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Multi-objective Capacitor Allocations in Distribution Networks using Artificial Bee Colony Algorithm

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Abstract –This article addresses an efficient heuristic-based approach to assign static shunt capacitors along radial distribution networks using the artificial bee colony algorithm. The objective function is adapted to enhance the overall system static voltage stability index and to achieve maximum net yearly savings. Load variations have been considered to optimally scope the fixed and switched capacitors required. The numerical results are compared with those obtained using recent heuristic methods and show that the proposed approach is capable of generating high-grade solutions and validated viability.

Keywords: Artificial bee colony, Capacitor allocations, Loss reduction, Net saving maximization, Static voltage stability index

Nomenclatures

$\|I_i\|$	magnitude of the branch current in line i
n	total number of lines
R_i	resistance of line i
X_i	reactance of line i
P_{Loss}	total network active loss
Q_{Loss}	total network reactive loss
$VSI(j)$	voltage stability index of bus j
R_{ij}	resistance of line i-j
X_{ij}	reactance of line i-j
$\|V_i\|$	voltage magnitude of bus i
$\|V_j\|$	voltage magnitude of bus j
P_j	total effective real power load fed through bus j
Q_j	total effective reactive power fed through bus j
C_e	rate of energy cost
ΔT_i	time period for load level slot i
$P_{L_a}(i)$	total active power loss after compensation for certain load level i
$P_{L_b}(i)$	total active power loss before compensation for certain load level i
C_{Ci}	cost rate of capacitor installation/location
N_B	number of candidate effective buses (that have compensations with values > 0)
N	number of network buses
C_C	purchase cost of the capacitor
C_{CO}	yearly operating cost of the capacitors/location
σ	depreciation factor
μ_F	magnifying factor
$L(i)$	the ith load level
W	weighting factor
m	number of load level slots
n_l	number of load buses
P_{Slack}	active power supplied from the slack bus
Q_{Slack}	reactive power supplied from the slack bus
$P_D(i)$	active power demand of load at bus i
$Q_D(i)$	reactive power demand of load at bus i
$P_L(j)$	active power loss at branch j
$Q_L(j)$	reactive power loss at branch j
$Q_C(i)$	amount of reactive power of installed capacitors at bus i
$V_{i,min}$	lower permissible voltage limit at bus i
$V_{i,max}$	upper permissible voltage limit at bus i
Q_{Ci}^{min}	lower reactive power limit of compensated bus i
Q_{Ci}^{max}	upper reactive power limit of compensated bus i
S_{li}	actual line flow of line i
S_{li}^{rated}	rated line transfer capacity
PF_{min}	lower limit of overall system power factor at substation (slack bus)
PF_{max}	upper limit of overall system power factor at substation (slack bus)
MCN	maximum cycle number
SN	colony size
D	number of optimized parameters
f_i	cost objective value of ith solution
fit_i	modified fitness/objective of ith solution
φ_{ij}	random number in the range [−1, 1]

1. Introduction

Electrical losses experienced in electrical power distribution systems have two components: technical losses and non-technical losses [1-3]. Technical losses mean losses that happen because of the physical nature of the equipment and infrastructure of the power distribution systems, such as power losses in the cables, overhead lines, distribution transformers, switches, connections and bus bars. It should be highlighted that non-technical losses are

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difficult to quantify. Technical power losses can be categorized into real power loss and reactive power loss. One of the main sources of real power losses in the distribution system is the copper losses in power overhead lines and cables. Since these losses are a function of current flow through the line [1, 2]. The real and reactive power losses in the network are given by,

$$P_{Loss} = \sum_{i=1}^{n} |I_i|^2 R_i, \; Q_{Loss} = \sum_{i=1}^{n} |I_i|^2 X_i \qquad (1)$$

The voltage drop problem may arise when using lateral radial feeders across long distance. Therefore, finding a solution of this problem becomes crucial. That is, the voltage at different buses of the system should be enhanced by means of reactive power injections.

Numerous authors have discussed different aspects of power loss minimization and voltage profile enhancement. Many methods have been developed for reducing the network losses and improving the voltage profile in distribution systems: network reconfiguration and load balancing [4-7], high voltage distribution system [8], distributed generations [9-12] and shunt capacitor allocations [13-31].

Reactive power addition can be beneficial only when correctly applied. Correct application means choosing the correct position and size of the reactive power support. It is not possible to achieve zero losses in a power system, but it is possible to keep losses to a minimum to reduce the system overall yearly costs. Several evolutionary/stochastic methods that assist in solving optimization problems that were previously problematic or unmanageable have been proposed and developed in the last decade. To attain a loss reduction package in distribution systems, it is necessary to use effective and efficient computational tools that allow quantifying the loss in each different network element for system losses reduction.

Recently and fortunately, many researchers have focused on various types of heuristic optimization techniques to solve the optimal capacitor allocation (OCA) problem such as heuristic strategies (HS) [13], genetic algorithms (GA) [14, 15], tabu search [16], particle swarm optimization (PSO)-based algorithm [17], harmony search algorithm [18, 19], an ant colony search [20, 21], a fuzzy-GA [22], a bacterial foraging solution [23], an immune-based optimization technique [24], an integrated differential evolution and pattern search (DE-PS) [25], a big bang-big crunch optimization [26], plant growth simulation algorithm (PGSA) [27], an artificial bees colony (ABC)-based algorithm [28, 29] and cuckoo-search algorithm (CSA) [30].

Algorithms for enhancing voltage stability of electrical systems by OCA have been developed, and a relationship between voltage stability and loss minimization and the concept of maximizing voltage stability through loss minimization has been characterized and described [31-34].

Swarm artificial intelligence is an innovative computational way to solving complex problems. It is inspired by the behavior of social insects such as fish schools and bird flocks and colonies of ants, termites, bees and wasps. In general, the computational method mimics the behaviors of the biological creatures within their swarms and colonies. The ABC algorithm was proposed by Karaboga for optimizing numerical complex problems [35]. It simulates the intelligent foraging behavior of honey bee swarms. It is a very simple, robust and population based stochastic optimization algorithm. The performance of the ABC algorithm has been compared with those of other well-known modern heuristic algorithms such as GA, DE and PSO on constrained and unconstrained problems [36, 37]. The algorithm has a well-balanced exploration and exploitation ability.

In this paper, which is an extension to our previous article [29], in which an ABC-based algorithm is utilized to ascertain the optimal size and select optimum locations of fixed and switched static shunt capacitors. Variations of loading are taken to optimally size fixed and switched capacitors for practical aspect attentions. High potential buses for capacitor placement are initially identified by the observations of loss sensitivity factor (LSF) with lower voltage stability index (VSI) buses. However, that method has proven less than satisfactory as LSF may not always indicate the appropriate placement. In the proposed ABC approach, the algorithm identifies optimal sizing and placement, and takes the final decision for optimum location within the number of buses nominated. The proposed method improves the voltage profile and reduces system losses in addition to enhancing static voltage stability and improving power factor. The method has been tested and demonstrated on a variety of radial distribution systems (small and large scales).

2. Voltage Stability Index

Many different indices have been introduced to evaluate the power systems security level from the point of voltage static stability [31-34]. A new steady state VSI is proposed [34] for identifying the node, which is most sensitive to voltage collapse and is expressed in Eq. (2). Fig. 1 shows the simple electrical equivalent of the radial distribution system.

$$\begin{aligned} VSI(j) = |V_i|^4 - 4\left[P_j.X_{ij} - Q_j.R_{ij}\right]^2 \\ -4\left[P_j.R_{ij} + Q_j.X_{ij}\right].|V_i|^2 \end{aligned} \qquad (2)$$

For stable the operation of the radial distribution networks, VSI (j) ≥ 0. The node at which the value of the VSI has lowest, is prone to collapse. The node with the lowest VSI is the weakest node and the voltage collapse phenomenon will start from that node. Therefore, to avoid the possibility of voltage collapse; the VSI of all nodes should be maximized.

3. Modeling of Objective Function and Constraints

The objective of capacitor placement in the distribution system is to maximize the active power loss reduction, reduce capacitor purchase, operating and installation costs (i.e. to maximize the annual net savings), and to enhance the system static stability subject to specific operating constraints. The objective function is mathematically formulated as shown in (3),

$$Maximise$$

$$\left\{ W.\left\{ \begin{array}{c} C_e.\sum_{i=1}^{m}\left(P_{L_b}(i)-P_{L_a}(i)\right).\Delta T_i - \\ \sigma \times \left[C_{Ci}.N_B + C_C.\sum_{i=1}^{N_B} Q_C(i)\right] - C_{Co}.N_B \end{array} \right\} + (1-W).\mu_F.\sum_{j=2}^{N} VSI(j) \right\} \tag{3}$$

The load levels of varying load conditions have an effective level which its value is calculated by (4),

$$L_{eff} = \frac{\sum_1^m L(i).\Delta T_i}{\sum_1^m \Delta T_i} \tag{4}$$

The magnifying factor, μ_F, for the specific network under study is calculated,

$$\mu_F = \frac{maximum\ net\ saving}{maximum\ total\ VSI}\bigg|_{L_{eff}} \tag{5}$$

Subject to the satisfaction of the active and reactive power flow balance equations and a set of inequality constraints:

3.1 Power balance constraints

Power balance (active and reactive) constraints, which are equality constraints and include two nonlinear recursive power flow equations, can be formulated as follows,

$$\left. \begin{array}{c} P_{Slack} = \sum_{i=1}^{n_l} P_D(i) + \sum_{j=1}^{n} P_L(j) \\ Q_{Slack} + \sum_{i=1}^{N_B} Q_C(i) = \sum_{i=1}^{n_l} Q_D(i) + \sum_{j=1}^{n} Q_L(j) \end{array} \right\} \tag{6}$$

3.2 Voltage limit constraint

The voltage magnitude at each bus must be maintained within its limits for all load levels and is expressed as,

$$V_{i,min} \le |V_i| \le V_{i,max}, \ \forall i \in N \tag{7}$$

3.3 Reactive compensation limit

The injected reactive power constraint must be within their permissible ranges at each candidate bus and is expressed as,

$$Q_{Ci}^{min} \le Q_{Ci} \le Q_{Ci}^{max}, \qquad \forall i \in N_B \tag{8}$$

3.4 Line capacity limit

The apparent power flow through the line S_l is restricted by its maximum rating limit as,

$$S_{li} \le S_{li}^{rated}, \ \forall i \in n \tag{9}$$

3.5 Maximum total compensation

From practical limitation, maximum compensation by using capacitor bank is limited to the total load reactive power demand.

$$\sum_{i=1}^{N_B} Q_C(i) \le \sum_{j=1}^{n_l} Q_D(j) \tag{10}$$

3.6 Overall system power factor

The system Power Factor should be maintained within desirable lower and upper limits.

$$PF_{min} \le PF_{overall} \le PF_{max} \tag{11}$$

4. Identification of Potential Buses Using LSF

The estimation of these candidate nodes works towards significant reductions of the search space for the optimization procedure. In this proposed work, LSF is utilized for this purpose [38]. It is intuitive that a section in a distribution system with high losses and lower voltage or VSI has higher priority for placement of capacitors. Whereas, low loss sections with good voltage are not optimal for capacitor placement.

The LSF may be able to predict which bus will have the greatest loss reduction when reactive compensation is put in place. Consider a distribution line connected between ‘i’ and ‘j’ buses as shown in Fig. 1.

Active power loss in the ith line between i-j buses is $\propto |I_{ij}|^2 R_{ij}$ can be expressed as shown in (12),

$$P_{ij-loss} \propto \frac{\left(P_j^2+Q_j^2\right)}{|V_j|^2}.R_{ij} \tag{12}$$

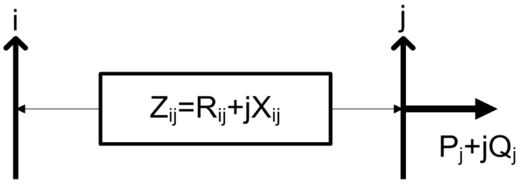

Fig. 1. Line i-j power system model

Thus, the sensitivity analysis factor is a derivative of the power loss with reactive power, Q_j, as indicated in (13),

$$\frac{\partial P_{ij-loss}}{\partial Q_j} \propto \frac{2\,Q_j}{|V_j|^2}.R_{ij} \tag{13}$$

The values are arranged in descending order for all the lines of the given system. The descending order of the element's vector will decide the sequence in which the buses are to be considered for compensation. Buses of higher LSF and lower VSI have a greater prospect of being selected as candidate locations for capacitor installations in the case of bi-objective (net saving and VSI). However, in case of pure maximization of VSI, only buses with lower VSI values are pre-identified.

5. Artificial Bees Colony Algorithm

Nowadays, the ABC algorithm is one of the most popular approaches used in optimization problems. ABC overcomes other well-known heuristic methods, such as GA, PSO and DE and requires fewer control parameters to be tuned. The ABC algorithm has three phases: employed bee, onlooker bee and scout bee. In the employed bee and the onlooker bee phases, the bees exploit the sources by local searches in the neighborhood of the solutions selected based on deterministic selection in the employed bee phase and the probabilistic selection in the onlooker bee phase. In the scout, bee phase which is an analogy of abandoning exhausted food sources in the foraging process, solutions that are no longer beneficial for search progress are abandoned, and new solutions are inserted in their places to explore new regions in the search space.

A bee carrying out random search is called a scout. In the ABC algorithm, the first half of the artificial colony consists of employed bees and the second half consists of the artificial onlookers. For every food source, there is only one employed artificial bee. The employed bee whose food source is exhausted by the employed and onlooker bees becomes a scout.

The main steps of the ABC algorithm in the form of Pseudo-code are given below [35-36]:

Step 1: Initialize the population of solutions: x_{ij}, $\forall i \in SN$ &&$\forall j \in D$
Step 2: Evaluate the population
Step 3: Cycle = 1
Step 4: Repeat
Step 5: Produce new solutions (food source positions) v_{ij} in the neighborhood of x_{ij} for the employed bees using the formula $v_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj})$ (k is a solution in the neighborhood of i) and evaluate them
Step 6: Apply the greedy selection process
Step 7: Calculate the probability values p_i for the solutions x_{ij} by means of their fitness values using (14)

$$p_i = \frac{fit_i}{\sum_{i=1}^{SN} fit_i} \tag{14}$$

In order to calculate the fitness values of solutions, the following (15) is employed;

$$fit_i = \begin{cases} \frac{1}{1+f_i} & if\ f_i \geq 0 \\ 1 + |f_i| & if\ f_i < 0 \end{cases} \tag{15}$$

Normalize p_i values into [0, 1]. f_i is obtained separately for each individual ith solution through Eq. (3).

Step 8: Produce the new solutions (new positions) v_{ij} for the onlookers from the solutions x_{ij} selected depending on P_i and evaluate them
Step 9: Apply the greedy selection process
Step 10: Determine the abandoned solution (source), if it exists, and replace it with a new randomly produced solution x_{ij} for the scout using (16)

$$x_{ij} = Q_{Cj}^{min} + rand(0,1).\left(Q_{Cj}^{min} - Q_{Cj}^{max}\right) \tag{16}$$

Step 11: Memorize the best food source position (solution) achieved so far
Step 12: Cycle = Cycle+1
Step 13: Until Cycle = MCN.

There are three control parameters used in the ABC-based algorithm; the number of the food sources which is equal to the number of employed or onlooker bees, the value of $limit$, and the MCN. In ABC, if a position cannot be improved further through predetermined number of cycles, then that food source is assumed to be abandoned. The value of the predetermined number of cycles is an important control parameter of the ABC algorithm, this is termed the "$limit$" for abandonment.

The ABC algorithm employs four different selection processes:

(1) A global selection process used by the artificial onlooker bees for discovering promising regions,
(2) A local selection process carried out in a region by the artificial employed bees and the onlookers depending on local information for determining a neighbour food source around the source in the

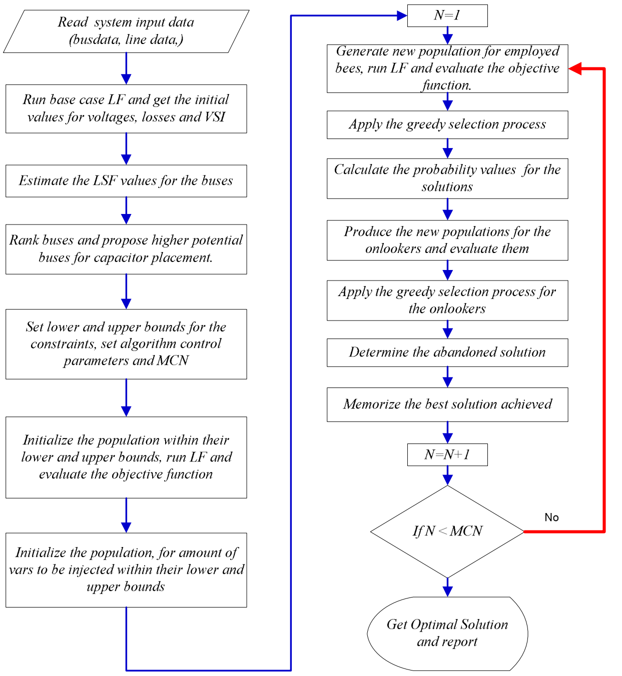

Fig. 2. Flow chart of ABC algorithm and capacitor allocations

memory.

(3) A local selection process called greedy selection process carried out by all bees.

(4) A random selection process carried out by scouts.

The procedure of the ABC algorithm to solve OCA can be summarized in the flow chart diagram of Fig. 2.

6. Test Cases, Numerical Results and Simulations

In order to test the effectiveness and performance of the proposed ABC-based algorithm, it was applied to several distribution radial test systems. Only two radial distribution systems: the 34-bus and the radial distribution system with 118-nodes are selected for reporting and demonstration in this article, to observe the applicability of the proposed approach. In all calculations, for all the test cases, the following constants are assumed and applied as shown in Table 1.

The net savings are calculated using:

$$Net\frac{Savings}{year} = \left\{ \begin{matrix} Total\ Cost\ of\ Energy\ Reductions - \\ \sigma.\{Cost\ of\ Installations + Cost\ of\ Purchase\} - \\ Operating\ cost/year \end{matrix} \right\} \quad (17)$$

The initial identification and the estimation of high potential buses assist considerably in the reduction of the search space for the optimization procedure. Setting the lower limit of capacitor range to 0 will permit the proposed approach to select the optimum locations within the range of bus list nominations initially identified by the LSF method which has to be set manually by the user (set the number of buses due for search). It is well-known that LSF observations may not lead to optimum locations. Due to the fact the LSF calculations depend on the network topology, configurations, loading, etc… and to challenge these limitations, the algorithm will search the optimum number of buses and select them for capacitor placements. After exhaustive trials, it was observed that naming 15 to 30% of total network number of buses after ranking using the LSF guarantees the optimal or near to optimal solutions. For small size networks, the user may nominate/set the initial number of higher potential buses to 25 to 30% of network buses, and for medium size, nominate 20 to 25% of network buses. However, for large scale radial networks, the user should set the number of potential buses for capacitor placement to 15 to 20% of network buses.

Table 1. Constants for the rates using a long with simulated test cases

Item	Proposed rate
Average energy cost	\$0.06/kWh
Depreciation factor	20%
Purchase cost	\$25/kVAr
Installation cost	\$1,600/location
Operating cost	\$300/year/location
Hours per year	

The proposed method has been encoded, modeled and implemented using MATLAB [39, 40]. The distribution power flow suggested in [41] has been utilized in this work. Simulations were carried out and executed on a Dell Laptop with Processor Intel® Core i5 CPU 2.40 GHz with a 4.0 GB of RAM with 32-bit operating system.

The sizing of fixed and switched capacitors in the case of different load patterns and the variation of load conditions, has been considered with good acceptable approximation for radial feeders as follows; light, medium and full by multiplying the base load uniformly by a factor of 0.5, 0.75 and 1.00 P.U. for period percentages of 25%, 35% and 40%, respectively [30]. For the sake of comparisons, two scenarios are proposed for each test case with assuming that 100% loading patterns over the year and then allow for load variations as aforementioned approximations.

The 34-bus test case has 4-lateral radial distribution system which is shown in Fig. 3. The data of the system are obtained from [13]. The total load of the system is (4,636.5+j 2,873.5) kVA.

In addition, this proposed ABC approach has been applied to a large scale radial distribution system with 118-nodes, as shown in Fig. 4, to evaluate its performance with a higher number of control variables. The network layout, including line data and load data, and its physical

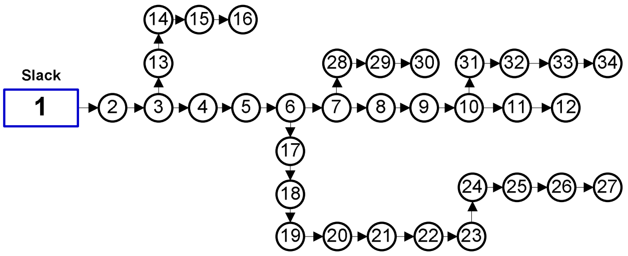

Fig. 3. Single line diagram of a 34-bus radial distribution network

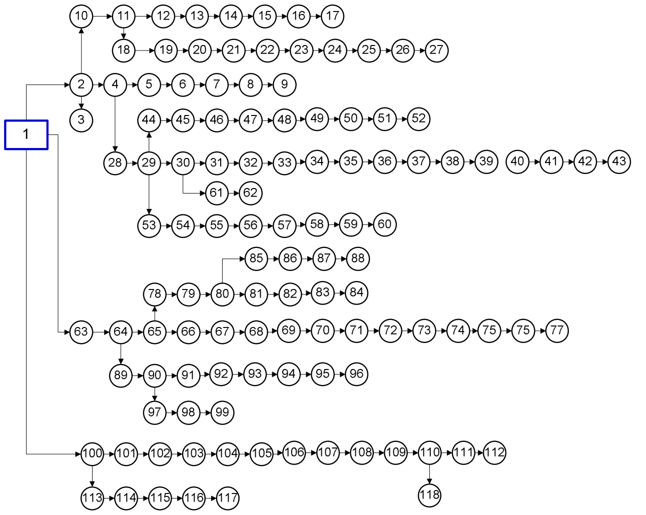

Fig. 4. Single line diagram of the 118-bus radial distribution system (The bus number is reordered)

characteristics are summarized and taken from [42]. This network has a total loads of (22.7097+j 17.0422) MVA.

After running initial LF; the conditions of the system before shunt capacitors allocations are shown and depicted in Table 2 with different loading profiles.

The calculated magnifying factor (μ_F) is approximately 590 and 1,650 for the test cases of 34-bus and 118-bus networks respectively, using the Eq. (5) at 100% loading condition over the year. However, in case of load variations with $L_{eff} = 78.8\%$, μ_F is 270 and 850 for the 34-bus and 118-bus test cases, respectively.

Table 3. Control parameters adopted for the ABC algorithm and target setting for the constraints

Item	Proposed Setting for 34-bus test case	Proposed Setting for 118-bus test case
Swarm size (SN)	70	150
Limit	35	105
Food source	35	75
MCN	100	100
Bus Voltage constraint	$0.95 \le V_i \le 1.05$	$0.90 \le V_i \le 1.05$
Power Factor Constraint	$0.95 \le PF_{overall} \le 0.99$	$0.90 \le PF_{overall} \le 0.99$
Allowable capacitor range	0 kVAr to 1500 kVAr with step of 50 kVAr	

Parameters adopted for the ABC algorithm for the test cases of a 34-bus and 118-bus networks, and the required inequality constraints that should be respected are given in Table 3.

6.1 Numerical results and simulations of the 34-bus network

Using base LF to candidate the potential buses for capacitor placement and based on LSF values; as follows; {19, 22, 20, 21, 23, 24, 25, 26 & 27}. However, ranking is based on lower VSI is {27, 26, 25, 24, 23, 22, 21, …}. Set the number of initial higher potential buses estimated by LSF to 9. After running the proposed optimization algorithm to select the optimal locations and determine the capacitor optimal sizes, the outcome leads to only 2 locations for capacitor placement, which are buses 19 and 24 with optimum capacitor ratings of 1050 kVAr and 800 kVAr, respectively. The CPU computational time needed is 15.45 s to accomplish this optimization process by the proposed ABC-based method, including load flow runs. The results of the proposed method compared with the results of GA method [15], PSO method [17], HS-based method [13], PGSA method [27] and evolutionary algorithm (EA) method [43] for the reactive compensation required and relevant bus allocations are shown in Table 4.

For comparison purposes, the reported figures in [15, 17, 13, 27] and [43] of injected reactive power at specific

Table 2. System Conditions before Capacitors allocations with different loading patterns for test cases

Item/ Load level	34-bus network test case			118-bus network test case		
	50%	75%	100%	50%	75%	100%
$VSI_{min}{}^a$	0.8909	0.8379	0.7860	0.7758	0.6705	0.5698
$VSI_{max}{}^a$	0.9885	0.9826	0.9765	0.9928	0.9891	0.9852
$\sum_{j=2}^{N} VSI(j)$	30.79	29.70	28.62	107.40	102.69	98.04
$V_{min}{}^a$	0.9715	0.9568	0.9416	0.9385	0.9049	0.8688
$V_{max}{}^a$	0.9971	0.9957	0.9941	0.9982	0.9973	0.9963
P_{loss} (kW)	52.86	121.74	221.74	296.77	695.92	1294.35
Q_{loss} (kVAr)	15.65	35.82	65.22	224.83	525.78	974.85
$PF_{overall}$	0.8528	0.8542	0.8556	0.7891	0.7885	0.7879

^{a}Excluding slack bus # 1

Table 4. Optimal location of capacitors and amount of KVArs with 100% loading condition

Method/ loading	Proposed ABC			GA [15]	PSO [17]	HS [13]	PGSA [27]	EA [43]
	50%	75%	100%	100% loading condition				
(Location, Size in kVAr)	(24, 600)	(19, 750) (24, 600)	(19, 1050) (24, 800)	(5, 300) (9, 300) (12, 300) (22, 600) (26, 300)	(19, 781) (22, 803) (20, 479)	(26, 1400) (11, 750) (17, 300) (4, 250)	(19, 1200) (22, 639) (20, 200)	(8, 1050) (18, 750) (25, 750)
Fixed & switched Capacitors	Fixed: (24, 600). Switched: (19, 1050) and (24, 200).			NA	NA	NA	NA	NA

Table 5. Results and comparisons of a 34-Bus radial feeder test case with OCA showing different heuristic approaches with w = 0.5 (i.e. bi-objective of net saving and VSI)

Point of Comparison	100% loading condition						Load variations		
	ABC	GA [15]	PSO [17]	HS [13]	PGSA [27]	EA [43]	50%	75%	100%
V_{min} (P.U.)[a]	0.9496	0.9478	0.9486	0.9522	0.9479	0.9501	0.9746	0.9623	0.9496
V_{max} (P.U.)[a]	0.9949	0.9949	0.9950	0.9953	0.9950	0.9952	0.9974	0.9962	0.9949
SVI_{min}[a]	0.8129	0.8071	0.8097	0.8219	0.8074	0.8149	0.9023	0.8576	0.8129
SVI_{max}[a]	0.9797	0.9796	0.9800	0.9811	0.9800	0.9808	0.9895	0.9848	0.9797
$\sum_{j=2}^{34} SVI(j)$	30.12	29.09	29.14	29.32	29.12	29.27	31.97	31.07	30.12
P_{loss} (kW)	167.77	164.96	169.36	168.48	171.96	161.27	42.53	92.52	167.77
Reductions in P_{loss} %	24.33%	25.61%	23.62%	24.02%	22.45%	27.27%	19.54%	24.00%	24.33%
Q_{loss} (kVAr)	49.02	49.96	47.18	48.45	48.67	49.05	12.45	27.03	49.02
Reductions in Q_{loss} %	24.90%	23.39%	27.67%	25.72%	25.37%	24.79%	19.99%	24.54%	24.90%
$\sum Q_C$(kVAr)	1,850	1,800	2,063	2,700	2,039	2,550	600	1,350	1,850
$PF_{overall}$	0.9798	0.9825	0.9970	0.9989	0.9738	0.9837	0.9410	0.9739	0.9798
Net Savings/year	$17,871	$15,093	$15,570	$12,017	$15,590	$17,173	$7,591		

[a]The reported values are shown excluding the slack bus # 1.

buses are recycled, as shown in Table 4, to compute the system losses and the net yearly savings (refer to Table 5) with the same rates shown in Table 1 and (17).

With 100% loading, the VSI of a 34-bus radial distribution system without and with compensations is depicted in Fig. 5.

Regarding the net savings, one may note the superiority of the proposed approach compared to the other heuristic methods as shown in Table 5. Moreover, it is importance to note that the net saving with load variation over the year is less than of 100% loading condition as depicted in Table 5. Nevertheless, Tables 4 and 5 conclude that the proposed ABC-based approach yields higher system stability indices and higher annual net savings compared to other heuristic methods with fewer numbers of locations which suggests an added value to the proposed approach.

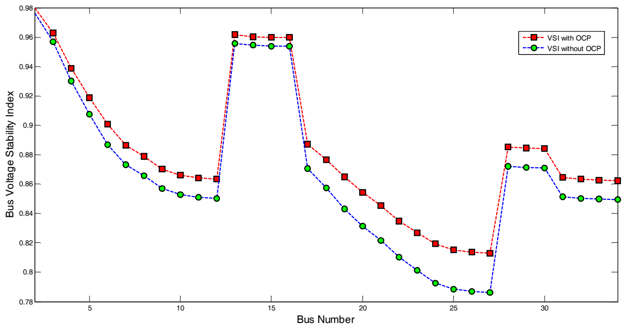

Fig. 5. VSI values against bus number for a 34-bus radial distribution feeder with and without OCA (2 locations)

Table 6 depicts the extracted summaries for the cases of VSI maximization and Ploss minimization as well, in addition to the best net saving savings and VSI maximization. In the case of VSI maximization, the nominated buses for capacitor allocations are identified based on lowest buses with VSI values only.

If the objective is to minimize the active power loss only, or to maximize VSI only, irrespective the net yearly cost savings, while maintaining the equality and inequality constraints. As well as, to extend the search space further with higher number of bus nominations, ignoring the pre-identification of well-known indices (say, identify 33 bus of the 34-bus network for OCA excluding slack bus) to freely allow the ABC algorithm to optimally select and size (see Table 6).

The proposed ABC-based approach can reduce peak real losses to 161.087 kW (i.e. the percentage of reduction is 27.35%) with total reactive compensation of 2600 kVAr allocated at buses of 8, 18 and 25 with ratings of 900 kVAr, 900 kVAr and 800 kVAr, respectively. The net yearly saving is $17,018.00 which is less than the obtained value in the case of bi-objective (both net saving and SVI maximizations) as indicated in Tables 5 and 6. However, the net saving is dramatically reduced in the case of a pure VSI maximization. In the case of large space option, the

Table 6. Summaries for the VSI and P_{loss} pure objectives and large search space option with 100% loading condition with OCA

Item	Best net yearly savings and VSI Maximisation (large search space)	Power loss Minimisation ($w = 1$ & $\sigma = 0$)	VSI Maximisation ($w = 0$)
SVI_{min} [a]	0.8101	0.8163	0.8238
SVI_{max} [a]	0.9799	0.9810	0.9807
$\sum_{j=2}^{34} SVI(j)$	30.15	29.28	30.31
P_{loss} *(kW)*	162.75	161.09	169.92
Q_{loss} *(kVAr)*	47.87	47.15	49.27
$PF_{overall}$	0.9801	0.9978	0.9952
$\sum Q_C$*(kVAr)*	1,950 {(10, 700), (21, 900) and (25, 350)} (3 locations)	2,600 (3 locations)	2,450 (8 locations)
Net Savings/year	\$19,395	\$17,018	\$10,026

[a]The reported values are shown excluding the slack bus # 1.

Table 7. Optimal locations and sizes (fixed and switched) for the 118-nodes test case at different load levels

Location/bus	Load levels		
	100%	75%	50%
	kVArs	kVArs	kVArs
32	850	0	500
35	1,050	800	0
40	1,300	1,200	900
50	800	450	0
70	550	550	0
73	1,300	750	750
79	1,200	850	500
105	700	0	300
106	250	0	0
109	800	800	0
110	1,200	1,000	950
Final fixed and switched optimal ratings (Location, Size)	Fixed: (32, 500), (40, 900), (73, 750), (79, 500), (105, 300) and (110, 950). Switched: (32, 350), (35, 1050), (40, 400), (50, 800), (70, 550), (73, 550), (79, 700), (105, 400), (106, 250), (109, 800) and (110, 250).		

Table 8. Results and comparisons of a 118-Bus radial feeder test case with OCA showing different heuristic approaches with w= 0.5 (i.e. bi-objective of net savings and VSI)

Point of Comparison	100% loading condition		Load variations		
	ABC	CSA [30][b]	50%	75%	100%
V_{min} *(P.U.)*[a]	0.90886	0.906	0.9539	0.9313	0.90886
V_{max} *(P.U.)*[a]	0.99741	0.997	0.9987	0.9981	0.997412
SVI_{min} [a]	0.68232	---	0.8279	0.7524	0.68232
SVI_{max} [a]	0.9896	---	0.9946	0.9922	0.9896
$\sum_{j=2}^{118} SVI(j)$	104.07	---	110.58	107.25	104.07
P_{loss} *(kW)*	854.39	858.89	207.52	471.78	854.39
Reductions in P_{loss} *%*	33.99%	33.64%	30.07%	32.21%	33.99%
Q_{loss} *(kVAr)*	639.08	644.94	156.62	355.83	639.08
Reductions in Q_{loss} *%*	34.44%	33.84%	30.34%	32.32%	34.44%
$\sum Q_C$*(kVAr)*	10,000 (11 locations)	9,000 (8 locations)	3,900	6,400	10,000
$PF_{overall}$	0.9295	0.92	0.8915	0.9068	0.9295
Net Savings/year	\$174,422	\$178,917	\$88,637		

[a]The reported values are shown excluding the slack bus # 1.

[b]It is worth to state that the CSA utilizes power loss indices to pre_identify the buses with cost objective only.

net yearly savings is higher than that obtained value by a limited search space which is relies on LSF with a percentage of 8.5%. However, the elapsed time required to accomplish this task is dramatically increased from 15.5 s to 140.5 s due to large search space and increased swarm size. The aforementioned proves that the LSF may perform unsatisfactory to achieve maximum net annual savings which is compatible with reporting in {25, 29 and 30} and with early indicated in this paper. The constraints have been checked for reactive power limits, node voltages and branch security flows and found within acceptable limits.

6.2 Numerical results and simulations of the 118-bus network

The most likely buses for capacitor placements pre-identified using both LSF and VSI values are {70, 48, 78, 68, 104, 69, 67, 106, 108, 49, 110, 79, 105, 72, 50, 33, 107, 73, ...} and based on lower VSI values only are {77, 76, 75, 74, 73, 72, 71, 43, 112, 42, 111, 118, 110, 41, ...}. Setting the number of initial higher buses range reported by the LSF observations to 25, allows the proposed algorithm to select the optimal locations and amount of compensations required accordingly. The approach has selected 8 buses for OCA with the relevant amount of reactive compensation required per each location which is depicted in Table 7 for all the proposed load patterns / levels. Once again, this proves the ability of the proposed approach to allocate capacitors at a minimum number of locations. The summaries and numerical results are tabulated and depicted in Table 8.

The approach has selected 11 buses for OCA with the relevant amount of reactive compensation required per each location (out of 25 high potential buses nominated by

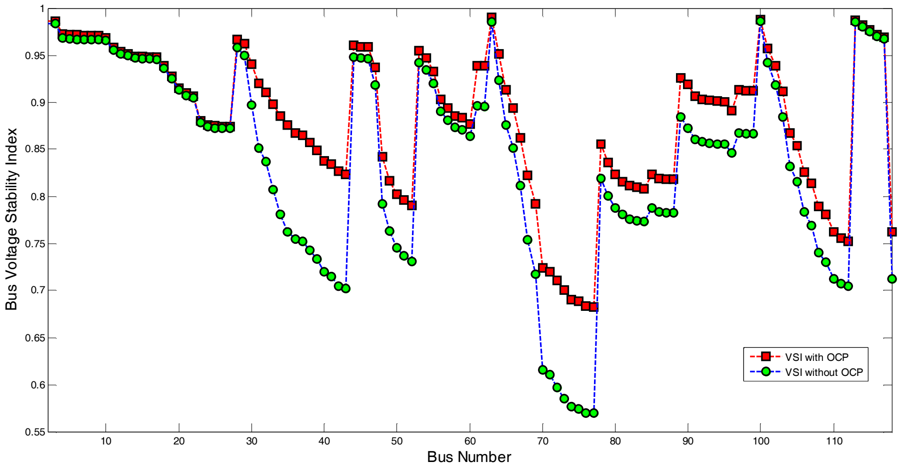

Fig. 6. VSI profile against bus number for a 118-bus radial distribution feeder with and without OCA (11 locations) [compromise objectives between net savings and VSI]

LSF and VSI values) which is shown in Table 7. Moreover, the net saving is recalculated with the considerations of load variations as assumed before and as noted the net saving is $88,637.00 which is lesser than the calculated numeral value of $174,422.00 with the assumption of 100% loading condition only over the year (see Table 8). A significant improvement has been witnessed regarding the system bus voltage stability aspects as shown in Fig. 6 for the case of bi-objective (net saving and VSI maximizations).

The CPU average elapsed time required to complete optimal selection of 11 buses and optimal sizes of capacitors out of 25 buses which is initially identified by LSF is 560.50 s including runs of distribution load flow.

7. Conclusion

The ABC-based optimization approach has been applied to solve the problem of capacitor allocations (sizing of fixed and switched stages and their placements) to maximize the net annual benefits and to improve system static voltage stability. The numerical results of the simulation point out a substantial improvement in active and reactive power loss reductions, bus voltage stability enhancements, and power factor corrections while maximizing the net annual savings. The results obtained via the proposed ABC-based method are preferable to the other methods in terms of the quality of the solution and the computational efficacy.

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