitive compensation has been depicted in Fig.5 and Fig.6. The corresponding voltage stability index values are depicted in Fig.3 and Fig.4. It can be noticed from Fig.3 and Fig.4 that after placement of shunt capacitor at appropriate locations in the test system, the stability of the system improves significantly. According to Fig.6 in the presence of three shunt capacitors, the bus voltage profile of the test system has been improved considerably in comparison with the voltage profile of the test system before compensation shown in Fig.5. The variation of total real and reactive power losses of the RDS with different types of load models is shown in Fig.7 and Fig.8. It clearly shows the decrease in real and reactive power loss of the voltage dependent load models as compared with the losses associated with the constant load model. These variations indicate the voltage dependency of the different types of load models in the distribution system. Simulation results for single and three capacitor placements on the test system with different load models are summarized in Table-1. According to Table-1 considering different load models, the optimal sizing of single and three capacitors differ from the case of constant power loads implies that the impact of different load models on optimal shunt capacitor sizes as well as power loss reduction.

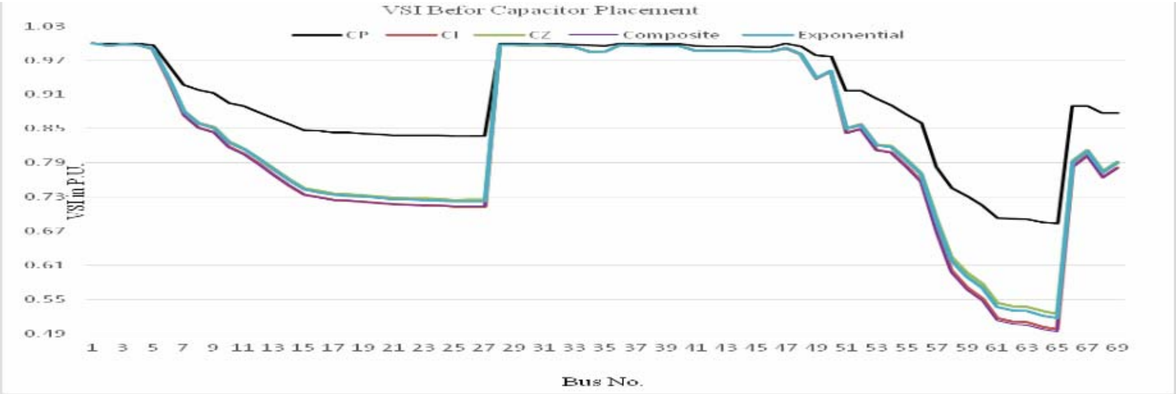

Figure-3. VSI of the test system before the placement of multiple shunt capacitors.

Table-1. Simulation results of 69 bus system with different load models before and after placement of single and multiple shunt capacitors.

	Before Compensation		Optimal location and ratings of shunt capacitor		After Compensation	
Type of load model	**Real power loss** (KW)	**Reactive power loss** (KVAr)	**Optimal location**	**Optimal capacitor size** (KVAr)	**Real power loss** (KW)	**Reactive power loss** (KVAr)
CP model Three capacitors	224.96	102.15	65, 64, 63	168 249 820	155	71.8
Single capacitor			65	982	169	78.92
CI model Three capacitors	191	89.2	65, 64, 63	150 150 912	136	65.0
Single capacitor			65	980	146	70.44
CZ model Three capacitors	167	78.7	65, 64, 63	150 150 894	122	58.8
Single capacitor			65	974	130	63.07
Composite load model Three capacitors	195	90.7	65, 64, 63	150 150 922	132	63.3
Single capacitor			65	933	145	69.973
Exponential load model Three capacitors	168	79.038	65, 64, 63	157 150 888	130	62.3
Single capacitor			65	928	138	66.55

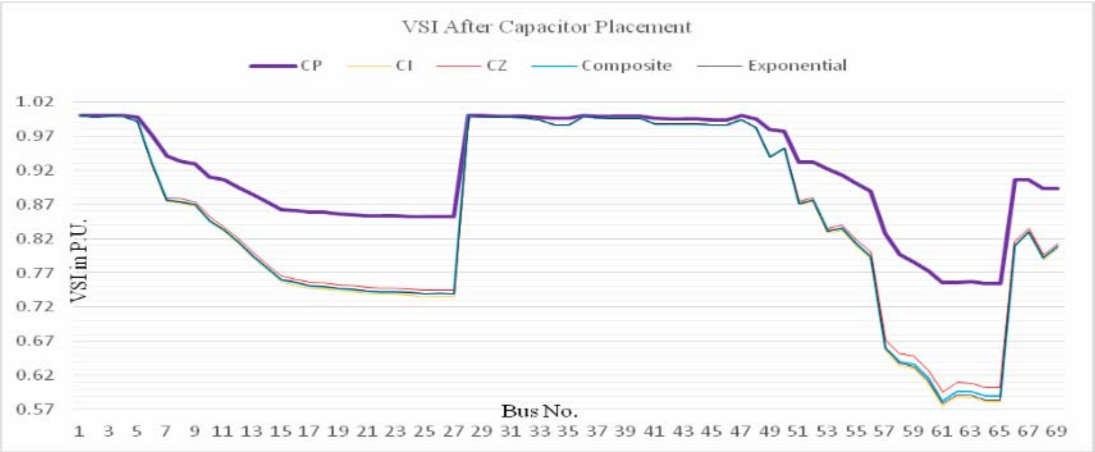

Figure-4. VSI of the test system after the placement of multiple shunt capacitors.

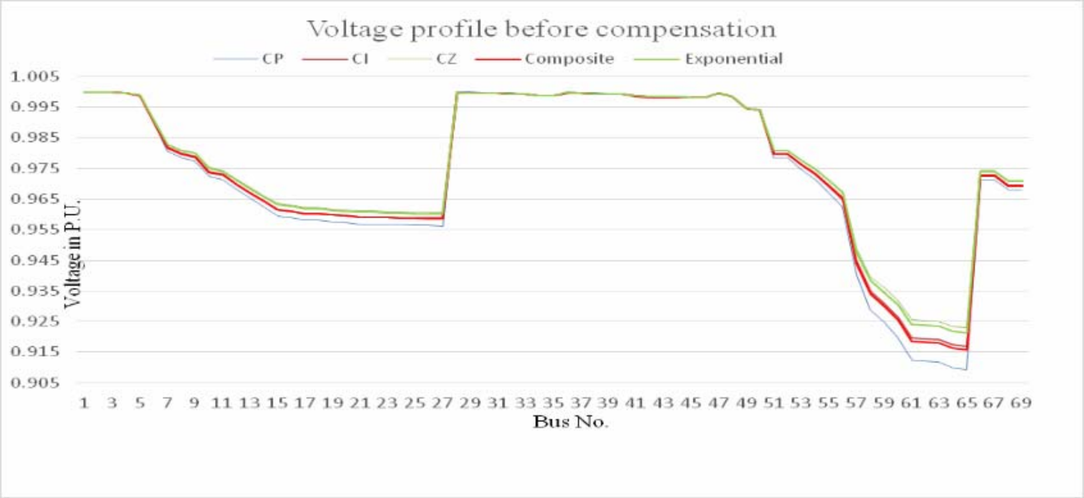

Figure-5. Bus voltage profile of the test system before the placement of multiple shunt capacitors.

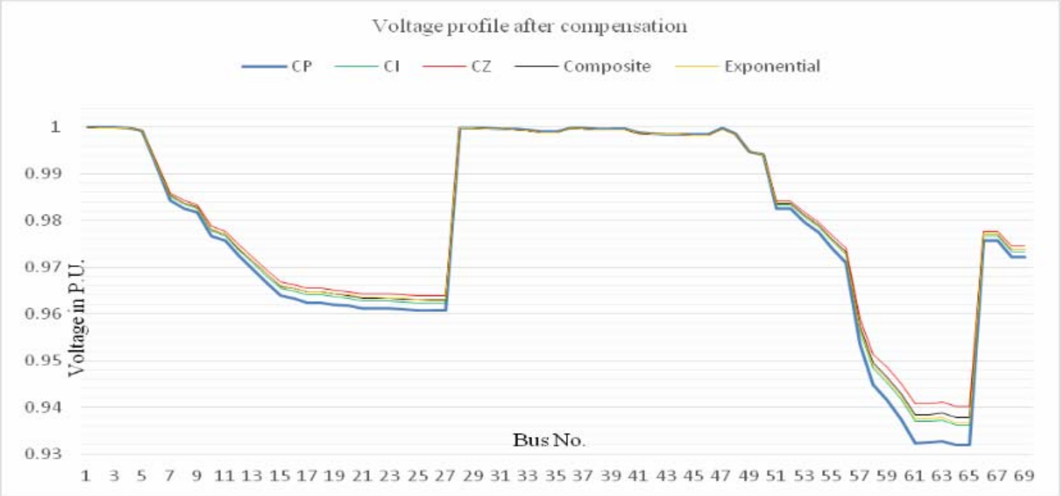

Figure-6. Bus voltage profile in the test system after the placement of multiple shunt capacitors.

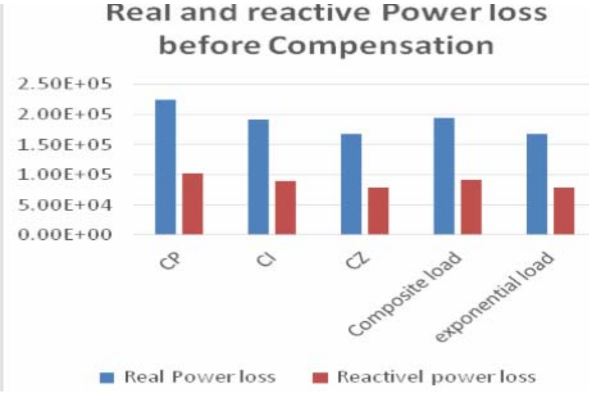

Figure-7. Variation of real and reactive power loss of 69 bus RDS with different types of load models before multiple capacitor compensation.

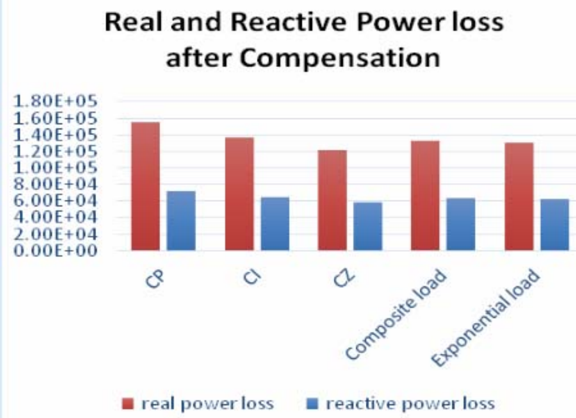

Figure-8. Variation of real and reactive power loss of 69 bus RDS with different types of load models after multiple capacitor compensation.

CONCLUSIONS

This work aims to minimize the power loss in the radial distribution systems with the consideration of different load models by optimally placing and sizing the shunt capacitors. In this proposed methodology, the backward/forward sweep based load flow technique is implemented for computation of load flow solution of the proposed test system with different load models. The shunt capacitors placed at optimal nodes are identified based on voltage stability index computation. The size of the shunt capacitors to be placed is optimized by using the ABC algorithm to realize the power loss minimization. The robustness of the proposed ABC approach has been tested on IEEE 69 bus radial distribution system with different load models such as constant power, constant current, constant impedance, composite and exponential loads and the outcomes shows the ABC algorithms ability to solve such constrained optimization problems.

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