Optimal Placement of Capacitors in Radial Distribution Systems Using Teaching Learning Based Optimization Algorithm

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Abstract: This project presents Teaching Learning Based Optimization (TLBO) approach to minimize power loss and energy cost by optimal placement of capacitors in radial distribution systems. The proposed algorithm is based on two basic concept of education namely teaching phase and learning phase. In first phase, learners improve their knowledge or ability through the teaching methodology of teacher and in second part learners increase their knowledge by interactions among themselves. To check the feasibility, the proposed method is applied on standard 15, 33, 69 and 85 bus radial distribution systems.

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I. INTRODUCTION

The topology based load flow program is used in this project. This involves construction of two network matrices based on topology and matrix operations. Computationally this method is very efficient. Another advantage of this method is that it requires less computer memory. Convergence is always guaranteed for any type of practical radial distribution network with a realistic R/Xratio while using this method. Loads, in the present formulation, have been represented as constant power. However, this method can easily include composite load modeling if the breakup of the loads is known. This load flow technique has been implemented using MATLAB. Several practical rural radial distribution feeders in India have been successfully solved using this method.

Distribution system provides a final link between high voltage transmission systems and consumer services. The power loss is significantly high in distribution systems because of lower voltages and higher currents, when compared to that in high voltage transmission systems. Studies have indicated that as much as 13% of total power generated is consumed as I^2R losses in distribution level. Reactive currents account for a portion of these losses.

Reduction of total loss in distribution systems is very essential to improve the overall efficiency of power delivery. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at distribution level.

In recent years, considerable attention has been focused in planning of a distribution system, to reduce the power and energy losses, to reduce the capital investment involved and to provide better quality supply to consumers. Improved modeling techniques and certain optimization and programming approaches have been presented to determine the best location, and suitable interconnections between substations so as to meet the increasing demands more reliably and economically. In these approaches, shunt capacitors are introduced to reduce losses and to provide reactive power compensation.

Several methods of loss reductions in distribution systems have been reported over years. Control of reactive power in distribution systems with fixed load and varying load have been reported giving generalized equations for calculating power loss, energy loss, reduction in energy loss by optimal capacitor placement. Other studies have been reported on reactive power compensation that used uniformly distributed load on a simple line feeder that had no lateral tree or a simple lateral feeder without branches. All these may not be considered as realistic distribution systems.

In this paper sensitivity analysis is used for capacitor placement problem. This method identifies the sensitive nodes that have a very large impact on reducing the losses in distribution systems. These nodes are very small in number when compared to the total number of load nodes. As capacitor placement is nonlinear optimization problem TLBO Algorithm is used for selecting the optimal size of the capacitors. It has been established that 70% of the total system losses are occurring in the primary and secondary distribution system, while transmission and sub- transmission lines account for only 30% of the total losses. Therefore the primary and secondary distribution systems must be properly planned to ensure losses within the acceptable limits.

Teaching learning based optimization (TLBO) introduced by Ravipudi Venkata Rao et al. This is a new variant of meta-heuristic optimization technique inspired by the natural phenomenon of teaching and learning process. It has emerged as one of the simple and efficient techniques for solving nonlinear optimization problem. In this optimization technique, a group of students in a class is considered as a population and the solution vector of the objective is analogous to the grade point of different subjects offered to the students. The result of a student is analogous to fitness function in other population-based techniques, to represent the quality of each solution set. TLBO is based on the concept of teaching–learning process in a class. In comparison to other meta-heuristics algorithms reported in the recent literature, the TLBO algorithm involves a very few mathematical computations for updating the solutions which makes the algorithm very fast. TLBO algorithm is based on the two natural phase of study, i.e. teaching and learning phase. Teacher is usually considered as highly educated person who motivates the students and shares his knowledge with the learners so that the students can enhance their knowledge. The teacher trains the students to improve their academic results in the class. However, the students not only learn from their teacher but also through mutual interaction with their classmates which also helps them to improve their results. The knowledge of the students is finally evaluated on the basis of their results.

Sneha Sultana et al presented teaching learning based optimization (TLBO) approach to minimize power loss and energy cost by optimal placement of capacitors in radial distribution systems [1]. Grainger and Lee have developed new generalized procedures for optimizing the net savings associated with reduction of power and energy losses through shunt capacitor placement on primary distribution feeders [2]. Hogan and Rettkowski presented a new OCP method that employs a branch-and-bound algorithm, which seeks to reduce the total number of possible alternative sizes and sites to test [3]. Khodr et al proposed a computationally efficient methodology for the optimal location and sizing of static and switched shunt capacitors in large distribution systems [4]. Khodr and Olsina et al proposed a computationally efficient methodology for the optimal location and sizing of static and switched shunt capacitors in radial distribution systems [5]. Jabr et al considered the problem of optimally placing fixed and switched type capacitors in a radial distribution network [6]. Oliveira and Carneiro presented an algorithm for reconfiguration associated with capacitor allocation to minimize energy losses on radial electrical networks considering different load levels [7]. The dispatch of capacitors in distribution systems for daily operation is investigated by Wu and Zhang [8]. An efficient heuristic algorithm is presented by Segura and Romero to solve the optimal capacitor placement problem in radial distribution systems [9]. Network reconfiguration reduction in distribution systems is a very important way to save energy. However, due to its nature it is an inherently difficult optimization problem. A new type of evolutionary search technique proposed by Song and Wang on evolutionary programming (EP), has been adopted and improved for this particular application [10]. The stress to elevate overall efficiency has forced utilities to look for greater efficiency in electric power distribution. Ching and Lee presented an effective approach to feeder reconfiguration and capacitor settings for power-loss reduction and voltage profile enhancement in distribution systems [11].

A method comprising of heuristic search technique and simulated annealing (SA) has been proposed by Ghose and Goswami for solving the problem of optimal capacitor placement in radial distribution system and the effects of network and load unbalances, supply harmonics and load non-linarites have been studied [12]. Goswami and Ghose developed a new method based on heuristics and greedy search technique for the placement of capacitors in radial distribution system [13]. A new iterative algorithm is proposed by Masoum and Ladjevardi for optimal sizing and placement of fixed and switched capacitor banks in radial distribution lines in the presence of linear and nonlinear loads [14]. Yu and Wu presented a particle swarm optimization (PSO) based approach to achieve optimal capacitor placement in radial distribution systems [15]. Prakash and Sydulu presented a novel approach that determines the optimal location and size of capacitors on radial distribution systems to improve voltage profile and reduce the active power loss [16]. A particle swarm optimization (PSO) approach for finding the optimal size and location of capacitors is reported by Singh and Rao [17]. Levitin presented a system approach to shunt capacitor placement on distribution systems under capacitor switching constraints [18]. Antunes and Pires have modeled the problem of locating and sizing capacitors for reactive power compensation in electric radial distribution networks as a multi-objective programming problem [19]. The high reactive power level demanded by the distribution systems, the loads growth and consequent increase of system losses introduce variations at the buses voltage magnitudes, which compromise the quality of the supplied electric energy.[20]. Das et al presented genetic algorithm (GA) based fuzzy multi-objective approach for determining the optimum values of fixed and switched shunt capacitors to improve the voltage profile and maximize the net savings in a radial distribution system [21]. Sydulu and Reddy presented a power loss based approach to determine suitable capacitor locations and an Index and genetic algorithm based approach for optimal capacitor sizing [22]. Highest suitability of nodes for capacitor placement and the corresponding sizes are determined. The proposed method has been tested on 15,31,34,69 and 85-bus distribution networks and the results are found to be very promising with considerable reduction in active power loss and improvement in voltage profile. Results for an 85-bus radial distribution system are presented.

II. TOPOLOGY BASED LOAD FLOW SOLUTION

2.1 Equivalent current injection: For distribution systems, the models which are based on the equivalent current injection as reported by Shirmohammadi et al., (1988), Chen et al. (1991.) and Teng and Lin (1994) are more convenient to use. At each bus 'k the complex power S_K is specified by,

$$S_i = \mathrm{P_i} + \mathrm{j}\ \mathrm{Q_i} \qquad (4)$$

- Corresponding equivalent current injection at the k-th iteration of the solution is given by,

$$I_i^k = I_i^r\left(V_i^k\right) + jI_i^i(V_i^k) = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \qquad (5)$$

V_i^k is the node voltage at the kth iteration.

I_i^k is the equivalent current injection at the k-th iteration.

I_i^r and I_i^i are the real and imaginary parts of the equivalent current injection at the k-th iteration respectively.

2.2 Bus-Injection to Branch-Current matrix:(BIBC)

The power injections can be converted into equivalent current injections using the equation (4). The set of equations can be written by applying Kirchhoff's current law (KCL) to the distribution network. Then the branch currents can be formulated as a function of the equivalent current injections.

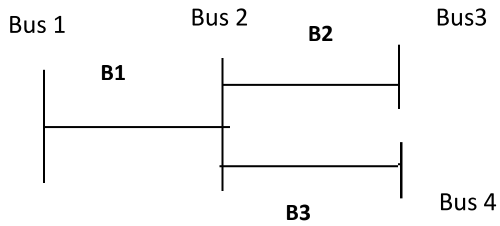

Fig. 1 Sample distribution system.

$$B_1 = I_3 + I_4 + I_2$$

$$B_2 = I_3$$

$$B_3 = I_4$$

WhereI_2, I_3 and I_4 are load currents respectively at buses 2, 3 and 4

$$[B] = [BIBC]\ [I] \quad (6)$$

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \end{bmatrix}$$

The constant BIBC matrix has non-zero entries of +1 only. For a distribution system with m-branch sections and n-buses, the dimension of the BIBC is m x (n-1).

2.3 Branch-Current to Bus-Voltage Matrix:

The relation between the branch currents and bus voltages can be obtained by following equations.

$$V_2 = V_1 – B_1 Z_{12}$$

$$V_3 = V_2 - B_2 Z_{23}$$

Where V_2 , V_3 are the voltages at node 2 and node 3. Z_{23} is the impedance between 2 and 3 nodes. The above equations can also be written as,

$$V_1 – V_2 = Z_{12} B_1$$

$$V_1 - V_3 = Z_{12} B_1 + B_2 Z_{23}.$$

In general, $[V_1] - [V_k] = [Z]\ [B]$ where Z matrix will have elements in the transposed matrix of BIBC matrix. V_1 matrix contains all elements equal to 1.0pu.

$$[\Delta V] = [BCBV][B] \tag{7}$$

That can be written as,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 \\ Z_{12} & Z_{23} & 0 \\ Z_{12} & 0 & Z_{24} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} \tag{8}$$

$$[\Delta \mathrm{V}] = [\mathrm{BCBV}][\mathrm{BIBC}][\mathrm{I}] \tag{9}$$

That can be written as,

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 \\ Z_{12} & Z_{23} & 0 \\ Z_{12} & 0 & Z_{24} \end{bmatrix} \begin{bmatrix} 1 & 1 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{10}$$

III. IMPLEMENTATION OF TEACHING LEARNING BASED OPTIMIZATION ALGORITHM

Optimal Location for placement of capacitor is obtained by sensitivity analysis. Optimal sizes of capacitors is obtained by using teaching learning based optimization algorithm for 15 Bus, 33 Bus ,69 Bus and 85 Bus Systems. Sample program is presented in the Appendix 5. Data for the load flow for 15 Bus, 33 Bus, 69 Bus and 85 Bus Systems is presented in Appendix 1 to Appendix 4 respectively.

3.1 Objective Function

The Objective function in the capacitor placement problem comprises of the minimization of the total real power losses in the given Radial Distribution System. The Objective function is given by:

$$MinP_{loss} = R[k]\left[\frac{P[k]^2+Q[k]^2}{V[n]^2}\right] \tag{1}$$

Where

P[k], Q[k] =Real and reactive power in the Branch k

V[n] =Voltage at node n

R[k] =Resistance of the branch k

3.2 Power Loss Indices

Using the load flow program power loss reduction of the system is obtained when reactive power injections are completely compensated at every node taking one node at a time. The loss reductions are then linearly normalized into [0 1] range with largest loss reduction having a value of 1 and smallest one having a value of 0. This procedure is obtained to every node of the distribution system under consideration. Loss reduction at a particular node is obtained by subtracting active power loss obtained from load flow with Q completely compensated at that node from power loss without any compensation provided. PLI for the nth node is obtained by,

$$PLI_{(n)} = \frac{\text{Loss reduction}_{(n)} - \text{Loss reduction}_{\min}}{\text{Loss reduction}_{\max} - \text{Loss reduction}_{\min}} \quad (2)$$

3.3 Teaching Learning Based Optimization Algorithm

For the learning phase, both Step 2 and Step 3 can be symbolized as

$$x_{k,j}^{t+1} = x_{k,j}^{t} + rand * \left(x_{kj}^{t} - x_{ij}^{t}\right)$$

where $x_{k,j}^{t+1}, x_{k,j}^{t}$ are the grade points of the jth subject of the kth student at tth a(t + 1)th iterations; x_{ij}^{t} is the grade point of the jth subject of the ith student (randomly selected) at tth iteration; $f(x_k), f(x_i)$ are the overall grade point of the kth and the ith students.where random number uniformly distributed between 0 and 1; round is the nearest integer value. x_{kj}^{t} *and* x_{ij}^{t} represent the minimum and maximum value for jth parameter. The population x is randomly initialized by a search space bounded by matrix of N rows and D columns.the jth parameter of the ith learner is assigned values randomly using the equation.

3.3.1 Teaching phase

This is the initial part of the algorithm which is mostly responsible for the global search of the algorithm. In this phase, the students enhance their knowledge with the help of the teacher and the teacher tries to improve the average result of the class from the initial level to his own level. However, in spite of his best effort, the teacher can only improve the mean grade of the class to some extent but not up to his own level. If the mean grade of the ith subject at the tth iteration is improved from k to k^t_{newi} , the difference of the previous and new mean k^t_{diffi} may be given by

$$\lambda_{diff_i}^{t} = r1 * \left(\lambda_{new_i}^{t} - t_f \lambda_i^{t}\right)$$

where r1 is a random number between (0, 1); t_f is the teaching factor and is given by

$$t_f = round(1 + r2)$$

Where r2 is a random number uniformly distributed between 0 and 1; round is the nearest integer value. The modification of grade point of different subjects of the students using teaching phase is described below:

$for\ i = 1{:}\ N_P$

$for\ j = i{:}\ N_D$

$x_{ij}^{t+1} = x_{ij}^{t} + \lambda_{diff_i}^{t}$

end

end

where $x_{j,i}^{t}, x_{j,i}^{t+1}$ are the grade of the ith subject of the jth student at the tth and (t + 1)th iteration.

3.3.2 Learning phase

This is the final part of the algorithm which is used in TLBO to improve the local search ability of the algorithm. This phase of the algorithm simulates the learning of the learners through mutual interaction with their classmates. Each student learns new things from another randomly selected student if the selected stu-dent has better knowledge than him. The improvement of the grade point of the students using the concept of learning phenomenon may be represented as follows:

$for\ k = 1{:}\ N_P$
$X_k = x(k,:); X_i = x(i,:);$
$if\ f(X_k) < f(X_i)$
$for\ j = 1 :\ N_D$
$x_{k,j}^{t+1} = x_{k,j}^{t} + rand * \left(x_{kj}^{t} - x_{ij}^{t}\right)$
end
$elseif\ if\ f(X_k) > f(X_i)$
$For\ j = 1{:}\ N_D$
$x_{k,j}^{t+1} = x_{k,j}^{t} + rand * \left(x_{i,j}^{t} - x_{k,j}^{t}\right)$
end
end
end
Matlab implementation of teaching learning based optimization algorithm:
for t=1:50
x(t,1)= x(t,1)+rand()(pbest(1)- x(t,1));*
x(t,2)= x(t,2)+rand()(pbest(2)- x(t,2));*

x(t,3)=x(t,3)+rand()(pbest(3)- x(t,3));*

end

3.4 Analysis on 15 Bus System

On 15 Bus system, two optimal locations were identified using power loss index method. They are Bus No. 2 and 5. Optimal sizes were obtained using teaching learning based optimization algorithm. The values of capacitors are presented in the Table 1 On 15 Bus system, loss without compensation is 61.80 kW and after compensation, active power loss is 32.96 kW. Fig.2 shows the voltages before and after compensation.

Table 1 Optimal locations and sizes of capacitors on 15 Bus system

Optimal Location (Bus No.)	Optimal Size (kVAr)
2	812
5	387

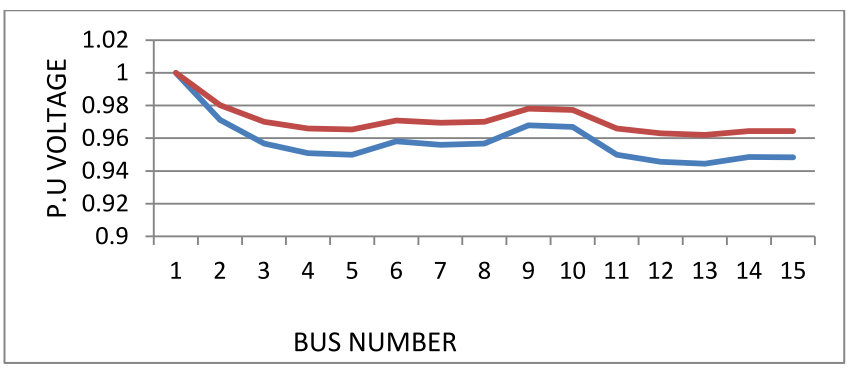

Fig 2 Voltage profile before and after capacitor placement on 15 Bus system

3.5 Analysis on 33 Bus Systems

On 33 Bus systems, three optimal locations were identified using power loss index method. They are Bus No. 7, 23 and 14. Optimal sizes were obtained using TLBO algorithm. The values of capacitors are presented in the Table 2 On 33 Bus system, loss without compensation is 210.74 kW. and after compensation, active power loss is 148.2 kW. Fig. 3 shows the voltages before and after compensation.

Table 2 optimal locations and sizes of capacitors on 33 Bus system

Optimal Location (Bus No.)	Optimal Size (kVAr)
7	142
23	768
14	627

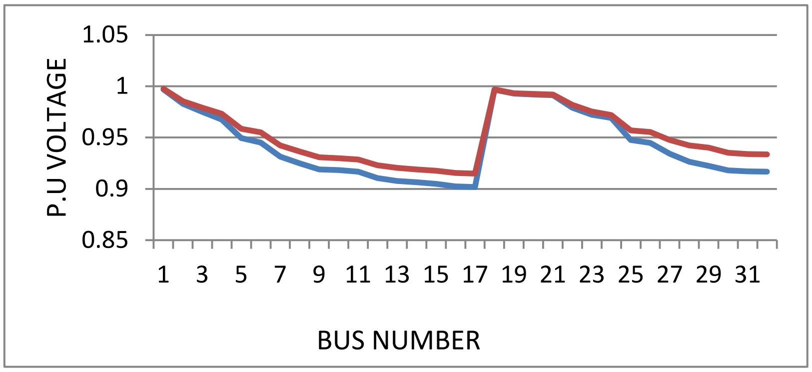

Fig. 3 Voltage profile before and after capacitor placement on 33 Bus system

3.6 Analysis on 69 Bus System

On 69 Bus systems, three optimal locations were identified using power loss index method. They are Bus No. 61, 64 and 59. Optimal sizes were obtained using TLBO algorithm. The values of capacitors are presented in the Table 3 On 69 Bus system, loss without compensation is 225 kW and after compensation, active power loss is 151.615 kW. Fig.4. shows the voltages before and after compensation.

Table 3. Optimal locations and sizes of capacitors on 69 Bus system

Optimal Location (Bus No.)	Optimal Size (kVAr)
61	660
64	299
59	448

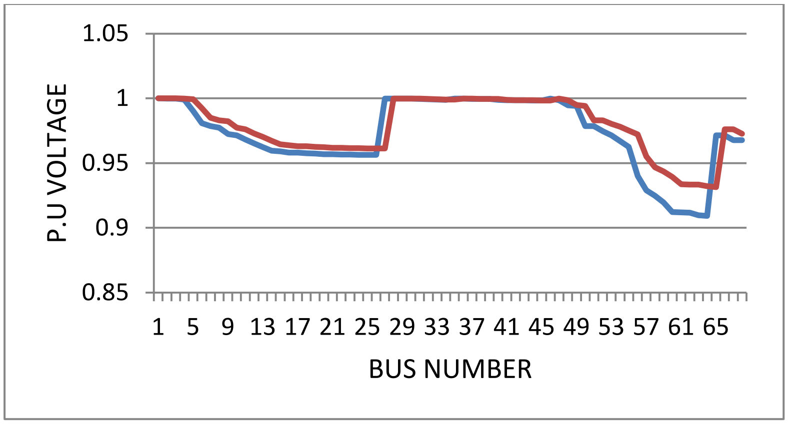

Fig. 4 Voltage profile before and after capacitor placement on 69 Bus system

3.7 Analysis on 85 Bus System

On 85 Bus system, Four optimal locations were identified using power loss index method.They are Bus No. 3,39, 2 and 18. Optimal sizes were obtained using TLBO algorithm. The values of capacitors are presented in the Table 4. On 85 Bus systems, loss without compensation is 316.11 kW. and after compensation, active power loss is 165.13 kW. Fig. 5 shows the voltages before and after compensation.

Table 4. Optimal locations and sizes of capacitors on 85 Bus system

Optimal Location (Bus No.)	Optimal Size (kVAr)
3	644
39	837
2	429
18	687

Fig.5 Voltage profile before and after capacitor placement on 85 Bus system

IV. COST FUNCTION CALCULATION

The proposed objective function of optimal capacitor location problem is to minimize the total cost which is determined by the following equation

$$Minimize\ s = k_e \sum_{j=1}^{L} TjPj + \sum_{i=1}^{ncp} K_c Q_{ci}$$

Where the constants are taken as

Where K_e is the energy cost per each kWh;

T_j is the duration for which jth load level operates;

P_j is the active power loss during jth load level;

K_c is the purchase cost of capacitor per kVAr;

Q_{ci} is the size of the capacitor placed at the ith bus;

ncap is the number of capacitor locations.

Table 5. Comparision of cost before and after compensation including net saving

s.no	Bus number	Annual cost before compensation (₹)obtained	Annual cost after compensation (₹)	Net saving obtained in %
1	15	2,366,636.46	1,524,282.22	55%
2	33	8,070,305.18	6,011,288.44	25%

3	69	8,616,394.89	6,143,087.43	29%
4	85	12,163,685.44	94,583.328	43%

V. RESULT &CONCLUSIONS

In this project work, a powerful algorithm called Teaching Learning Based optimization Algorithm (TLBO) is implemented for optimal allocations and sizing of capacitors in various distribution systems. The candidate buses for installing capacitors are identified using Power Loss Index (PLI). Then the TLBO algorithm is employed to deduce the size of capacitors and their locations from the elected buses. The objective function is designed to reduce the total active power loss. The proposed algorithm is tested on 15, 33, 69 and 85 bus radial distribution systems.

On 15 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 2 and 5. Optimal sizes were obtained using teaching learning based optimization algorithm. On 15 Bus system, loss without compensation is 61.80 kW and after compensation, active power loss is 32.96 kW.

On 33 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 7,23 and 14. Optimal sizes were obtained using teaching learning based optimization algorithm. On 33 Bus system, loss without compensation is 210.74 kW. and after compensation, active power loss is 148.2 kW.

On 69 Bus system, three optimal locations were identified using power loss index method. They are Bus No. 61,64, and 59. Optimal sizes were obtained using teaching learning based optimization algorithm. On 69 Bus system, loss without compensation is 225 kW and after compensation, active power loss is 151.615 kW.

On 85 Bus system, four optimal locations were identified using power loss index method. They are Bus No. 3, 39, 2 and 18. Optimal sizes were obtained using teaching learning based optimization algorithm. On 85 Bus system, loss without compensation is 316.11 kW and after compensation, active power loss is 165.13 kW.

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