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Optimal Capacitor Placement in Radial Distribution Network Based on Power Loss Sensitivity Index Using Ant Lion Optimizer Considering Different Loading

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Abstract

In this paper, the reactive resources placement including capacitor bank in radial distribution network is studied. The placement purpose is to reduce the cost of power loss, the cost of capacitor purchase and installation. The location and size of the capacitors in the distribution network are determined using the intelligent ant lion optimizer (ALO) method, which is inspired by the hunting behavior of the ant lions. Based on the power loss sensitivity factor (LSF), candidate buses are selected for capacitor installation using the ALO. The proposed method is implemented ona 33-bus radial distribution networks. In this study, the effect of loading changes on the placement problem and distribution network characteristics including power losses, minimum voltage, voltage profile and net savings are evaluated. The results show that after optimal capacitor placement the characteristics of the distribution network includes active and reactive power loss are significantly reduced and also the network voltage profile is improved compared to former capacitor placement. The performance of the proposed method is compared to particle swarm optimization (PSO), teaching-learning based optimization (TLBO) and previous studies, which showed the superiority of the proposed method in achieving lower cost and greater net saving.

Keywords: Radial Distribution Network, Capacitor Placement, Power Loss Sensitivity Index, Cost, Ant Lion Optimizer.

1. INTRODUCTION

Distribution network losses are divided into two major divisions, with 60% of them being lost in network lines and 40% in transformers. Reducing even a tiny fraction of these amounts can bring significant

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economic savings. [1]. On the other hand, the rapid increase in energy costs and investment costs of generation and the problems arising from the installation of generation resources have attracted more attention to assess the impact of losses on the operation and performance of power distribution systems. Therefore, reducing power losses is one of the most interesting issues of studies of power distribution system [1]. Several methods have been proposed for achieving acceptable power quality and improving the efficiency of achieving possible economic benefits. The total power delivered to the distribution network is calculated on the basis of the total power generation and transmission system power losses. Reduction of distribution system losses is considered to improve efficiency. In the last three decades, there have been numerous studies on the reduction of losses as well as the improvement of voltage profiles in distribution networks. The major ways to reduce losses in distribution networks include the use of capacitors, reconfiguration of distribution networks, and allocation of distributed generation in distribution networks. Capacitors are mainly used in high voltage distribution networks, rearrangements in low voltage distribution systems and more distributed generation under the conditions of small generators [2-3]. Installation of capacitors in distribution feeders is one of the most important and widely used methods of loss reduction. Among the most important benefits of this method are improved power factor, voltage profile improvement, loss reduction, and feeder capacity increase. Therefore, it is important to determine the optimum location and capacity of the capacitor in the distribution network to achieve the stated goals. Solving the problem of optimal placement of capacitors in the distribution network can be accomplished through various methods which the use of smart algorithms is one of the most widely used methods today [4-5]. Numerous studies have been conducted on the use of capacitors in the distribution network. In [6], a Teaching-learning-based optimization (TLBO) method with the aim of reducing power losses and energy costs by optimizing the capacitor placement in a radial distribution network is presented. In [7], cuckoo optimization algorithm (COA), In [8] artificial bee algorithm (ABC), in [9] particle swarm optimization, in [10] krill herd optimization (KHO), in [11] flower pollination algorithm (FPA) are presented to optimize the capacitors in distribution networks with objective power loss and reactive cost minimization and also voltage profile and stability improvement. In [12], biogeography-based optimization is applied for optimal sitting and sizing of capacitor in radial network for power loss and harmonic reduction. In [13], harmony search optimization (HSO), IN [14] bacterial foraging optimization (BFO), in [15] gravitational search algorithm (GSA) are used for losses cost and capacitor cost reduction and also maximization of net saving.

As it is clear that in literature review, different optimization algorithms and some objective function are used for optimal sitting and and sizing of the capacitor in radial networks. In most studies, reactive losses have been presented, which is included in this paper. In this study, a robust optimization method with high optimization speed and accuracy is used to solve the problem. Also due to variation of distribution network load demand, effect of different loading is investigated on capacitor placement problem and network active and reactive losses, voltage profile and also net saving.

In this paper, the Ant Lion Optimization (ALO) method [16-18], which is inspired by the Ant Lion hunting behavior, is used to solve the capacitor placement problem in order to reduce the cost of loss, reduce the cost of purchase and install the capacitor. The ALO method has optimized speed and accuracy andbeen used in various studies of power system optimization in recent years. The decision variables include determining the location and capacity of the capacitors in the distribution network, which is determined by the ALO optimization algorithm. The performance of ALO method in solving the capacitor placement problem is also compared with each of the PSO and TLBO methods as well as the FPA method in [19]. The results of the capacitance replacement problem include the values of active and reactive losses, the cost of purchasing and installing the capacitors, the minimum and maximum voltage, the amount of network financial savings for each of the different methods are presented.

The highlights of this paper are as follows:

- Optimum allocation of capacitors in distribution networks based on ALO algorithm
- Using of loss sensitivity factor (LSF) to determine candidate buses for capacitor allocation
- Reduce power losses cost and increase network net saving using optimal capacitor allocation
- Evaluation of different loading condition in optimal capacitor sitting and sizing
- Superiority of ALO compared with PSO, TLBO and FPA in optimal capacitor allocation

2. PROBLEM FORMULATION

The optimal placement of the capacitors in the distribution network with the aim of reducing the cost of losses, reducing the cost of purchasing and installing the capacitors is provided by the ALO algorithm. Initially, Candidate buses are specified to determine the optimum location and capacity of the capacitors using Loss Sensitivity Factor (LSF). Then, the best location and capacitance of the capacitors from the candidate buses is determined by the ALO method. The proposed method is implemented on a 33-bus radial network.

2.1. Determining Candidate Buses for Capacitor Installation

Loss Sensitivity Factor (LSF) has been used to determine loss-sensitive buses and also to reduce computing time and serach space. According to Fig. 1, power losses in the branch are defined by RI^2 [19-20].

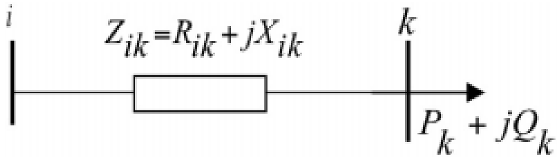

Fig. 1. Equivalent circuit of distribution network [20].

The LSF factor can be calculated as follows [20]:

$$P_{ik-loss} = \frac{(P_k^2 + Q_k^2)R_{ik}}{(V_k)^2} \qquad (1)$$

$$\frac{\partial P_{ik-loss}}{\partial Q_k} = \frac{2Q_k R_{ik}}{(V_k)^2} \qquad (2)$$

If the bus is selected as the candidate bus, the bus voltage value is less than 1.01. Candidate buses have both a higher LSF and the $\frac{V_{bus}}{0.95} \prec 1.01$ p.u condition which must be met. System buses are sorted in descending order of LSF values.

2.2. Objective Function of The Problem

The proposed objective function for optimal capacitor placement is the total cost reduction shown by the following equation. In this objective function, the cost of distribution network active power loss is included, along with the cost of purchasing and installing the capacitor [19].

$$\begin{aligned} Cost\_Cap = {} & K_p \times P_{loss} \times T \\ & + K_i \times N_{Cap} \\ & + K_c \sum_{i}^{N_{cap}} Q_{ci} \end{aligned} \qquad (3)$$

where K_p is the cost factor of loss, K_i is the factor of installation cost and K_c is the cost factor of each kVAR capacitor which their values are taken from [6], and their values are presented in Table 1. Also, T is the annual hour of capacitor operation and N_{Cap} is the number of installed capacitors and Q_{ci} is the reactive power injected by the ith capacitor.

2.3. Constraints

The optimization response is acceptable if some conditions and requirements of the distribution network are met which are defined as equal and unequal constraints below to control the optimization of these constraints at each iteration.

- ***Load flow constraints***

Common methods of load flow such as Newton Raphson and Gauss Seidel cannot be applied to distribution networks. The backward-forward sweep is used to load flow in distribution system. The algebraic sum of the input and output power in the distribution system must be equal [19], thus:

$$P_{Swing} + \sum_{i=1}^{N_{DG}} P_{DG}(i) = \sum_{i=1}^{L} P_{Lineloss}(i) + \sum_{q=1}^{N} Pd(q) \qquad (4)$$

$$Q_{Swing} + \sum_{i=1}^{N_{DG}} Q_{DG}(i) = \sum_{i=1}^{L} Q_{Lineloss}(i) + \sum_{q=1}^{N} Qd(q) \qquad (5)$$

- ***The voltage constraint***

$$V_{min} \le |V_i| \le V_{max} \qquad (6)$$

Table 1. ***Values of losses cost factor, capacitor installation and Purchase Costs [19].***

Parameter	Kp (\$ / kWh)	Ki (\$)	Kc(\$ / $kVAr$)
Value	0.06	1000	3

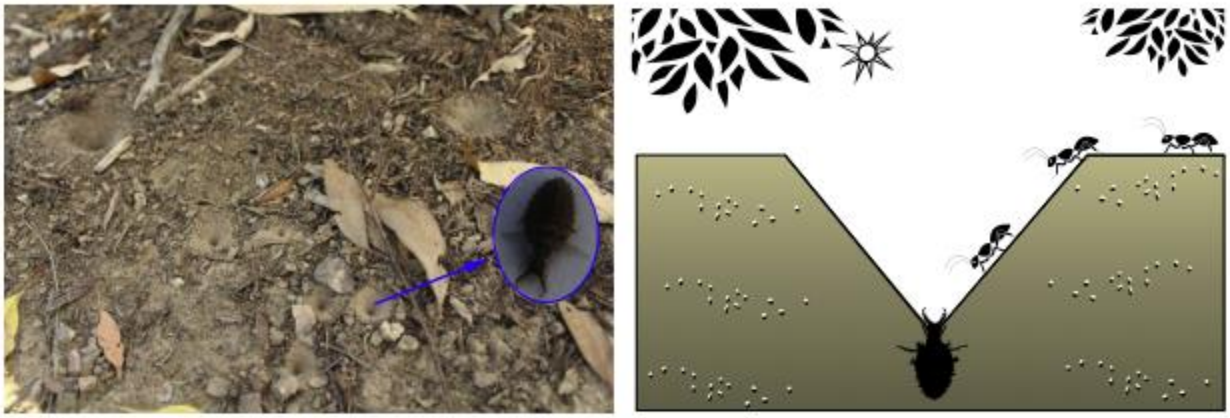

Fig. 2. Cone-shaped trap and ant lion hunting behavior [18-16].

The bus voltage range must be in a predetermined range. in other words:

- ***The constraint of total compensated reactive power***

$$\sum_{b=1}^{comp} Q(i) \le 0.75 \times \sum_{q=1}^{N} Qd(q) \qquad (7)$$

The total compensatory reactive power in the grid shall not exceed 0.75 of the total reactive power of the grid so that the grid does not retain its lag state and is not leed [19].

- ***The constrant of capacitor equipment reactive injection***

$$Q^{min} \le Q\ (i) \le Q^{max} \qquad (8)$$

Reactive injectable power is discrete with 50 kV steps and is constrained by the following equation:

3. PROBLEM SOLVING OPTIMIZATION METHOD

In this study, the ALO algorithm was used to solve the optimization problem. Following is the introduction of the ALO algorithm and its implementation in solving the problem of capacitor placement in the distribution network.

3.1. Overview of ALO Algorithm

Figure 2 (a) illustrate several conical holes of different sizes. After digging the hole, the insect baby is hiding under the cone and in the basement and waiting for the insects (Sit like a hunter and wait) (Possibly ants) to be trapped in the hole as described in Figure 2(b).

Random move or walk to model the movement of ants is selected as follows [18-16].

$$x(t) = [0,\ cumsum(2r(t_1)-1),\ cumsum(2r(t_2)-1),\ \ldots,\ cumsum(2r(t_n)-1)] \qquad (9)$$

r (t) is a random function that is defined by [18-16]:

$$r(t) = \begin{cases} 1 & if\ rand > 0.5 \\ 0 & if\ rand \le 0.5 \end{cases} \qquad (10)$$

where, t is random walking and *rand* is a random number over [1,0] [16-18]. To maintain steps randomly within the search space, they are normalized by [18-16]:

$$X_i^t = \frac{\left(X_i^t - a_i\right)\times\left(d_i - c_i^t\right)}{d_i^t - a_i} + c_i \tag{11}$$

where, a_i and b_i refer to minimum and maximum step i in variable i, the c_i^t and d_i^t are minimum and maximum variable of i in iter t.

The random steps of the ants are affected by the antlions' trap. For the mathematical modeling of this assumption, the following relation is proposed [18-16]:

$$\mathrm{c}_{\mathrm{i}}^{\mathrm{t}} = \mathrm{Antlion}_{\mathrm{j}}^{\mathrm{t}} + \mathrm{c}^{\mathrm{t}} \tag{12}$$

$$\mathrm{d}_{\mathrm{i}}^{\mathrm{t}} = \mathrm{Antlion}_{\mathrm{j}}^{\mathrm{t}} + \mathrm{d}^{\mathrm{t}} \tag{13}$$

where c^t and v refre to minimum and maximum variables in iter t. c_j^t and d_j^t refer to minimum and maximum variables of i^th^ ant. Also, antlion $_j^t$ refer to situation of jth antlion in iter t.

When antlions find a trapped ant, dump the soil into the center of the hole. This behavior causes the trapped ant to slip who tries to escape. This behavior is modeled as follows [18-16]:

The antlion pulls the ant into the soil and eats its body. To imitate this step, prey catches occur when the ants are fitter from their respective antlions. The antlion then needs to update its position with the last situation of ant hunting for improvement the chances of getting a new prey. This behavior is modeled as follows [18-16]:

$$c^t = c^t / I \tag{14}$$

$$d^t = d^t / I \tag{15}$$

where c^t and v refer to minimum and maximum variables in iter t.

The ant pulls the ant into the soil and eats its body. To mimic this stage, it is assumed that prey capture occurs when the ants are fitter than their respective antlers. It is then necessary for the milkman to update his position with the latest hunted ant position to improve his chances of getting a new flavor. This behavior is modeled as follows [16-18]:

$$Antlion_j^t = Ant_i^t \quad if \quad f\left(Ant_i^t\right) > f\left(Antlion_j^t\right) \tag{16}$$

where, t represents the current iteration, $\mathrm{Antlion}_j^t$ is the position of chosen jth ant lion in iteration t and Ant_i^t represents the position of Ith Ant in the same iteration.

The best ant lion ever obtained is stored in each iteration and considered as an expert. It is assumed that each ant will simultaneously walk around a selected ant by an expert roulette wheel [16–18]:

$$Ant_i^t = \frac{R_A^t + R_E^t}{2} \tag{17}$$

where, R_A^t refres to random walking of ant lion in iter t, R_E^t is walking with expert randomely in iter t. Ant_i^t is position of ith ant in iter t.

3.2. Implementation the ALO in Problem Solving

The problem-solving implementation process using the ALO algorithm is presented as follows:

Step 1) After setting the parameters of the ALO algorithm, system data including network bus data and lines are applied.

Step 2) Base load distribution is executed and initial values of voltage and losses are calculated.

Step 3) After ranking the basses, the candidate basses are identified to install the capacitor using the LSF factor.

Step 4) Problem constraints and maximum iteration of the algorithm are examined.

Step 5) Optimization (population) variables are executed for each lion between its permissible range and load distribution. The target function is then calculated. It should be noted that optimization variables include the location and capacity of the capacitors in the network.

Step 6) The population is applied to the capacity of the optimization variables within the permissible range.

Step 8) A new population of antlers is used to change the position and load distribution is implemented. Then the target function is computed.

Step 9) Unauthorized answers are identified.

Step 10) The best answer is saved.

Step 11) Convergence conditions are met? Yes, we will go to step 12 otherwise we will go to step 8.

Step 12) Stop Algorithm

4. SIMULATION RESULTS AND DISCUSSION

In this section, the results of optimal placement of the capacitors in the radial distribution network are presented using the ALO algorithm regarding the loss sensitivity index and with the aim of reducing the cost of losses and the cost of capacitor installing and purchasing. The proposed problem is addressed on the 33 IEEE standard radial bus network. Results including active and reactive losses, total compensation capacity, total system cost, minimum voltage, and net savings are calculated before and after optimization. The performance of the proposed method has also been compared with previous studies.

4.1. Network Studied

The test network studied for reactive compensation using ALO and LSF loss sensitivity index is a 33-bus network and is illustrated in Fig. 3 as a single-line diagram. The 33-bus network has one main feeder and 3 sub-feeders. This network is extracted from Ref. [19].

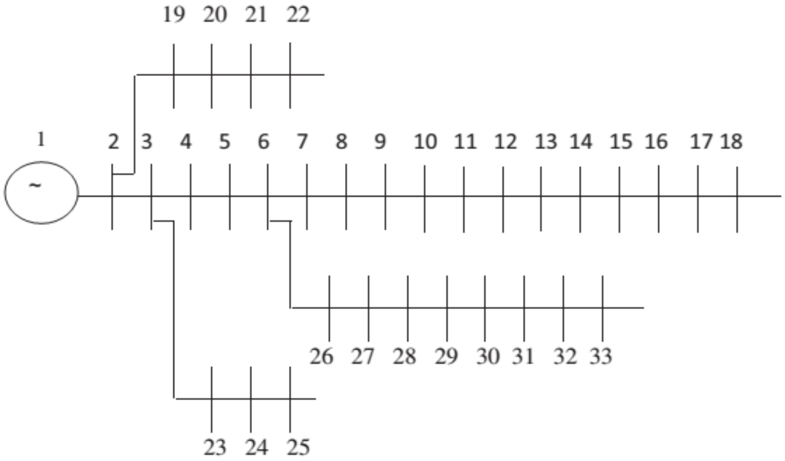

Fig. 3. Linear diagram of the 33bus radial network [19].

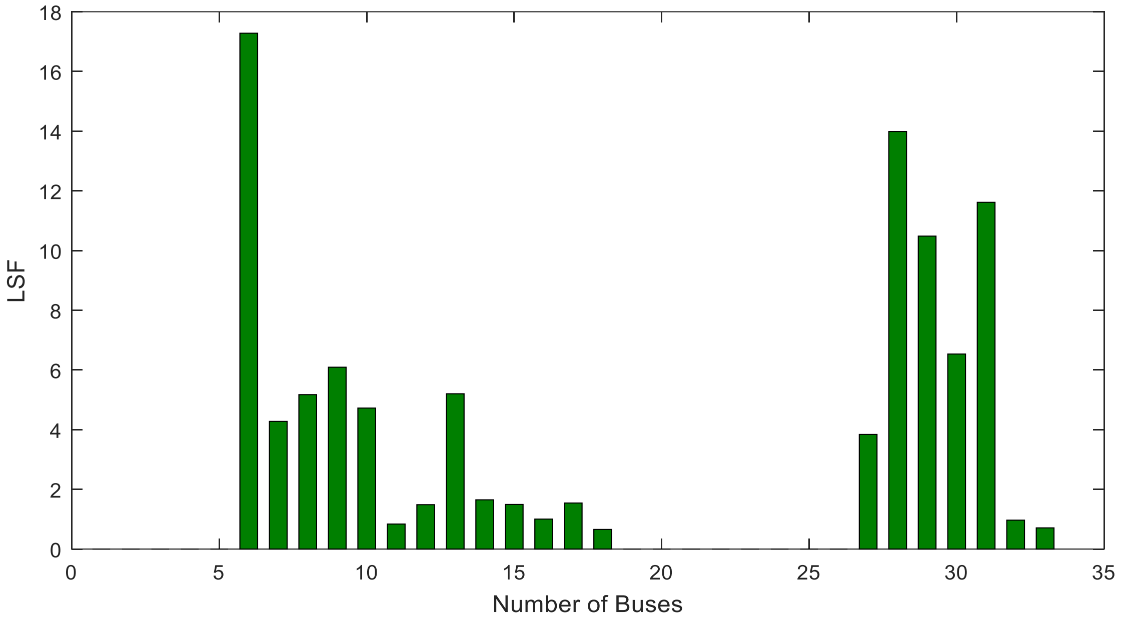

Fig. 4. LSF curve for 33-bus network.

Table 2. ***Candidate buses for capacitor installation.***

Test Network	Candidate Buses
33-bus	6, 28, 31, 29, 30, 9

The LSF curve for the 33-bus test network is shown in Fig. 4. The 6 buses in the network are selected to install the capacitors and determine the optimal size by the ALO method. The ALO algorithm can install and determine at least one and up to 6 capacitors. In Table 2, the candidate buses for compensating are presented.

4.2. Capacitor Placement Results

In order to validate the ALO method in solving the problem, the capacitor placement has been compared with particle swarm optimization (PSO) and teaching-learning based optimization (TLBO) methods which are high power and accuracy optimization methods. Also, the results are compared with the results of the flower pollination algorithm (FPA) in [19]. The maximum size of each capacitor bank is 1.5 MVAr and the minimum size is 50 kVAr. Compensation size value in the network is also set to 3 MVAr. The convergence curve of different methods is presented in Fig. 5. As can be seen, the ALO method achieves less cost in lower iteration with higher optimization speed than the other methods. Therefore, the superiority of the proposed method compared to the PSO and TLBO methods is confirmed in capacitor placement problem. The optimal placement results and optimal size determination of the shunt capacitors for the 33-bus distribution network are presented in Table 3. The ALO method selects buses 9 and 30 for capacitors installation with sizes of 500 and 950 kVAr, respectively. But the FPA method in [19] determined three buses of 6, 9 and 30 with sizes of 250, 400 and 950 kVAr. In the 33-bus test network, power loss without compensation is 202.66 kW, which decreased to 136.53 kW after compensation according to Table 2. In addition, reactive power losses have also decreased from 135.18 to 90.99 kW. The minimum voltage also increased from 0.9131 p. u to 0.9329 p.u.

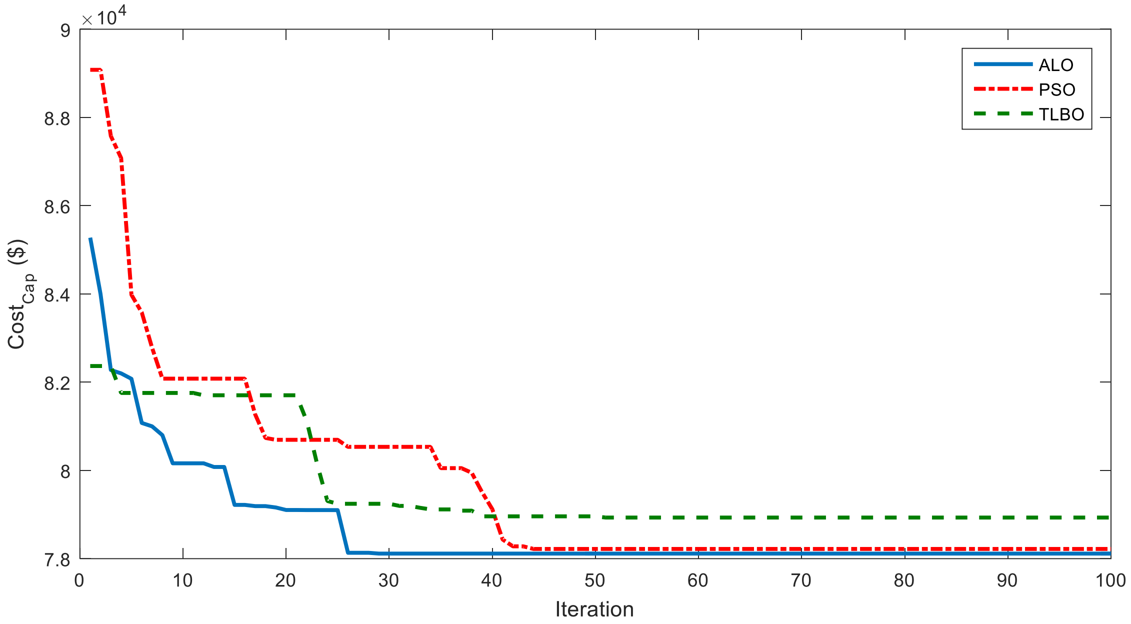

Fig. 5. Convergence curve of different methods in the capacitor placement problem.

Table 3. ***Results of optimal capacitor placement of the 33-bus network.***

	Base Network	**FPA [19]**	**PSO**	**TLBO**	**ALO**
$P_{loss}\,(kw)$	202.66	135.31	137.02	135.62	136.53
$Q_{loss}\,(kVAr)$	135.18	90.35	91.33	90.49	90.99
$P_{grid}\,(kw)$	3917.68	3850.31	3852.02	3850.62	3851.54
$Qc_i\,(bus,kVAr)$	--	6, 250 30, 950 9, 400	30, 1000 9, 400	6, 250 0, 850 9, 450	30, 950 9, 500
$\sum Q_{ci}\,(kVAr)$	--	1600	1400	1550	1450
$V_{Min}\,(p.u)$	0.9131	0.9332	0.9314	0.9333	0.9329
LSF	17.28	4.98	5.00	4.98	4.98
$fitness$($)	106528.27	79919.90	78220.24	78931.94	**78115.06**
$saving$($)	-	27608.36	28308.02	27596.32	**18413.22**
$saving$(%)	-	25.91	26.57	25.90	**26.67**

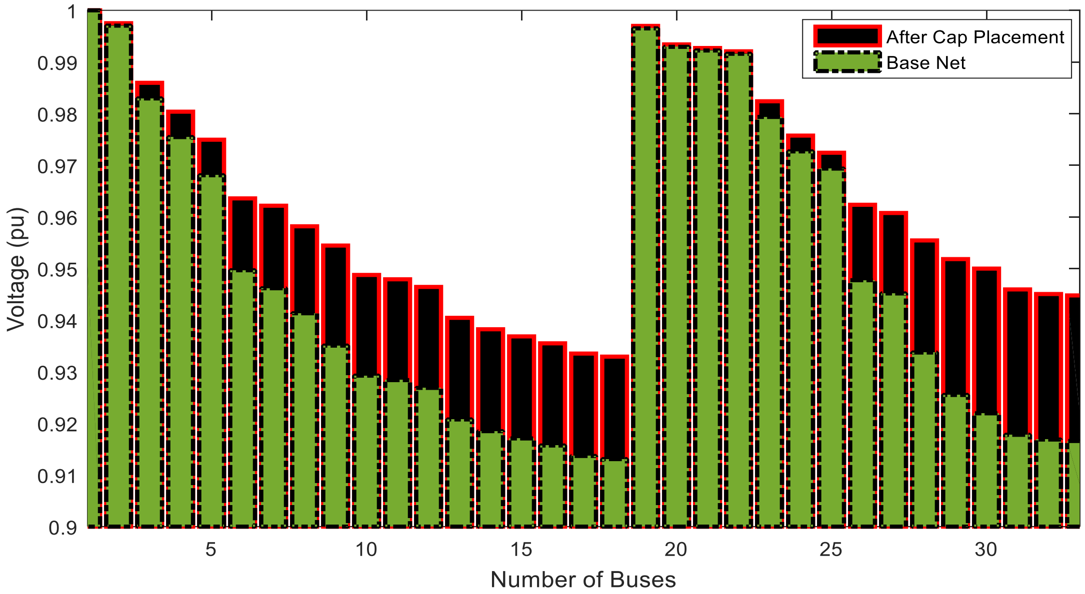

Fig. 6. Voltage profile of 33-bus network.

Furthermore, without compensation the active power received from the main feeder is 3917.68 kW which decreased to 3851.54 kW. This reduction in the active power received from the main network also reduces the cost of the total distribution network. The maximum value of the LSF index also decreased from 17.28 to 4.98 (71% decreasing). The total cost of the proposed objective function is obtained 78,115.05 $, which is the lower value than the other methods and also a net saving of 28,413.2 $, which is more than the PSO, TLBO and FPA [19]. Also, the net saving percentage with the proposed ALO is 26.67% which is better than the PSO, TLBO and FPA [19] methods. According to Table 2, it is observed that with the optimal allocation of capacitors, the minimum voltage value increased from 0.9131 p. u to 0.9329 p.u. The improvement of the network voltage profile after capacitor placement is shown in Fig. 6. As can be seen, the voltage deviation of the network is declined with capacitor placement and injection the reactive power to the network.

4.3. Effect of Different Loading Conditions

In the following, the effect of network load changes is evaluated on the problem based on ALO. Therefore, the light load period is 62.5% of the normal load and the heavy load period is 125% of the normal load. The results are presented in Table 4. The results show that as the network load increases, the number of capacitors used in the network increases, resulting in increased capacitor utilization costs and reduced the net saving. The minimum voltage of the network is also decreased with increasing the network load.

5. CONCLUSION

In this paper, optimal capacitor placement in 33-bus radial distribution network with the aim of reducing the cost of losses, reducing

Table 4. ***Results of optimal capacitor placement for the 33-bus network in Different Loading.***

	Light load	**Normal load**	**Heavy load**
$P_{loss}\,(kw)$	52.21	136.53	225.29
$Q_{loss}\,(kVAr)$	35.07	90.99	151.18
$P_{grid}\,(kw)$	2374.08	3851.54	4869.04
$Qc_i\,(bus,kVAr)$	6, 250 30, 700	30, 950 9, 500	6, 650 31, 600 29, 450
$\sum Q_{ci}\,(kVAr)$	950	1450	1700
$V_{Min}\,(p.u)$	0.9562	0.9329	0.9066
LSF	0.94	4.98	7.64
$fitness(\$)$	32293.23	**78115.06**	126516.06
$saving(\$)$	74235.03	**28413.22**	19987.79
$saving(\%)$	69.68	**26.67**	18.76

the cost of purchasing and installing the capacitor are studied using the ant lion optimization (ALO) algorithm. The decision variables are considered as the optimum location and size of the capacitors. Candidate buses are first determined for capacitors placement using loss sensitivity factor and then location and size of the capacitors are determined using ALO. In order to validate the ALO in solving the problem, capacitor placement problem is compared with PSO, TLBO and FPA methods. The results showed that the ALO method has a lower cost and more net savings than the other methods. The loading changes also showed that as the load level of the network increased, the number of capacitors used in the network increased and as a result, the cost of operating the capacitors increased and the net saving of the network decreased. Also, the minimum voltage of the network is weakened by rising the load level. The ALO method achieves a 26.67%, 69.68% and 18.76% net savings in the normal, light and heavy loading conditions, respectively.

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