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Multi-objective Placement of Capacitor Banks in Distribution System using Bee Colony Optimization Algorithm

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Abstract

Optimal sitting and sizing of shunt capacitor banks at the distribution networks for the purpose of power quality improvement is drawn much attention of electric power utilities in the last decades. Determining the optimal number, location and sizing of capacitor using Bee Colony Optimization algorithm (BCO) is being presented in this paper. The BCO algorithm is a new population based meta-heuristic approach exalted by intelligent foraging behaviour of honey bee swarm. The objectives include improvement of reliability and voltage profile and minimization of line losses. Also effect of capacitor installation on reducing carbon dioxide emissions of the grid has been considered in the objective function. This method has been executed on a 33-bus test system and comparative studies are conducted before and after capacitor installation in the test system. Results illustrate significant losses and carbon dioxide emission reduction and voltage profile and reliability improvement with appropriate presence of capacitor banks in distribution system.

Keywords: *Capacitor, Loss, Reliability, Carbon Dioxide Emission, Bee Colony Optimization Algorithm*

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1. Introduction

Much importance has been attached to energy over the past decade. Optimum consumption of electrical energy is particularly important regarding the fact that fossil fuels are not renewable and nuclear fuels are hazardous. Nowadays, reduction in greenhouses gases is a major concern around worldwide. On the other hand, a power network should supply its customers with minimal outages and maximal power quality. Several facilities such as capacitors are used to achieve these goals. Optimal placement and sizing of this equipment has significant effect on decreasing power losses and greenhouses gases emissions of network, voltage profile improvement and also reliability enhancement. Several researches were provided in recent years about optimal placement and sizing of the capacitor in order to achieve different aims in distribution system.

Shunt capacitor banks are used for various objectives in distribution networks such as power loss reduction, voltage profile improvement, system capacity release, reactive power compensation, power factor correction and reliability enhancement [1-8]. To achieve these aims, one must determine the capacitors number and their suitable locations and sizes.

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It is necessary to apply a compensative function for better analysis problem optimal placement of capacitor in distribution system. The desired solution would be closer to reach if more objectives are considered in the allocation problem. Also the investment cost of capacitor is a significant problem that prevents engineers using them widely in system planning. In this paper, a multi-objective optimization is used for the placement and sizing of capacitor banks by bee colony optimization algorithm. The objectives consist of minimization of the real power losses, capacitor's investment cost, carbon dioxide emissions and reliability enhancement and optimization of voltage profile of distribution system. None of the studies done so far, all of these goals together are not considered.

The reminder of the paper is structured as follows: Section 2 describes the formulation of the multi-objective function. Bee Colony Optimization algorithm is illustrated in Section 3, briefly, and also stages of proposed algorithm for capacitor placement is presented in this section. Simulation results for capacitor installation in 33-bus test system are presented and discussed in section 4. Finally, section 5 summarizes the main points and results of this paper.

2. The problem formulation

As mentioned earlier, the optimal capacitor placement problem has been formulated in this work with the objective of simultaneous optimization of power quality parameters and economic costs incurred. In this sense, this is essentially a multi-objective optimization problem where the objective function comprises five components i.e. five objectives, the goal is to converge these five objective functions into one.

2.1. The objective function

Mathematically, the multi-objective function is formulated as:

$$\mathrm{f} = \mathrm{Min}(\mathrm{f}_1 + \mathrm{f}_2 + \mathrm{f}_3 + \alpha \mathrm{f}_4 + \mathrm{f}_5) \qquad (1)$$

2.2. Real power losses

An essential requirement in a distribution system, for efficient power system operation, is to achieve reduction in the real power loss, as far as possible.

The real power loss of the line section connecting buses i and i+1 may be computed as:

$$\mathrm{P}_{\mathrm{Loss}}(\mathrm{i}, \mathrm{i}+1) = \mathrm{R}_{\mathrm{i,i+1}} \mathrm{I}_{\mathrm{i,i+1}}^2 \qquad (2)$$

Where $I_{i,i+1}$ is the magnitude of the current, $R_{i,i+1}$ and $X_{i,i+1}$ are resistance and reactance of the line section buses i , i+1 respectively. The total real power loss of the feeder is determined by summing up the losses of all line sections of the feeder, which is given as:

$$\mathrm{P}_{\mathrm{T,loss}} = \sum_{\mathrm{i}=1}^{\mathrm{NB}} \mathrm{P}_{\mathrm{Loss}}(\mathrm{i}, \mathrm{i}+1) \qquad (3)$$

Where NB is the number of line section in the distribution system. The loss cost function i.e. f_1 given dy:

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$$f_1 = K_P \times P_{T,loss} + K_E \times P_{T,loss} \times H \qquad (4)$$

Where K_P is the factor to convert peak active power losses to dollar ($/kW), K_E is the factor to convert energy losses to dollar ($/kWh) and H is design time duration. It should be noted that value of K_P and K_E is set to 168 and 0.07 in this paper [3], respectively.

2.3. Reliability

Capacitor placement can supply part of the reactive power demands, respectively. Therefore, due to the reduction of the magnitude of current, the resistive losses decrease. As a result, destructive effects of temperature on the reliability of overhead lines and underground cables are moderated [2]. These impacts on reliability take into consideration as a failure rate reduction of distribution feeder components. Before capacitor placement, any feeder i has an uncompensated failure rate of λ_i^{uncomp}. If the reactive component of a feeder branch is fully compensated, its failure rate reduces to λ_i^{comp}. If the reactive component of current are not completely compensated, a failure rate is defined with linear relationship to the percentage of compensation. Thus, the compensation coefficient of the ith branch is defined as:

$$\alpha_i = \frac{I_r^{new}}{I_r^{old}} \qquad (5)$$

Where I_r^{new} and I_r^{old} are the reactive components of the ith branch current before and after compensation, respectively. The new failure rate of the ith branch is computed as follows:

$$\lambda_{i-new} = \alpha_i \left(\lambda_i^{uncomp} - \lambda_i^{comp}\right) + \lambda_i^{comp} \qquad (6)$$

In this paper, expected interruption cost (ECOST) is included as part of the objective function. ECOST is a powerful tool for system planning. ECOST at bus i is calculated as follows [2]:

$$ECOST_i = L_{a(i)}\, C_i\, \lambda_i \qquad (7)$$

Where $L_{a(i)}$ is the active average load connected to load point i in kw and C_i is the cost of interruption (in $/kw) for the ith bus which is evaluated using composite customer damage function (CCDF). CCDF shows the cost of interruption as a function of interruption duration [9]. Since it accounts for reliability worth and the reliability level, ECOST is a comprehensive value used for this study. The total ECOST of the distribution feeder i.e. f_2 is calculated as follows:

$$f_2 = \sum_{i=1}^{NB} L_{a(i)}\, C_i\, \lambda_i \qquad (8)$$

2.4. Gas emission of network

Minimizing the carbon dioxide emission of network is selected as the third objective function for the placement of capacitor. The carbon dioxide emission function i.e. f_3 is calculated as follows [5]:

$$f_3 = \beta\ K_{co2}\, P_{T,Loss}\, H \qquad (9)$$

Where β is the emission coefficient that corresponds to the quantity of CO_2 emissions per kWh, K_{CO2} is the social cost of CO_2 emissions and H is design time duration.

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2.5. Voltage profile

One of the benefits of correct selection of location and size of capacitor is improvement of voltage profile. Voltage profile improvement function i.e. f_4 indicates higher voltage deviations from 1.0 per unit and calculated with the following equation:

$$f_4 = \sum_{i=1}^{NB} |V_i - 1| \tag{10}$$

Where V_i is the magnitude voltage on the ith bus. In equation (1) α which is an appropriate weight coefficient, implied in f_4.

2.6. Capacitor's investment cost

Considering shunt capacitors, practically there exists a certain number of standard sizes which are integer multiples of the smallest size Q_o^c. In general, capacitors of larger size have lower unit prices. The available capacitor size is usually limited to:

$$Q_o^{max} = L\, Q_o^c \tag{11}$$

Where L is an integer number. Therefore, for each location for capacitor installation, L sizes $\{Q_o^c, 2Q_o^c, \ldots, LQ_o^c\}$ are available for capacitor. Capacitor cost has two parts, a fixed part and a variable part depending upon the kvar capacity. Besides, the cost per kvar varies from one size to another. The capacitor installation costs are given in Table 1 [10].

Table. 1: Possible choices of capacitor sizes and cost/kVar

Case	1	2	3	4	5	6	7	8	9
Q_c(kVar)	150	300	450	600	750	900	1050	1200	1350
$/kVar	0.5	0.35	0.253	0.22	0.276	0.183	0.228	0.17	0.207
Case	10	11	12	13	14	15	16	17	18
Q_c(kVar)	1500	1650	1800	1950	2100	2250	2400	2550	2700
$/kVar	0.201	0.193	0.187	0.211	0.176	0.197	0.17	0.189	0.187
Case	19	20	21	22	23	24	25	26	27
Q_c(kVar)	2850	3000	3150	3300	3450	3600	3750	3900	4050
$/kVar	0.183	0.18	0.195	0.174	0.188	0.17	0.183	0.182	0.179

2.7. Operational constraints

From the point of view of system stability, power quality, etc., voltage magnitude at each bus must be maintained within its limits. The current in each branch must satisfy the branch's capacity. These constraints are expressed as follows:

$$V_{min} < |V_i| < V_{max} \tag{12}$$

$$|I_i| \leq I_{i,max} \tag{13}$$

Where is $|V_i|$ voltage magnitude of bus i, V_{min} and V_{max} are minimum and maximum bus voltage limits, respectively. $|I_i|$ is current magnitude and $I_{i,max}$ is maximum current limit of ith branch.

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3. Bee colony optimization algorithm (BCO)

Within the Bee Colony Optimization Metaheuristic (BCO), artificial bees collaborate in order to solve difficult combinatorial optimization problem. All artificial bees are located in the hive at the beginning of the search process. During the search process, artificial bees communicate directly. Each artificial bee makes a series of local moves, and in this way incrementally constructs a solution of the problem. Bees are adding solution components to the current partial solution until they create one or more feasible solutions. The search process is composed of iterations. When flying through the space our artificial bees perform forward pass or backward pass. During forward pass, bees create various partial solutions. They do this via a combination of individual exploration and collective experience from the past. After that, they perform backward pass, i.e. they return to the hive. In the hive, all bees participate in a decision-making process [11].

We assume that every bee can obtain the information about solutions' quality generated by all other bees. In this way, bees exchange information about quality of the partial solutions created. Bees compare all generated partial solutions. Based on the quality of the partial solutions generated, every bee decides whether to abandon the created partial solution and become again uncommitted follower, continue to expand the same partial solution without recruiting the nest mates, or dance and thus recruit the nest mates before returning to the created partial solution. Depending on the quality of the partial solutions generated, every bee possesses certain level of loyalty to the path leading to the previously discovered partial solution [12-14].

During the second forward pass, bees expand previously created partial solutions, and after that perform again the backward pass and return to the hive. In the hive bees again participate in a decision-making process, perform third forward pass, etc. The iteration ends when one or more feasible solutions are created. The algorithm parameters whose values need to be set prior the algorithm execution are as follows [11]:

nPop - The number of bees in the hive

nMove - The number of constructive moves during one forward pass

In the beginning of the search, all the bees are in the hive. The following is the pseudo code of the BCO algorithm:

```
1. Initialization: every bee is set to an empty solution;
2. For every bee do the forward pass;
    a) Set $k = 1$; //counter for constructive moves in the forward pass;
    b) Evaluate all possible constructive moves;
    c) According to evaluation, choose one move using the roulette wheel;
    d) $k = k + 1$; If $k \leq nMove$ Go To step b.
3. All bees are back to the hive; // backward pass starts;
4. Sort the bees by their objective function value;
5. Every bee decides randomly whether to continue its own exploration and become a recruiter, or to become a follower (bees with higher objective function value have greater chance to continue its own exploration);
6. For every follower, choose a new solution from recruiters by the roulette wheel;
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7. If the stopping condition is not met Go To step 2;

8. Output the best result.

The stopping condition could be the maximum number of forward/backward passes or the maximum number of forward/backward passes, without improving the objective function.

The Stages of proposed algorithm for capacitor placement is shown in Figure 1.

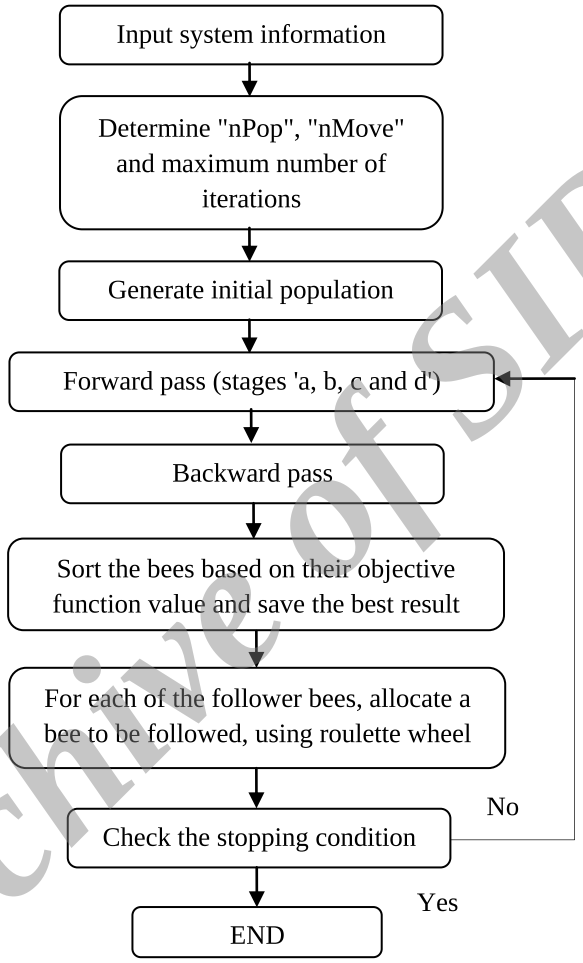

Fig. 1. Flowchart of BCO algorithm for capacitor placement.

4. Simulation result

For simulation purpose, a 33-bus distribution system is considered for capacitor bank installation. For the calculation of reliability indices and determination of optimal capacitor placement, it is assumed that the section with the highest resistance has the biggest failure rate of 0.5 f/year and the section with the smallest resistance has the least failure rate of 0.1 f/year [2]. Based on this assumption, failure rates of other sections are calculated linearly proportional to these two values according to their resistances.

Furthermore, it is assumed if the reactive component of a section current is fully compensated, its failure rate reduces to 85% of its uncompensated failure rate [2] and

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for partial compensation; the failure rate is calculated using (6). Also, it is assumed that there is only one breaker at the beginning of the main feeder and also there is one sectionalized at the beginning of each section. Besides, for each line, the repair time and total isolation and switching time are considered 8 hours and 0.5 hours, respectively. Also, other components such as transformers, bus bars, breakers and disconnects are assumed to be fully reliable, in this paper. Furthermore, the substation voltage (bus 1) is considered as 1.0 p.u and the lower and upper limit of voltage magnitude of buses 0.90 and 1.10 p.u are assumed, respectively.

4.1. 33-bus distribution system

The 12.66 kV, 33-bus, 4-lateral radial distribution system is considered as test system. In this paper assumed that load level is in peak condition (4458+ j 2760) kVA. The data and single line diagram of the 33-bus system is represented in Table 2 and Fig. 2, respectively [15].

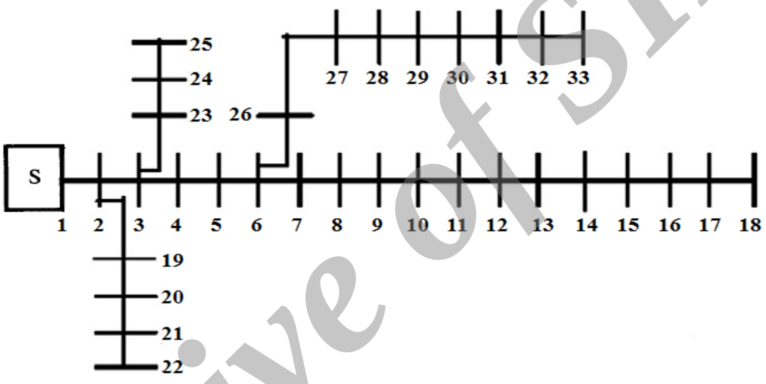

Fig. 2. Single line diagram of a 33-bus system.

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Table. 2: Load and line data of 33-bus system

Bus no.	Load		Feeder Section		Length (km)	R (Ω)	X (Ω)	λ (f/yr)
	kW	kVar	Sending	Receiving				
2	120	72	1	2	0.60	0.0922	0.0470	0.1000
3	108	48	2	3	0.75	0.4930	0.2511	0.2000
4	144	96	3	4	0.60	0.3660	0.1864	0.1680
5	72	36	4	5	0.60	0.3811	0.1941	0.1713
6	72	24	5	6	0.80	0.8191	0.7070	0.2800
7	240	120	6	7	0.60	0.1872	0.6188	0.1234
8	240	120	7	8	0.75	0.7114	0.2351	0.5000
9	72	24	8	9	0.80	1.0300	0.7400	0.3316
10	72	24	9	10	0.80	1.0440	0.7400	0.3351
11	54	36	10	11	0.60	0.1966	0.0650	0.1258
12	72	42	11	12	0.60	0.3744	0.1238	0.1700
13	72	42	12	13	0.80	1.4680	1.1550	0.4400
14	144	96	13	14	0.75	0.5416	0.7129	0.2110
15	72	12	14	15	0.75	0.5910	0.5260	0.2232
16	72	24	15	16	0.75	0.7463	0.5450	0.2616
17	72	24	16	17	0.80	1.2890	1.7210	0.3956
18	108	48	17	18	0.80	0.7320	0.5740	0.2580
19	108	48	2	19	0.75	0.1640	0.1565	0.1177
20	108	48	19	20	0.60	1.5042	1.3554	0.4488
21	108	48	20	21	0.80	0.4095	0.4784	0.1784
22	108	48	21	22	0.75	0.7089	0.9373	0.2523
23	108	60	3	23	0.75	0.4512	0.3083	0.1887
24	504	240	23	24	0.75	0.8980	0.7091	0.3000
25	504	240	24	25	0.80	0.8960	0.7011	0.2985
26	72	30	6	26	0.80	0.2030	0.1034	0.1274
27	72	30	26	27	0.60	0.2842	0.1447	0.1474
28	72	24	27	28	0.60	1.0590	0.9377	0.3388
29	144	84	28	29	0.80	0.8042	0.7006	0.2760
30	240	720	29	30	0.80	0.5075	0.2585	0.2026
31	180	84	30	31	0.75	0.9744	0.9630	0.3180
32	252	120	31	32	0.80	0.3105	0.3619	0.1540
33	72	48	32	33	0.60	0.3410	0.5302	0.1614

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The result of the program running for installation of capacitor banks, using 80 bees, and 250 iterations is shown in Fig. 3. It can see which the proposed algorithm has good convergence in reaching to the final solution. The best number, place and size to installation capacitor banks optimally demonstrated in Table 3. As it is illustrated in Table 4, optimal placement of capacitor leads to loss reduction and carbon dioxide emission, reliability and voltage profile improvement of 33-bus distribution system.

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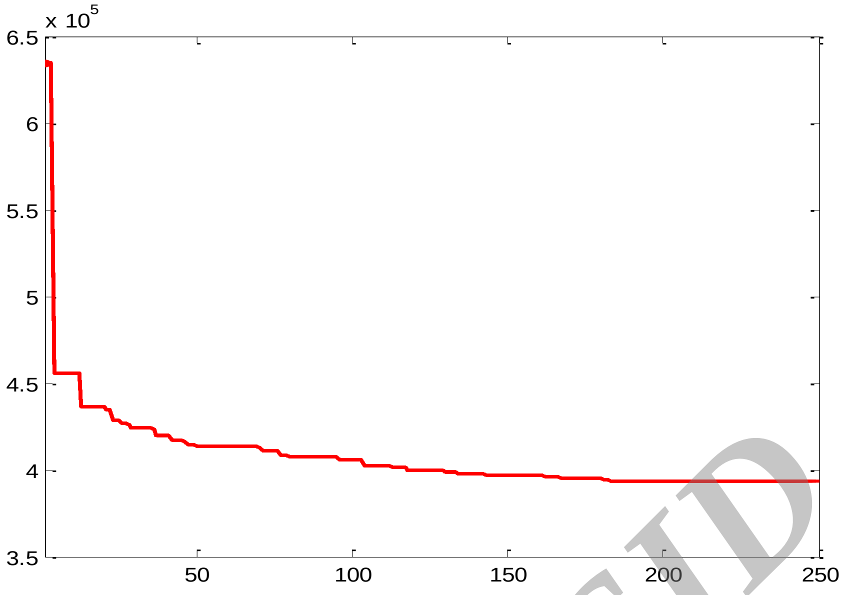

Fig. 3. The result of the program running.

Table 3: Optimum size and location of capacitor in 33-bus system

Location	Size (kVar)
Bus 7	600
Bus 9	150
Bus 14	300
Bus 25	450
Bus 30	600
Bus 31	450

Table 4: Results before and after installation of capacitor in 33-bus system

Case	ECOST ($)	$P_{T,Loss}$ (kW)	$Q_{T,Loss}$ (kVar)	f_3 ($)	f_4 (pu)
Base case	162960	314.45	213.3	94335	0.4921
After installation	148540	200.82	137.2	60246	0.2908

The percentage of improvement in the objective function parameters is also shown in Fig. 4. Considering Fig. 5, which is related to the voltage profile of 33-bus system, it can be perceived that when capacitor is located optimally, buses' voltage level increased suitably.

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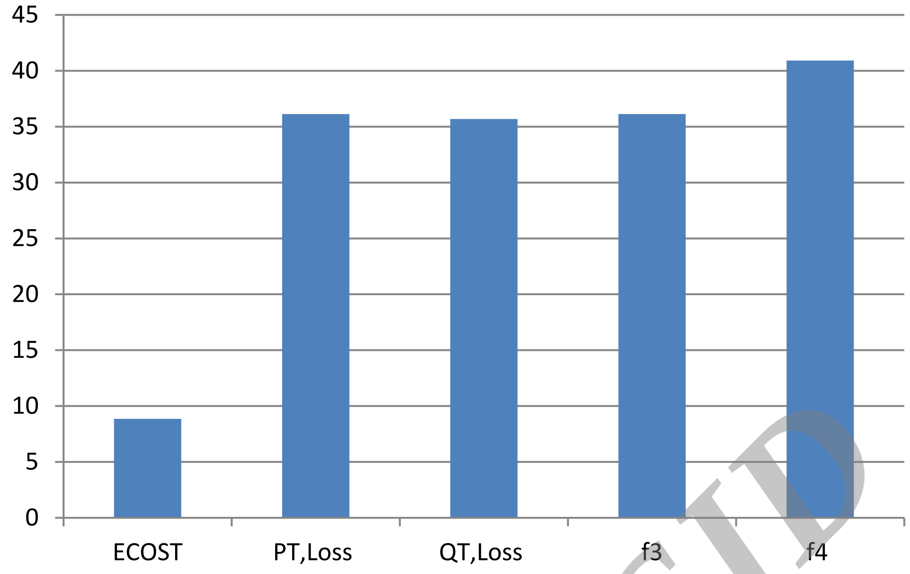

Fig. 4. (%) improvement in the objective function parameters

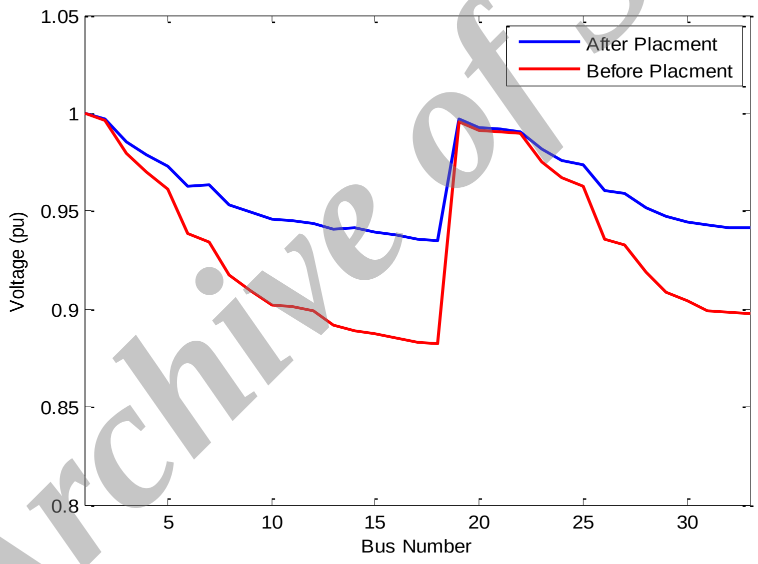

Fig. 5. Voltage profile for before and after installation of capacitor in 33 bus system

5. Conclusions

In this paper a multi-objective function has been proposed for optimum placement and sizing of capacitor bank in distribution system, that in it, reliability improvement, network loss and carbon dioxide emission reduction, and voltage profile improvement of electricity network are considered. In order to solve the optimization problem, is used a heuristic BCO algorithm. The proposed method has been applied on 33-bus distribution system. The results illustrate that optimal placement of capacitor in the distribution system causes to significant power losses and carbon dioxide emission reduction and also reliability and voltage profile improvement.

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