Optimal Sizing and Locations of Capacitors Using Slime Mould Algorithm

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Abstract- A new and powerful approach called Slime Mould Algorithm (SMA) is suggested in this paper, for optimal siting and sizing of capacitors for an IEEE distribution network. First, the most nominee buses for installing capacitors are developed using various indices. Loss Sensitivity Factors (LSF), Voltage Stability Index (VSI), and Power Loss Index (PLI) are employed to determine the selected buses. Then the proposed SMA is used to deduce the size of capacitors and their positions from the picked buses. The objective function is introduced to minimize the net cost and then, increase the total saving per year. The developed approach is tested on the IEEE distribution network. The obtained results are compared with others to highlight the advantages of the developed approach. Also, the results are presented to confirm its influence in minifying the losses, and net cost and to improve the voltage profile and total saving for a radial distribution network.

Key-Words: Slime Mould Algorithm; Loss Sensitivity Factors; Voltage Stability Index; Power Loss Index; Optimal Capacitor Locations; Distribution System.

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1. Introduction

Transmission and distribution system losses are considered the main consumption in any power network. Due to the growth in the load, and environmental limits, the transmission, and distribution networks are being worked under overloaded situations, and losses in the distribution systems have become the main concern. To attain economic advantages, the fundamental conditions to get agreeable power quality and enhanced efficiency have formed a very auspicious environment for the matter of loss minimization approaches and using recent operational practices. Power loss reduction is the only alternative to enhance the efficacy of the distribution network. Therefore, it is noted that in the last few decades many researchers have concentrated on distribution network loss reduction and voltage stability. There are many helpful techniques in the literature for distribution network loss reduction [1]. However, the most often used mechanisms like (a) capacitor siting, (b) network restructure [2] (c) DG siting [3], (d) DSTATCOM sitting and its mixed versions to realize upper potential interests are (e) simultaneous restructure and capacitor sitting, (f) simultaneous restructure and DG sitting, (g) simultaneous DG and DSTATCOM siting, and (h) simultaneous restructure, capacitor, and DG siting are presented in [1]. Conventionally, loss reduction has focused mainly on network restructure optimizing or capacitor siting for reactive power policy. Since installing capacitors are the simplest and most famous solution, they are getting steadily to be important components of the distribution network [1].

Pending last years, diverse algorithms are presented to find the proper locations and optimal sizes of shunt capacitors. Simulated Annealing (SA) [4], Tabu Search (TS) [5], Genetic Algorithm (GA) [6], Mixed Integer Nonlinear Programming Approach (MINPA) [7], Direct Search Algorithm (DSA) [8], Teaching Learning Based Optimization (TLBO) [9], Plant Growth Simulation Algorithm (PGSA) [10], Heuristic Algorithm [11], Cuckoo Search Algorithm (CSA) [12], Particle Swarm Optimization (PSO) [13], Fuzzy Genetic Algorithm (FGA) [14], Differential Evolution (DE) [15], Flower Pollination Algorithm (FPA) [16-17], Improved Harmony Search (IHS) [18], Mine Blast Algorithm (MBA) [19], and Moth Swarm Algorithm (MSA) [20] are developed to deal with the capacitor placement task. However, these techniques may drop to compass the optimum cost. To conquer these abuses, the SMA is chosen in this article to treat the process of optimum capacitor placement.

SMA is a vigorous population-based optimizer based on the oscillation mode of slime mould in nature [21-23]. It proves its effectiveness in many applications [24-25]. It is suggested here as a modern optimization approach to minify the net active power losses, the net cost and to promote the voltage profiles for an

IEEE distribution network. The stations of the shunt capacitors procedure are acquired firstly by inspecting the points according to many indices. Then SMA is submitted to deduct the optimum siting and sizing of capacitors from specific nodes. The validation of the suggested algorithm in progressing the voltage profile and lowering resistive losses is given for an IEEE distribution system. The results of the SMA are compared with several algorithms to assert its superiority.

The rest of the paper is constituted as follows: Section 2 shows the different indices for capacitor installing techniques. Section 3 presents the cost function and limits. Section 4 introduces Slime Mould Algorithm. Section 5 examines the results on voltage profiles and power loss. Section 6 gives the conclusion and future works to treat the distribution network optimization process.

2. Various Indices

In this section, three different indices with their equations are introduced.

2.1 Power Loss Index

In this article, PLI is utilized to specify the nominee points for capacitors. The region of inspection is diminished greatly and then wasted time in the optimization procedure. The demerit of this index is the pivotal computations. It is desired to execute load flow and define the attenuation in power losses by intromission reactive power at every bus except the slack one [26-27]. The PLI is given as the following equation.

$$\text{PLI(i)} = \frac{lr(i) - lr_l}{lr_u - lr_l} \tag{1}$$

Where

lr_u : The upper attenuation in actual power losses.

lr_l : The lower attenuation in actual power losses.

$lr(i)$: The attenuation in actual power losses at the bus i.

The buses of greater PLI will have the primacy to be the nominee bus to constitute compensator apparatus.

2.2 Loss Sensitivity Factors

LSFs are appointed to specify the nominee buses to install capacitors [28]. Figure 1, shows a transmission line 'l' linked between 'i' and 'k' buses.

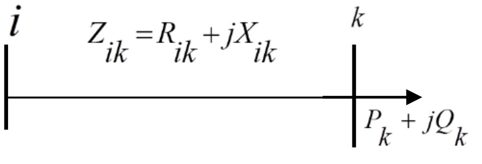

Fig. 1. Radial distribution network equivalent circuit.

The actual power loss is obtained by $I_l^2 R_{ik}$ in this line that can be computed by

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

The LSFs can be given from the following equation:

$$\frac{\partial P_{ik-loss}}{\partial Q_k} = \frac{2Q_k * R_{ik}}{(V_k)^2} \tag{3}$$

The typical voltages are specified by dividing the base voltages by 0.95. If these voltages are lower than 1.01 they can be suggested as nominee nodes for capacitor installation. It is account note that the LSFs judge the series in which nodes are to be prepared to install capacitors.

2.3 Voltage Stability Index

VSI amount is close to 1 so the least VSI amounts, the mightily sensitive points to voltage collapse. Thus, VSI is utilized to elect the lowest points that have more probability of voltage collapse along all points. VSI amount is designated as the following equation [29-31]:

$$\begin{aligned} VSI(k) = {} & \left|V_i\right|^4 - 4\left\{P_k \cdot X_{ik} - Q_k \cdot R_{ik}\right\}^2 \\ & - 4\left\{P_k \cdot R_{ik} + Q_k \cdot X_{ik}\right\} \cdot \left|V_i\right|^2 \end{aligned} \tag{4}$$

where

V_i : The magnitude of the voltage at the bus i.

3. Cost Function

The developed cost function of the optimum capacitor position task is to lessen the net cost which is planned as the following equation:

$$\begin{aligned} Cost = {} & K_P * P_{Loss} * T + \\ & D\left(K_I * CB + K_C * \sum_i^{CB} Q_{Ci}\right) + K_o CB \end{aligned} \tag{5}$$

Where the parameters are given as [17].

K_P : The price per KW-Hours equalizes to 0.06 \$/KW-Hours,

P_{Loss} : The net losses after compensation,

T : The time in Hours equalizes to 8760,

D : The depreciation agent equalizes to 0.2,

CB : The number of compensated points,

K_C : The price per Kvar equalizes to 25 \$/Kvar,

K_I : The price per inauguration equalizes to 1600\$,

Q_{Ci} : The value of inaugurated reactive power in Kvar,

K_o : The working price equalizes to 300 \$/year/position.

The overhead equation is constricted whereas accepting the following equality and inequality limits.

3.1 Equality Limit

- **Load flow limit**

Conventional methods cannot be utilized in distribution networks due to ill conditions. The forward sweep method has been presented in [29] to treat the load flow process of distribution networks. The equality limit is shown by the following equation:

$$P_{Slack}=\sum_{i=1}^{L}P_{Lineloss}(i)+\sum_{q=1}^{N}Pd(q) \qquad (6)$$

$$Q_{Slack}+\sum_{b=1}^{CB}Q_C(b)=\sum_{i=1}^{L}Q_{Lineloss}(i)+\sum_{q=1}^{N}Qd(q) \qquad (7)$$

where

P_{Slack} : The active power of the slack node,

Q_{Slack} : The reactive power of slack node,

L : The size of the transmission line in a distribution network,

$Pd(q)$: The request for active power at bus q,

$Qd(q)$: The request for reactive power at bus q,

N : The size of total nodes.

3.2 Inequality Limits

- **Voltage Limit**

The magnitude of the voltage at every node must be constrained by the following limit:

$$0.90\le V\le 1.05 \qquad (8)$$

- **Compensation Limit**

The injected reactive power at every nominee node should be lower than its efficient reactive power.

- **Power Factor Constraint**

Power Factor (PF) should override the lower amount and less than the upper amount as given by the following limit.

$$PF_{\min}\le PF\le PF_{\max} \qquad (9)$$

- **Total Reactive Power Limit**

Remarkably, the net injected reactive power is lower than 0.7 of the net reactive power request to extend the operating of the power system with lagging PF and prohibition the leading one.

$$\sum_{b=1}^{CB}Q_C(b)\le 0.7\sum_{q}^{N}Qd(q) \qquad (10)$$

4. Conventional SMA

Physarum polycephalum has been named slime mould because it is considered a fungus [21].

4.1 Approach food

SMA is illustrated by the mathematical equations of [21,22]. The equations represent the contraction mechanism as follows:

$$\vec{X}(t+1)=\begin{cases}\vec{X}_b(t)+\vec{vb}.\left(\vec{W}.\vec{X}_A(t)-\vec{X}_B(t)\right) & if\ r<p\\ \vec{vc}.\vec{X}(t) & if\ r\ge p\end{cases} \qquad (11)$$

Where, $\vec{vb}$ is a value $[-a,a]$,

$\vec{vc}$ is reduced linearly from 1 to 0,

t is the t_{th} iteration,

$\vec{X}_b$ is the individual location with the most concentrated scent,

$\vec{X}$ is the location of slime mould (solution),

$\vec{X}_A$ and $\vec{X}_B$ are the random selection of two individuals from the population,

$\vec{W}$ is the weight solution,

p is computed as:

$$p=\tanh\left|S(i)-DF\right| \qquad (12)$$

$i\in 1,2,3,\cdots,n, S(i)$ is to the competence of $\vec{X}$,

DF is the most competence calculated over all iterations.

$\vec{vb}$ is computed as follows:

$$\vec{vb}=[-a,a] \qquad (13)$$

$$a=\arctan h(-\left(\frac{t}{\max\_t}\right)+1) \qquad (14)$$

$\vec{W}$ is computed as follows:

$$\vec{W}_{(SmellIndex(l))} = \begin{cases} 1 + t.\log\left(\frac{bF - S(i)}{bF - wF} + 1\right) & condition \\ 1 - t.\log\left(\frac{bF - S(i)}{bF - wF} + 1\right) & others \end{cases} \quad (15)$$

$$smellIndex = sort(s) \quad (16)$$

Where

$S(i)$ ranks the first half of the given solutions,

r a random number $[0,1]$,

bF is the optimal competence exist in the current iteration,

wF is the worst competence exist in the current iteration,

$smellIndex$ is the sequence of the sorted competence values.

Fig. 2 shows the impacts of (11).

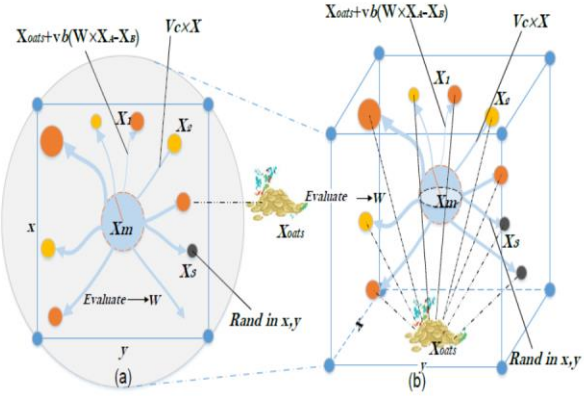

Figure 2. Potential location in 2_dimensional and 3_dimensional

4.2 Wrap food

When the search area extends to an area with a rather low concentration of food, its importance will decrease and the food group will go to explore other areas. Fig. 3 shows the competence evaluation functions for slime mould [23-24].

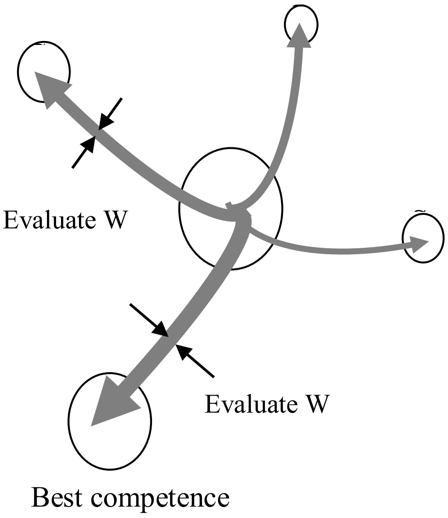

Figure 3. Evaluation of the competence function

The solution location is updated according to the following equation:

$$\vec{X}^{*} = \begin{cases} rand.(UB - LB) + LB & rand < z \\ \vec{X}_b(t) + \vec{vb}.\left(\vec{W}.\vec{X}_A(t) - \vec{X}_B(t)\right) & if\ r < p \\ \vec{vc}.\vec{X}(t) & if\ r \geq p \end{cases} \quad (17)$$

Where, LB is the lower limit of the search space,

UB is the upper limit of the search space,

r is a random value $[0,1]$.

4.3 Grabble food

$\vec{vb}$ is a random vector between $[-a, a]$ and regularly accessed zero as the repetitions advance.

The $\vec{vc}$ values lay between $[-1,1]$ and are driven to zero in the end. Synergistic cooperation between $\vec{vb}$ and $\vec{vc}$ imitate the specific manner of slime mould. Although sticky mould is a better source of nutrition, it is preferable to distribute the organic matter to explore other areas to find the best food source rather than pouring it all into one source to find a more reliable source of food. The Pseudo-code of the SMA algorithm is shown below [25].

Pseudo-code of SMA

```
Initialize population $\_size$, $\dim$, $LB$, $UB$, $z$, $Max\_iter$;
Initialize a set of Slime Mould random locations $X_i (i = 1,2,\cdots,n)$;
While ($t \le Max\_iter$)
    Compute and sort the competence of all Slime Mould;
    Update the best and the worst competence
    Calculate the weight of Slime Mould ($\vec{W}$);
    Update the best competence, the best location $\vec{X}_b$
    For each search agent
        Update $p$, $\vec{vb}$, $\vec{vc}$
        Update the position of search agent
    End For
    $t = t + 1$
End While
Return the best competence, best location $\vec{X}_b$
```

5. Results and Discussion

The prevalence of the suggested SMA is applied to an IEEE distribution systems. The results of 15 radial distribution systems are offered below in detail. The suggested algorithm has been completed via Matlab [32]. Simulations were performed under the Matlab environmental (release 2013 a) and done on a Lenovo laptop with Intel core i7 CPU 2.90 GHz processor with 4 GB RAM and a 64-bit operating system.

15 Bus Test System

The tested case is 15 bus system as given in Figure (4). The system data are displayed in [29]. The total load for this system is 1752 KVA with PF=0.7. The losses without compensation are 60.5844 KW. Figure (5) gives the nominee buses according to their PLI. The ordered of these buses are 15, 11, 4, 7, 6, 12, 14, 3, 8, 13, .. 2. The nominee buses are obtained in Figure (6) according to LSF. The ordered of buses are 6, 3, 11, 4, 12,…Figure (7) shows the nominee buses according to VSI values. The improvements in system voltages due to install one and two capacitors are shown in Figures (8, 9) respectively. A comparison between various indices is performed and shown in Table (1, 2) for installing one and two capacitors respectively. It is clear that, PLI gives better results than VSI and LSF for this system. Based on these results, SMA is proposed with PLI to give the better response in terms of cost and losses. The notability of the suggested SMA is demonstrated compared with other algorithms in [13, 14, 15, 33, and 34]. The value of installed capacity of reactive power is 850 KVAR. The minimum voltage is increased from 0.9424 to 0.9679 p.u. The losses with compensation are decreased to 32.2499 KW due to capacitors installation as given in Table (3). The percentage reduction in losses is increased to be 46.768%. Moreover, the value of total cost due to the proposed objective algorithm is 23060.54 $ which is the smallest one. Also, the net saving with the proposed SMA is improved to 29.183 % which is the maximum one compared with other algorithms.

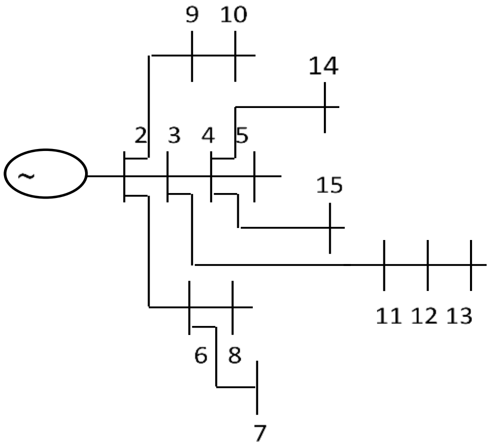

Fig. 4. The connection diagram of the 15-point system.

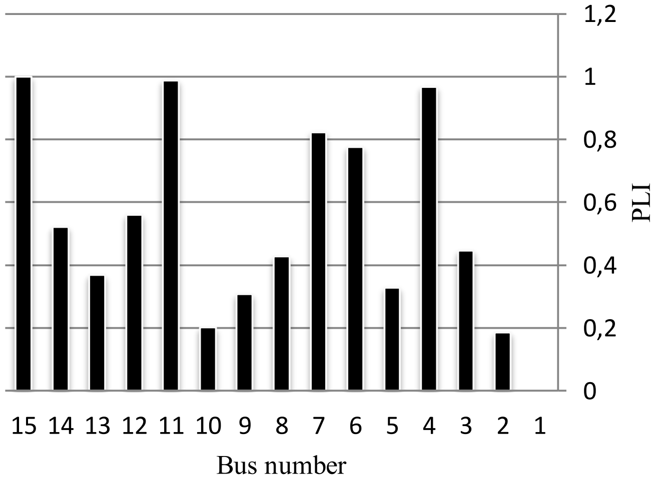

Fig. 5. PLI for the 15 system.

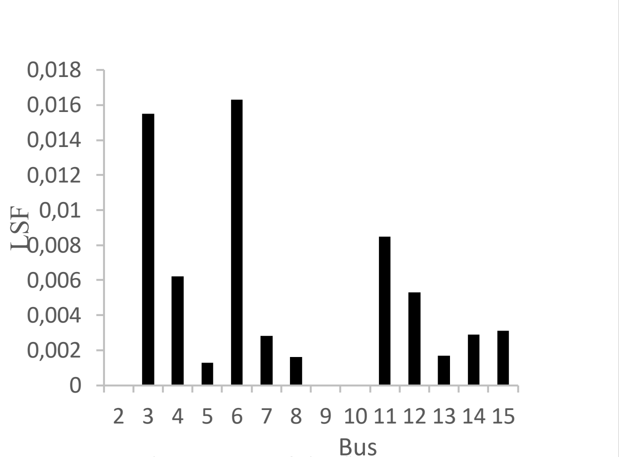

Fig. 6. LSF of the first system.

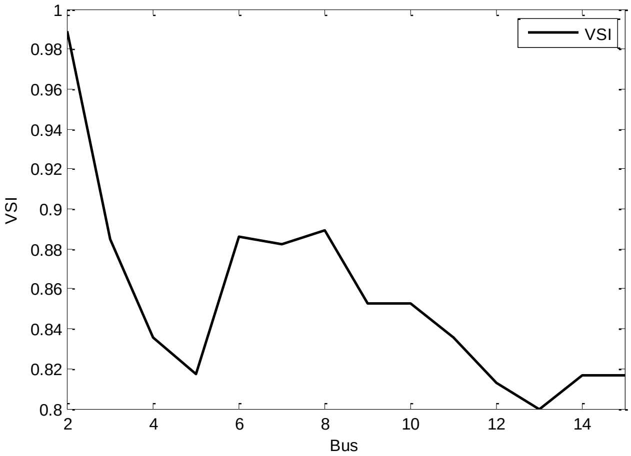

Fig. 7. VSI for the 15 system.

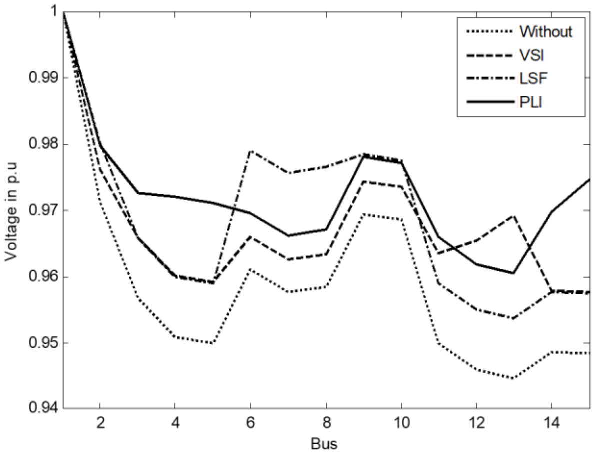

Figure. 8. Effect of installing one capacitor on system voltage.

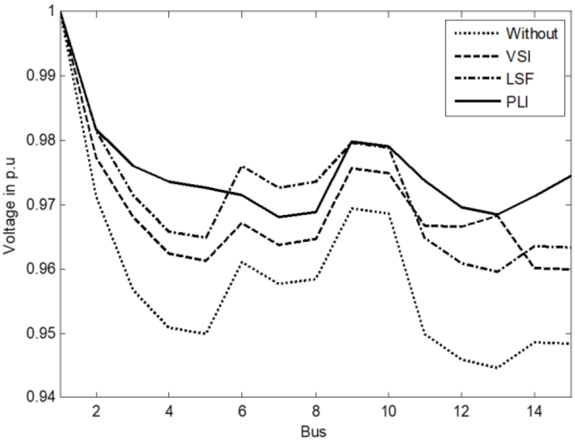

Figure. 9. Effect of installing two capacitors on system voltage.

Table (1) Comparison of various indices for injection of one capacitor.

Items	Un-compensated	Compensated		
		PLI	LSF	VSI
Total losses (Kw)	60.5844	40.2634	43.8035	47.365
Loss reduction (%)	-	33.54	27.698	21.819
Minimum voltage	0.9459	0.9619	0.9550	0.9601
Optimal location and size in Kvar	-	700@ Bus15	750@ Bus 6	400@ Bus 13
Total Kvar	-	700	750	400
Annual cost($/year)	32563.4	25282.44	27393.12	27515.04
Net saving ($/year)	-	7280.96	5170.28	5048.36
% saving	-	22.36	15.877	15.5

Table (2) Comparison of various indices for injection of two capacitors

Items	Un-compensated	Compensated		
		PLI	LSF	VSI
Total losses (Kw)	60.5844	34.9447	35.1231	42.5608
Loss reduction (%)	-	42.32	42.026	29.75
Minimum voltage	0.9459	0.9697	0.9615	0.9623
Optimal location and size in Kvar	-	450@ Bus15 400@ Bus11	450@ Bus 3 400@ Bus 6	250@ Bus 13 250@ Bus 11
Total Kvar	-	850	850	500
Annual cost($/year)	32563.4	23856.93	23950.7	26109.96
Net saving ($/year)	-	8706.47	8612.7	6453.44
% saving	-	26.74	26.45	19.82

Table (3) Comparison between various algorithms.

Items	Un-compensated	Compensated											
		FGA[14]		[33]		PSO[13]		DE [15]		[34]		**Proposed**	
Total losses (KW)	61.9547	30.4411		32.6		32.7		32.3		33.2		**32.2499**	
Loss reduction (%)	-	50.86		47.38		47.22		47.86		46.41		**46.768**	
Lower voltage	0.9424	0.9677		-		-		-		-		**0.9679**	
Optimum siting and size in KVAR	-	4	200	3	805	6	871	3	454	3	150	**6**	**250**
		6	100	6	388	11	321	6	500	4	300	**11**	**300**
		7	300					11	178	6	300	**15**	**300**
		11	300							11	150		
		15	200										
Total KVAR	-	1100		1193		1192		1132		900		**850**	
Annual cost($/year)	32563.4	24599.8		24339.6		24387.1		24496.8		24429.9		**23060.54**	
Net saving ($/year)	-	7963.6		8223.8		8176.3		8066.4		8133.5		**9502.86**	
% saving	-	24.46		25.26		25.11		24.77		24.98		**29.183**	

6. Conclusion

In this paper, SMA has been applied successfully to solve the tasks of optimum positions and sizing of capacitors in distribution system that have been established as an objective optimization task with competing power losses, cost of installation, operation and injected vars. The superiority of the suggested approach is clarified by using IEEE test system. Also, the results have been compared with those obtained using recent optimization techniques. Moreover, it provides a promising and preferable performance over other approaches in terms of voltage profiles, active power losses, net cost, and total saving. Implementation of the network reconfiguration and distributed generation with the most novel optimization algorithm to enhance the voltage profile and to reduce the active losses is the future scope of this work.

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