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Reactive power optimization in distribution systems considering load levels for economic benefit maximization

Introduction. *The need for electrical energy has been increased sharply due to hasty growth in industrials, social and economic improvements. From the previous studies, it has been agreed that almost 13 % of the total power generated is wasted as heat loss at distribution level. It has been extensively recognized that the node voltage profile along the distribution system can be enhanced under steady state power transfer controlled by proper reactive power compensation. Capacitors have been acknowledged as reactive power compensating device in distribution systems to achieve technical and economical benefits.* ***Novelty*** *of this work is the application of Archimedes optimization algorithm for reactive power optimization in distribution systems so as to obtain an improved solution and also a real 94-bus Portuguese network and modified 12-bus network has been taken and validated for three different load levels which are totally new.* ***Purpose*** *of the proposed work is to maximize the economic benefit by reducing the power loss and capacitor purchase cost at three different load conditions subject to satisfaction of equality and inequality constraints.* ***Methods.*** *The economic benefit has been validated using Archimedes optimization algorithm for three load levels considering three distribution systems.* ***Results.*** *The computational outcomes indicated the competence of the proposed methodology in comparison with the previously published works in power loss minimization, bus voltage enhancement and more economical benefit and proved that the proposed methodology performs well compared to other methods in the literature*. References 17, tables 6, figures 6.

Key words: **reactive power compensation, distribution system, power loss minimization, economic benefit, Archimedes optimization algorithm.**

Вступ. *Потреба в електроенергії різко зросла через стрімке зростання промисловості, соціальних та економічних поліпшень. З попередніх досліджень було встановлено, що майже 13 % усієї електроенергії, що виробляється, витрачається марно у вигляді втрат тепла на рівні розподілу. Загальновизнано, що профіль напруги вузла вздовж розподільчої системи може бути поліпшений при передачі потужності в режимі, що встановився, керованої відповідною компенсацією реактивної потужності. Конденсатори були визнані як пристрої компенсації реактивної потужності в розподільчих системах для досягнення технічних та економічних переваг.* ***Новизна*** *цієї роботи полягає у застосуванні алгоритму оптимізації Архімеда для оптимізації реактивної потужності в розподільчих системах з метою отримання покращеного рішення, а також було взято та перевірено реальну португальську мережу з 94 шинами та модифіковану мережу з 12 шинами для трьох різних рівнів навантаження. які абсолютно нові.* ***Мета*** *запропонованої роботи полягає в тому, щоб максимізувати економічний ефект за рахунок зниження втрат потужності та вартості купівлі конденсатора за трьох різних режимів навантаження за умови дотримання обмежень рівності та нерівності.* ***Методи***. *Економічний ефект було підтверджено з використанням алгоритму оптимізації Архімеда для трьох рівнів навантаження з урахуванням трьох систем розподілу.* ***Результати*** *розрахунків показали компетентність запропонованої методології порівняно з раніше опублікованими роботами в галузі мінімізації втрат потужності, підвищення напруги на шині та більшої економічної вигоди, а також довели, що запропонована методологія добре працює порівняно з іншими методами в літературі.* Бібл. 17, табл. 6, рис. 6.

Ключові слова: **компенсація реактивної потужності, розподільча система, мінімізація втрат потужності, економічний ефект, алгоритм оптимізації Архімеда.**

Problem definition. Now-a-days modern distribution systems (DSs) are becoming large and difficult causing reactive currents to raise losses result in increased ratings for distribution components. The power loss and the reduction in bus voltages in the DS are disturbing the whole power system performance which can be effectively controlled by proper position and sizing of reactive power compensating device thereby reduction in economical loss.

It is widely recognized that installation of shunt capacitors reduces a portion of power loss of the DS, which in turn increase the overall efficacy of the power delivery. The other benefits such as sub-station power factor improvement, better power flow control; enhancement in bus voltage profile; system stability improvement; reduction in total kVA demand and feeder capacity release can be possible only when the capacitors are located at optimal locations with appropriate capacity [1]. Hence optimal capacitor placement problem is a complex, combinatorial, mixed integer and non-linear programming problem with a non-differential objective function due to the fact that the costs of the capacitor varies in discrete manner. Selection of appropriate nodes and determination of optimal capacitor sizing are the two main steps to obtain the best result in capacitor allocation problem.

Related past publications. Polar bear optimization algorithm (PBOA) as optimization method, optimal allocation and sizing of capacitors has been presented in [2]. Application of Clonal Selection Algorithm (CSA) for optimal capacitor placement problem has been presented in [3]. Loss sensitivity constant based optimization of capacitor allocation problem using analytical method has been proposed in [4]. Water cycle algorithm (WCA) and grey wolf optimizer (GWO) as optimization tools, optimal capacitor placement and sizing has been analyzed in [5]. Six test systems were considered to prove the efficacy of the proposed method. Optimal reactive power optimization in radial DS using Weight Factor based Improved Salp Swarm Algorithm (ISSA-WF) has been reported in [6]. In [3-6] was discussed reactive power optimization considering 3 load levels. P_{Loss} reduction cost and capacitor investment cost are taken as objective function [2-6]. Reduction in P_{Loss}, Q_{Loss} and voltage stability maximization as objective, optimal allocation and sizing of real and reactive power compensation devices using CSA as optimization tool has been performed in [7]. P_{Loss} reduction, voltage stability maximization, profit maximization as objective, allocation of capacitors using Loss Sensitivity Factor (LSF) has been presented in [8]. CSA has been utilized to find out the necessary sizing. Chu and Beasley Genetic Algorithm (CBGA) as optimization method, reduction in P_{Loss} and capacitor cost as objective, reactive power compensation using capacitors has been suggested in [9]. P_{Loss} reduction as objective, optimal allocation of capacitors using Mixed-Integer Second-Order Cone Programming (MI-SOCP) has been done in [10]. P_{Loss} minimization, voltage stability enhancement and capacitor cost reduction as objective, optimal location of capacitors using LSF has been done in [11]. Appropriate sizing of capacitors are done by Modified Teaching Learning Based Optimization (MTLBO) algorithm. Reactive power compensation in radial DS using Particle Swarm Optimization (PSO) and Dice Game Optimizer has been presented in [12]. However it is to be noted that the reactive power compensation using PSO (4 nodes) exceeds the total maximum reactive power demand of the DS taken for evaluation.

Proposed work. In this study, Archimedes Optimization Algorithm (AOA) which is powerful in solving wide range of optimization problems has been engaged to solve the objective function due to its merits such as good convergence acceleration, lower plainly of stuck in local optima, accelerated process in getting excellent solutions and has higher feasibility and efficiency in producing global optima. Capacitor sizes in discrete steps are taken for validation. No sensitivity factor (based on loss or voltage) has been utilized to select the most appropriate buses for reactive power compensation. Single objective function comprising capacitor purchase cost with cost based P_{Loss} reduction has been evaluated under three load levels subject to maintain all the constraints within its permissible limits. The proposed method has been tested and evaluated with the help of the modified 12-bus test system, standard IEEE 33 bus system and 94-bus Portuguese DSs using MATLAB coding.

The **purpose** and **contribution** of this work is to yield a better solution for reactive power compensation. Taking into consideration the above published studies, the contributions of this work include:

1. Suggestion of futuristic AOA to solve the objective function (with decreased / increased load demand);
2. Utilizing a new modified 12-bus test system for reactive power optimization;
3. Considering 3 load levels for capacitor allocation and sizing for 94-bus Portuguese DS.

Problem of statement. The objective function is to obtain maximum economic benefits by optimal placement and sizing of shunt capacitors in the radial DS while satisfying both system equality and inequality constraints.

Objective function is:

$$\text{Minimize} = \frac{\left(K_C \times \sum_{l}^{TCN} Q_{C(l)}\right)}{\left(K_{P_{loss}} \times \left(TP_{Loss}^{BO} - TP_{Loss}^{AO}\right)\right)}, \quad (1)$$

where K_C is the cost of capacitor (discrete), \$; $Q_{C(l)}$ is the capacity of capacitor at l^{th} node, kVAr; TCN is the number of capacitor nodes; K_{Ploss} is the cost of real power loss, \$; TP_{Loss} is the total real power loss, kW; AO means after optimization; BO means before optimization.

Subject to equality constraints:

$$Q_{MS} - \sum Q_D + \sum_{l}^{TCN} Q_{C(l)} - TQ_{Loss}^{AO} = 0, \quad (2)$$

where Q_{MS} is the reactive power from main source, kVAr; Q_D is the reactive power demand, kVAr; TQ_{Loss} is the total reactive power loss, kVAr.

Inequality constraints are:

$$Q_{C(l)}^{\min} \le Q_{C(l)} \le Q_{C(l)}^{\max}; \quad (3)$$

$$V_{(i)}^{\min} \le V_i \le V_{(i)}^{\max}; \quad (4)$$

$$\sum_{l}^{TCN} Q_{C(l)} \le \left(\sum Q_D + TQ_{Loss}^{AO}\right), \quad (5)$$

where V_i is the voltage at i^{th} node (p.u);

$$TP_{Loss} = \sum_{m=0}^{TNB} P_{Loss(m,\, m+1)};$$

and

$$P_{Loss(m,\, m+1)} = \frac{P_m^2 + Q_m^2}{\left|V_m^2\right|} \times R_{(m,\, m+1)},$$

where R_m is the resistance of the branch m; P_m is the real power of the branch m, kW; Q_m is the reactive power of the branch m, kVAr; TNB is the total number of branches.

Practical capacitors are available in standard capacities which are the multiple integer values of the smallest size denoted as Q_C^0. The per kVAr cost of the capacitor changes across its sizes which are available commercially. The available capacitor sizes are typically taken as

$$Q_C^{\max} = A \times Q_C^0. \quad (6)$$

Thus for each capacitor installation node, the sizes are A times that of capacitor size (i.e) $\{Q_C^0, 2Q_C^0, 3Q_C^0, ..., AQ_C^0\}$, where A is an integer multiplier.

In this paper, recursive function and a linked-list data structure designed power flow [13] has been used which have advantages of solving power balance equation for radial nature of DS, low X/R system and also the ability to update easily to accommodate the reconfiguration technique and embedded generation.

Solution methodology. In [14] proposes a population based metaheuristic optimization algorithm called AOA inspired by the law of physics called as Archimedes' principle. In order to find global optimal solutions, AOA keeps a population of solutions and examines a huge area. Hence this work considers AOA as optimization tool to solve capacitor allocation problem anticipates that AOA maintains a good balance between exploration and exploitation. Similar to other population based algorithms, AOA begins the search procedure with initial Solution Vectors (SVs) with random volumes, densities, and accelerations. Also each object is set with its arbitrary location in fluid. During the evaluation process, AOA updates the density and volume of every object in every iteration and based on the condition of its collision with any other adjacent object the acceleration is being updated. The updated new solution vectors (density, volume, acceleration) replace the existing positions. The mathematical model of AOA is discussed below.

Process 1. Initialize the SVs randomly using (7):

$$ob_d = BL_d^{\min} + \left\lfloor rand \times \left(BL_d^{\max} - BL_d^{\min}\right)\right\rfloor; \quad d = 1,2,3...,\quad (7)$$

where ob_d is the d^{th} object in a SV of N objects; $BL^{\min}$ and $BL^{\max}$ are the minimum and maximum values of the search agent respectively; *rand* is the M dimensional vector randomly generates number between 0 and 1.

Equation (8) indicates the acceleration initialization of d^{th} object. Estimate the object with the best fitness value:

$$ac_d = BL_d^{\min} + \left[rand \times \left(BL_d^{\max} - BL_d^{\max}\right)\right] \quad (8)$$

Process 2. The volume and density for each object d for the iteration IT+1 is updated using (9). Assign x^{bt}, de^{bt}, vo^{bt} and ac^{bt} :

$$\begin{cases} de_d^{IT+1} = de_d^{IT} + \left[rand \times \left(de_d^{bt} - de_d^{IT}\right)\right]; \\ vo_d^{IT+1} = vo_d^{IT} + \left[rand \times \left(vo_d^{bt} - vo_d^{IT}\right)\right]; \end{cases} \quad (9)$$

where vo^{bt} and de^{bt} are the volume and density connected with the best object established so far; IT is the current iteration.

Process 3. During the commencement of process in AOA, collision between the objects occurs and drives the objects towards the equilibrium state after a specified period done by a transfer operator (TO), which changes search from exploration to exploitation as given in (10). The value of TO increases gradually towards 1:

$$TO = \exp\left[\frac{IT - IT_{\max}}{IT_{\max}}\right], \quad (10)$$

where TO is transfer operator.

In the same way, density decreasing factor g also helps AOA in achieving global to local search with respect to time using (11):

$$g^{IT+1} = \exp\left[\frac{IT - IT_{\max}}{IT_{\max}}\right] - \left[\frac{IT}{IT_{\max}}\right], \quad (11)$$

where g^{IT+1} decreases with respect to time which gives the capability to converge in previously recognized promising value. To achieve a good balance between the exploration and exploitation process, appropriate control of this variable must be confirmed.

Process 4. As already discussed, collision between the object occurs, if the value of TO is less than or equal to 0.5. Select a Random Material (MR) and update object's acceleration for iteration IT + 1 using (12):

$$ac_d^{IT+1} = \frac{de_{MR} + vo_{MR} \times ac_{MR}}{de_d^{IT+1} \times vo_d^{IT+1}}, \quad (12)$$

where de_d, vo_d and ac_d are the density, volume, and acceleration of object d; ac_{MR}, de_{MR} and vo_{MR} are the acceleration, density, and volume of MR respectively. It is significant to state that TO is less than or equal 0.5 conforms the exploration during one third of iterations. However, if TO value is greater than 0.5 no collision between objects occurs and hence update the object's acceleration for iteration IT+1 using (13):

$$ac_d^{IT+1} = \frac{de^{bt} + vo^{bt} \times ac^{bt}}{de_d^{IT+1} \times vo_d^{IT+1}}, \quad (13)$$

where ac^{bt} is the acceleration of the best object.

Process 5. To calculate the percentage of change, normalize the acceleration using (14):

$$ac_{d-nor}^{IT+1} = b \times \frac{ac_d^{IT+1} - ac_{\min}}{ac_{\max} - ac_{\min}} + k, \quad (14)$$

where b and k are the range of normalization and set to 0.9 and 0.1, respectively. The left-hand side of (14) regulates the % step that each agent will change. The value of acceleration is high when the object d is far away from the global optimum, which indicates that the object will be in the exploration phase; or else, in exploitation phase. Under normal case, the acceleration factor starts with larger value and moves towards the lower value with time.

Process 6. If the object d is in exploration phase, the updation has been done using (15) and if the object d is in exploitation phase then updation has been done using (16)

$$x_d^{IT+1} = x_d^{IT} + P_1 \times rand \times ac_{d-nor}^{IT+1} \times g \times \left(x_{rand} - x_d^{IT+1}\right); \quad (15)$$

$$x_d^{IT+1} = x_{bt}^{IT} + F \times P_2 \times rand \times ac_{d-nor}^{IT+1} \times g \times \left(T \times x_{rand} - x_d^{IT+1}\right), \quad (16)$$

where T increases with respect to time and directly proportional to TO and is defined as $T = P_3 \times TO$; F is the flag to change the direction of motion. The value of F is +1 for P is less than or equal to 0.5, otherwise –1.

The value of P is calculated as:

$$P = 2 \times rand - P_4. \quad (17)$$

Below is the pseudo code for AOA [14].

Set the population size (N), total number of iterations (Itmax)
Fix the value for P_1, P_2, P_3 and P_4 as 2, 6, 2 and 0.5 as mentioned in [13].
Initialize the population, random positions, densities, acceleration and volumes using (7) and (8)
Evaluate the initial population and select the one with the best fitness function value
Set the iteration count IT=1
while** ($IT < IT_{max}$) **do
for** each search agent 'd' **do
Update density and volume of each object using (9)
Update TO and 'g' using eqn. (10) and (11) respectively
if** $TO \le 0.5$ **then (Exploration phase)
update the acceleration using (12) and normalize acceleration using (14)
update the position using (15)
else (Exploitation phase)
update acceleration using (13) and normalize acceleration using (14)
update direction flag 'F' using (17)
update the position using (16)
end if
end for
evaluate each object and select the one with the best fitness function value
set IT = IT+1
end while
***return** object with the best fitness value*
end of procedure

Test parameters, results and discussions. To prove the usefulness of the proposed optimization algorithm (AOA), in minimizing the P_{Loss} with enhancement in bus voltage and maximizing the economic benefit, 3 radial power DSs such as modified 12-bus, IEEE 33-bus and Portuguese 94-bus DS have been considered in this work. The single-line diagrams of all the test systems before optimization (BO) are shown in Fig. 1–3.

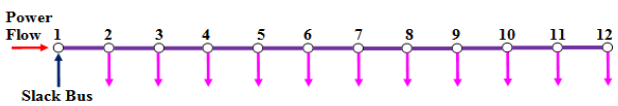

Fig. 1. Indian 11 kV, 12-bus system (BO)

For all the test cases, bus number 1 has been considered as substation bus/slack bus whose bus voltage is fixed as 1 p.u. The remaining buses are considered as load buses and capacitor will be installed in any of the potential load nodes that require compensation.

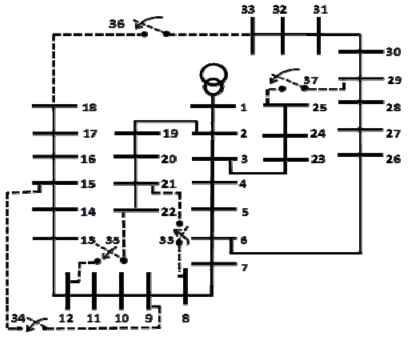

Fig. 2. IEEE 33-bus test system (BO)

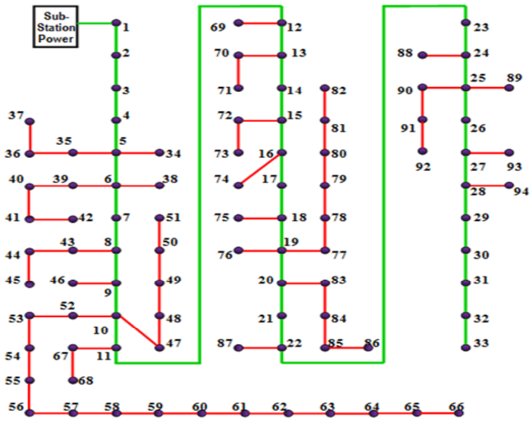

Fig. 3. Real 94-bus Portugal test system (BO)

In this work, maximum number of nodes for capacitor installation is limited to 3 for all the test systems. The algorithm parameters details such as agent size and number of iterations are selected as 800 and 100 respectively. The variables used to calculate the net savings per annum are power loss cost \$168/kW/year and the cost data pertaining to commercially available capacitor sizes (\$/kVAr) used in this work has been taken from [9]. Table 1 reveals the parameter results pertaining to BO.

Modified 12-bus test system. First radial test system is a modified 12-bus single feeder Indian DS which has 12 nodes and 11 branches. Further details of this DS can be found in [15, 16]. However, similar to [17], the loads on each bus are multiplied by five (both active and reactive power). The base kV and base MVA are 11 kV and 100 MVA respectively.

Table 2 reveals the results obtained by the proposed method under 3 load levels After Optimization (AO). Verifying Table 1 and 2, it is obvious that the power loss has reduced between 47.5 % and 61.5 % by injecting 86.4087 %, 93.5 % and 85.4276 % of the total (Q_D + $Q_{Loss(AO)}$) respectively. The minimum bus voltage has enhanced by 5.1522 %, 11.832 % and 32.273 % respectively at bus number 12. Considering the cost factor, the change in power loss cost (ΔP_{Loss}) cost is \$12561.2424, \$37174.77 and \$112947.93 respectively. Thus the total economical benefit is found to be between 47 % and 61 % compared to BO.

Table 1

Parameter details of test systems under 3 different load levels – BO

Load level	Load demand, kVA	P_{Loss} + j Q_{Loss}, kVA	Bus voltage, p.u.	Cost of P_{Loss}, \$
Modified 12-bus DS				
50 %	1087.5 + j 1012.5	153.0848 + j 59.2462	0.8443 (12)	25718.2464
75 %	1631.2 + j 1518.8	420.1375 + j 161.9583	0.7387 (12)	70583.1
100 %	2175 + j 2025	1090.7 + j 416.8654	0.5689 (12)	183237.6
IEEE 33-bus test DS				
50 %	1857.5 + j 1150	48.7903 + j 33.0487	0.9540 (18)	8196.7704
100 %	3715 + j 2300	211 + j 143.135	0.9038 (18)	35448
160 %	5944 + j 3680	603.4843 + j 410.2165	0.8360 (18)	101385.362
Real 94-bus Portuguese DS				
50 %	2398.5 + j 1161.95	79.6036 + j 110.9393	0.9299 (33)	13373.405
100 %	4797 + j2323.9	361.67636 + j 503.7688	0.85413 (33)	60761.63
160 %	7675.2 + j 3718.24	1155.5 + j 1595.2	0.7242 (33)	194124

Table 2

Performance of AOA – modified 12 bus system – all the 3 load levels

Parameter details	50 % load levels	75 % load levels	100 % load levels
P_{Loss} (AO), kW	78.3155	198.8591	418.3909
P_{Loss} reduction, %	**48.842**	**52.6681**	**61.64**
Capacitor nodes, kVAr	300 (4)	450 (4)	900 (5)
	300 (7)	600 (7)	600 (8)
	300 (10)	450 (10)	450 (10)
V_{min}, p.u	0.8878	0.8261	0.7525
P_{Loss} cost (AO), \$/year	13157.004	33408.3288	70289.6712
Cost of capacitor, \$/(kVAr-year)	315	359.7	410.55
Net savings, \$	12246.242	36815.0712	112537.3788
Economic benefit, %	**47.61694**	**52.1585**	**61.4161**

Figure 4 shows the graph of the bus voltages before and after optimization. From Fig. 4, it is visible that drastic fall in voltages are evidenced from bus number 1 to 5 and 7 to 9 compared to other buses both BO and AO.

Two ways of comparison (IEEE 33-bus) have been given from Tables 3 to 5 – one based on P_{Loss} reduction and the other based on economic benefits.

IEEE 33-bus test system. The next DS is a renowned system which has 33 nodes, 32 main branches and 5 looping branches as shown in the Fig. 2. The details pertaining to IEEE 33-bus can be taken from [10]. The base kV and base MVA of this test system are 12.66 kV and 100 MVA respectively. For this DS the comparison have been shown in 2 ways. First one based on P_{Loss} reduction alone and second one based on P_{Loss} as well as economic benefit.

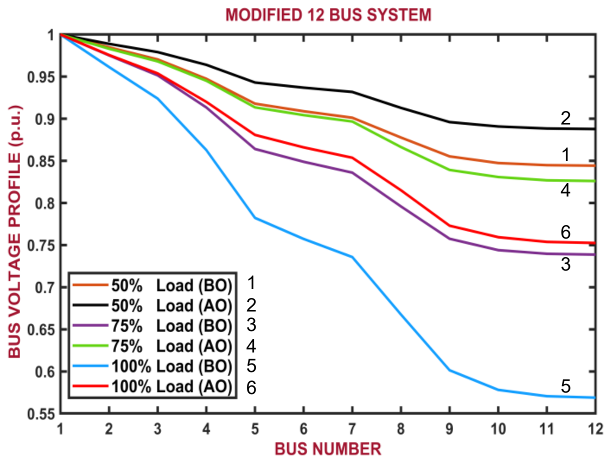

Fig. 4. Bus voltage – modified 12 bus – all load levels

From Tables 3 to 5, it is obvious that the P_{Loss} has reduced by around 32.1 %, 34.4 % and 36.945 % respectively after optimal reactive power support of 77.543 %, 83.03 % and 86.174 % of the total (Q_D + $Q_{Loss(AO)}$), at 3 optimal nodes considering 3 load levels. The bus voltage has enhanced by 1.4465 %, 3 % and 6.746 % respectively. The change in the P_{Loss} cost is found to be \$2630.93, \$12194.112 and \$37456.858 and the net annual financial benefits are between 28 % and 36.5 %.

Tables 3–5 discuss the comparison between AOA and other methods in the literature for 50 %, 100 % and 160 % load levels individually [2-10]. Considering 50 % load level and from Table 3, AOA achieves better performance compared to [2-5] in terms of P_{Loss} reduction and economic benefit. Taken into consideration the cost factor, AOA achieves more than 1 % compared to [5]. However, AOA equals ISSA-WF. Considering 100 % load level and from Table 4, AOA achieves better performance in terms of P_{Loss} reduction and net economic benefit compared to [2, 6-10]. From Table 4, it is witnessed that the difference in P_{Loss} reduction and economic benefit are minuscule compared to [6, 9, 10]. Finally, under 160 % load level and from Table 5, the performance of AOA is better than [3-6].

Table 3

Performance of AOA – IEEE 33 bus – 50 % load – P_{Loss} and economic based comparison

Parameter details	PBOA [2]	CSA [3]	Analytical [4]	GWO [5]	WCA [5]	ISSA-WF [6]	AOA
P_{Loss} (AO) / P_{Loss} (BO), kW	48.7868 / 35.03134	32.0895 / 47.0709	33.04 / 47	32.42 / 47.07	32.43 / 47.07	33.13 / 48.7903	33.13 / 48.7903
P_{Loss} reduction, %	28.195	31.8273	29.8	31.12	31.1	32.097	**32.097**
Capacitor size, kVAr/nodes	125 (13)	150 (12)	300 (14)	300 (5)	300 (5)	300 (6)	300 (6)
	72 (28)	100(24)	250 (30)	150 (12)	150 (12)	150 (14)	150 (14)
	162 (29)	600 (30)	170 (32)	300 (29)	300 (29)	450 (30)	450 (30)
V_{min}, p.u	0.966	0.9678 (18)	0.9734 (18)	0.9694 (18)	0.9687(18)	0.9678 (18)	0.9678 (18)
P_{Loss} cost (AO), \$	–	–	–	5446.56	5448.24	5565.84	5565.84
Cost of capacitor, \$/(kVAr-year)	–	–	–	285	285	293.85	293.85
Net savings, \$	–	–	–	2176.2	2174.52	2337.08	2337.08
Economic benefit, %	–	–	–	27.52	27.49856	28.5122	**28.5122**

Table 4

Performance of AOA – IEEE 33 bus – 100 % load – P_{Loss} and economic based comparison

Parameter details	PBOA [2]	CSA [7]	CSA [8]	CBGA [9]	ISSA-WF [6]	MI-SOCP [10]	AOA
P_{Loss} (AO) / P_{Loss} (BO), kW	135.1018 / 202.6774	138.54 / 210.99	138.65 / 210.99	138.416 / 211	138.511 / 211	138.416 / 210.987	138.416 / 211
P_{Loss} reduction, %	33.33	34.338	34.286	34.4	34.355	34.395	**34.4**
Capacitor size, kVAr/nodes	318 (6)	495(11)	450 (11)	450 (12)	450 (12)	450 (12)	450 (12)
	294 (13)	500(24)	400 (24)	450 (24)	600 (24)	450 (24)	450 (24)
	709 (29)	946(30)	950 (30)	1050 (30)	1050 (30)	1050 (30)	1050 (30)
V_{min}, p.u	0.9365 (18)	0.9321 (18)	0.9321 (18)	0.93 (18)	0.93093 (18)	–	0.9309 (18)
P_{Loss} cost (AO), \$	–	–	–	23253.888	23269.9	23253.888	23253.888
Cost of capacitor, \$/(kVAr-year)	–	–	–	467.10	485.25	467.10	467.10
Net savings, \$	–	–	–	11727.012	11692.9	11692.9	11727.012
Economic benefit, %	–	–	–	33.0823	32.9861	32.98607	**33.0823**

Table 5

Performance of AOA – IEEE 33 bus – 160 % load – P_{Loss} and economic based comparison

Parameter details	CSA [3]	Analytical [4]	GWO [5]	WCA [5]	ISSA-WF [6]	AOA
P_{Loss} (AO) / P_{Loss} (BO), kW	393.2709 / 575.3682	384 / 575.36	364.82 / 575.36	368.56 / 575.36	381.1067 / 603.4843	380.5268 / 603.4843
P_{Loss} reduction, %	31.64883	33.21	36.5927	35.943	36.849	**36.945**
Capacitor size, kVAr/nodes	550 (12)	840 (14)	1200 (5)	1050 (5)	600 (13)	600 (12)
	100 (24)	650 (30)	450 (13)	600 (12)	1050 (24)	1050 (24)
	1050 (30)	520 (32)	1200 (29)	1050 (29)	1650 (30)	1650 (30)
V_{min}, p.u	0.8528 (18)	0.9	0.8982 (18)	0.8982 (18)	0.8924 (18)	0.8921 (18)
P_{Loss} cost (AO), \$	–	–	61289.76	61918.08	64025.926	63928.5024
Cost of capacitor, \$/(kVAr-year)	–	–	521.85	610.8	689.85	689.85
Net savings, \$	–	–	34848.87	34131.6	36669.5844	36767
Economic benefit, %	–	–	36.0529	35.3108	36.16852	**36.2646**

Figure 5 reveals the bus voltage profiles of IEEE 33 bus test system under three different load levels. From Fig. 5 it is evident that bus voltage has improved well in all the load buses.

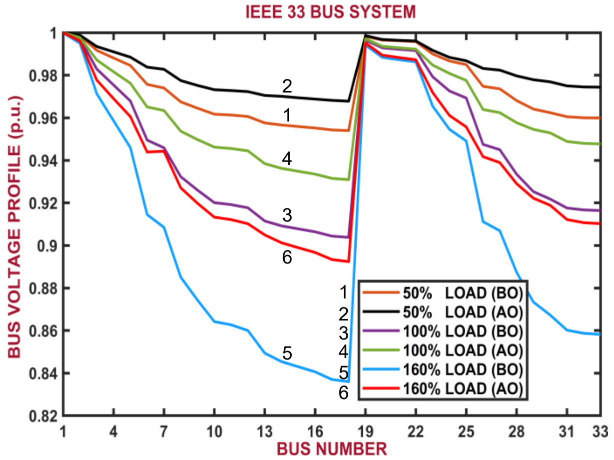

Fig. 5. Bus voltage – IEEE 33-bus – all load levels

Portuguese 94-bus test system. Final test system taken for evaluation is a real 94-bus Portuguese DS which has 94 nodes, 93 branches and 22 laterals. The base kV and base MVA of this test system are 15 kV and 100 MVA respectively. The line and load data for this real test system can be viewed in [11].

From Table 6 it is observable that the P_{Loss} has reduced between 21 % to 34 % after reactive power injection of above 95 % of the total (Q_D + $Q_{Loss(AO)}$), at 3 optimal nodes considering 3 load levels. The difference in bus voltage enhancement is found to be between 3 % and 16.75 %. The change in power loss cost (ΔP_{Loss}) after reactive power compensation is \$2854.488, \$15871.296 and \$65333.352 respectively considering 3 load levels. Thus the net annual economic benefit is found to be between 19 % and 33.3 %. By comparing the $P_{Loss(AC)}$ with [11], AOA achieves better performance.

Figure 6 shows the graph of the bus voltages before and after compensation. From Fig. 6, it is observable that enhancement of bus voltage is better in all the buses.

Table 6

Performance of AOA – Portugal 94-bus – all load levels – P_{Loss} based comparison

Parameter details	GA [11]	PSO [11]	TLBO [11]	MTLBO [11]	AOA		
					50% load levels	100% load levels	160% load levels
P_{Loss} (AO) / P_{Loss} (BO), kW	279.1 / 362.858	301.5 / 362.858	278.98 / 362.858	269.91/ 362.858	62.613 / 79.6036	268.386 / 362.8578	766.611 / 1155.5
P_{Loss} reduction, %	23	16.91	23.1	25.63	**21.3444**	**26.035**	**33.6555**
Capacitor size, kVAr/nodes	450 (65) 450 (73) 600 (84) 250 (87)	650 (58) 450 (73) 450 (84) 300 (90)	800 (59) 450 (72) 500 (83) 300 (90)	850 (58) 400 (72) 500 (84) 250 (89)	450 (19) 150 (25) 450 (57)	750 (10) 750 (20) 900 (58)	900 (15) 1200 (20) 1500 (57)
V_{min}, p.u	0.9094	0.9124	0.9039	0.9065	0.9584	0.9065	0.8454
P_{Loss} cost (AO), \$	46888.8	50652	46868.64	45344.88	10518.984	45088.848	128790.648
Cost of capacitor, \$/(kVAr-year)	–	–	–	–	302.7	578.7	670.2
Net savings, \$	–	–	–	–	2551.788	15292.596	64663.152
Economic benefit, %	–	–	–	–	**19.08106**	**25.16818**	**33.31023**

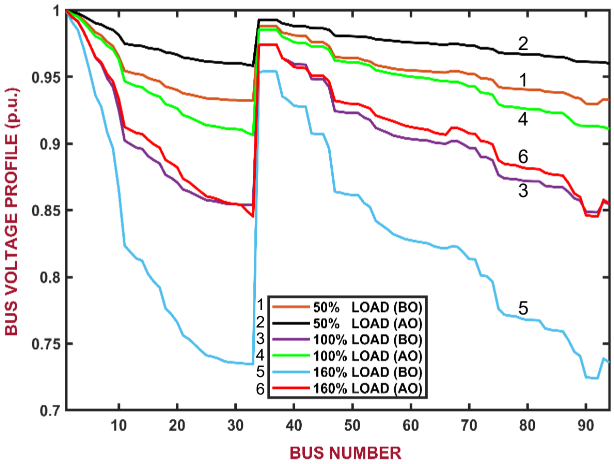

Fig. 6. Bus voltage – Portugal 94-bus – all load levels

Conclusions. In this paper, a new powerful swarm intelligence algorithm has been utilized to solve the cost based objective function which is the combination of power loss P_{Loss} cost with capacitor investment cost so as to get more economic benefits under 3 different load levels. The merits of adopting Archimedes optimization algorithm for this problem have already been discussed. The proposed method has been successfully applied to a new modified 12-bus, standard IEEE 33-bus test system and a real 94-bus Portuguese test systems. Following are the key points which are worth noted:

1. No sensitivity factor based optimal node selection for reactive power compensation has been adopted in this paper.
2. Considering modified 12-bus system, an overall P_{Loss} reduction (under 3 load levels) of around 49 % to 62 % with economical benefit of 47.6 %, 52 % and 61.4 % have been observed. Regarding standard IEEE 33 bus system, the overall P_{Loss} reduction is found to be between 32 % and 37 % with economical benefit of 28.5 % to 36.246 % have been witnessed. Finally, considering practical 94-bus test system, the P_{Loss} reduction under 3 load levels are seemed to be between 21 % to 34 % with economical benefit of 19 % to 33.3 % are evidenced.
3. Considering the standard IEEE 33-bus system and 94-bus real Portuguese system, the performance has been analyzed and compared to the recent methods presented in the literature. It is obvious that the difference in P_{Loss} reduction and economic benefit achieved by the proposed method are found to be better and significant. Hence Archimedes optimization algorithm has been recommended to be another strong and efficient method to solve capacitor allocation problem in terms of P_{Loss} reduction, bus voltage enrichment and economic benefit.

Conflict of interest. The authors declare that they have no conflicts of interest.

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