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Research Paper

Optimal Reactive Power Injection in Distribution Networks to Maximise Cost Savings via AOA

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Abstract: Utilities have been forced to raise the overall efficiency towards a better position in radial distribution systems (DS). The literature has proved that reactive power compensation performs well in minimising the power loss (P_{Loss}) and enhancing the bus voltage profile within the permissible range in radial DSs. This work presents Archimedes optimisation algorithm (AOA) to resolve the problem efficiently. The merit of this technique is that it can offer a global or near-global optimum for capacitor siting and sizing. The main intention of this study is to obtain maximum annual financial benefit (AFB) using the placement and sizing of capacitors optimally. This can, however, be achieved by minimising the objective function composed of cost-based Power loss and capacitor investment cost in radial DSs. The proposed technique has been tested on four renowned DS: the Indian 10-bus, modified 12-bus, PG&E 69-bus, and 94-bus Portugal DSs. The previously published papers are compared with the outcomes of AOA in terms of Power loss reduction with/without AFB and prove that AOA yields better performance.

Keywords: Capacitor siting and sizing, Radial distribution system, power loss minimisation, Archimedes Optimisation algorithm

1. Introduction

The most critical issues that occur in the entire distribution system (DS) are power loss and poor voltage profile. In developed countries like Europe and US, the power loss is 10% only. On the other hand, the average transmission and distribution Power loss is roughly 27% of the total power generated in India [1]. Such a significant quantity of power loss must be addressed since it reflects on financial aspects and the overall efficiency of the power DS. Further, it is mandatory to maintain an acceptable voltage profile for the end users. Therefore, Power loss reduction and bus voltage improvement methods are essential to achieve financial goals.

It is widely recognized that installing capacitors along the DS reduces a portion of the power loss, increasing the overall efficacy of the power delivery. The other benefits, such as sub-station power factor improvement, enhancement in bus voltage profile, network stability improvement, reduction in total apparent power (AP) demand, and feeder capacity release, can be possible only when the capacitors are located at optimal locations with appropriate capacity [2]. Hence optimal capacitor placement problem is a complex, combinatorial, mixed integer, and non-linear optimisation problem.

To perform reactive power compensation using capacitors, many researchers used two different objectives. Either minimisation of Power loss cost against capacitor purchase cost or maximisation of net annual financial benefit (AFB). However, some authors still consider Power loss reduction as the only objective [3,4]. Considering economic-based criteria in the capacitor allocation problem is

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essential to achieve the best solution [5]. Selecting appropriate nodes and determination of optimal capacitor sizing are the two main steps to obtain the best result in the capacitor allocation problem. Though sensitivity factor-based identification of appropriate nodes for reactive power compensation helps reduce the search space during optimisation, the outcome may not indicate the appropriate location for reactive power compensation [6]. Many research articles consider capacitor sizing as a continuous type instead of a discrete one. On the other hand, the sizes available in the market are for discrete kinds only. Also, it has already been proved that continuous variable methodology might not yield a better result. Therefore, the capacitor sizes are taken as discrete variables [7].

The order of the remaining work is as follows. The literature and inspiration for this work are reviewed in Section 2. Segment 3 presents the basic distribution system power flow (DSPF), the objective function (with equality and inequality constraints), the mathematical model of AOA, and its capability to solve the reactive power optimisation with the block diagram. Segment 4 reveals the results obtained by AOA. Segment 5 describes the outcomes of AOA after the compensation, and finally, segment 6 concludes the results and observations, followed by the references.

2. Literature Survey

Reactive power compensation has been carried out in [9] using the Chu and Beasley genetic algorithm (CBGA) as an optimisation approach, with decreasing Power loss and minimising capacitor cost as the objectives. This work includes bus voltage deviation and penalty factor-based line thermal limit in the objective function. From [9], it is observed that the methodology adopted is different from the latest one, and the result obtained is not an optimal global value. The bus voltage after optimisation still needs to be discussed. Salp-swarm algorithm (SSA) based allocation of capacitors in radial DSs considering three load levels has been presented in [10]. Using a combination of the flower pollination algorithm (FPA), the voltage stability index (VSI), and the loss sensitivity factor (LSF), the study of capacitor placement and sizing has been carried out in [11]. LSF and VSI were utilised to identify the potential nodes for reactive power optimisation. The main objective of [11] is to find the energy loss reduction with the reduction in capacitor purchase cost, capacitor installation, and operation cost under three different load levels. 10-bus, 69-bus, and 118-bus test systems have been utilised to prove the efficacy of FPA. Hybrid FPA and exhaustive search (ES) approach (FPAES) based reactive power optimisation in radial DS has been performed in [12]. FPA has been utilised to find the optimal buses, and ES has done the optimal sizing. The authors strongly agree that due to the limited search space of the predetermined discrete capacitor sizing, the computing effect to determine the optimal capacity of the capacitor is considerably diminished. 10-bus, 34-bus, and 85-bus test systems determine the potency. Optimal capacitor allocation and sizing under three load levels, such as 50%, 100%, and 160% in radial DSs using a water cycle algorithm (WCA) and grey wolf optimizer (GWO), is performed in [13]. Apart from standard test systems (33-bus, 69-bus, and 85-bus), this work considers three Indian practical radial DSs such as 28-bus, 47-bus, and 52-bus are also taken to prove the efficacy of the proposed methods. It is obvious that fixed and switchable-based capacitors with changes in investment cost need to be considered for load-level-based optimization. But [13] considered only fixed-type capacitors. FFPA-based capacitor siting and sizing optimisation in four renowned DSs (IEEE 33-bus, 34-bus, PG&E 69-bus, and Indian 85-bus) have been proposed in [14]. Power loss cost and capacitor investment cost minimisation have been considered as objectives. Data structure-based load flow analysis has been utilised in [14] to determine the Power loss and bus voltage profile. To determine the optimal allocation of capacitors in two DSs, a combined optimisation approach (COA) based on SSA and LSF has been considered [15]. VLSF and reactive power loss sensitivity factor QLSF-based ranking of load buses have been adopted in this paper. The COA based on a three-stage procedure has been implemented to reduce the search space and achieve computation time reduction. Power loss minimisation and energy loss minimisation with a reduction in capacitor investment cost have been taken as the objective function. The algorithms were validated using 69-bus, 85-bus, and 30-bus (part of the Unified Egyptian Network) DSs. Slime mould optimisation algorithm (SMOA) based optimisation of capacitor siting and sizing in two radial DSs (69-bus and 85-bus) has been reported in [16]. Apart from SMOA, two more metaheuristic algorithms, such as bonobo optimisation algorithm (BOA) and tunicate swarm algorithm (TSA), have been utilised for comparison purposes. This work takes the capacitor values as integral multiples of 100 KVAR & 150 KVAR, respectively. The optimisation has been done for both the DSs with and without voltage constraints. Optimisation of reactive power compensation using capacitors in two radial DSs via teaching learning-based optimisation algorithm (TLBO) and modified teaching learning-based optimisation algorithm (MTLBO) to use the energy loss reduction cost, minimise the capacitor investment expenses and voltage stability enhancement has been carried out in [17]. Besides, it is understood from [17] that there is no guarantee that either TLBO or MTLBO will escape from sub-optimal solutions. Reactive power optimisation at three optimal nodes using sequential power loss index (PLI) based method and PSO have been carried out in [18]. 34-bus, Indian 85-bus, and real Portugal 94-bus systems are evaluated. The optimal buses for reactive power optimisation are decided using a formula based on the total reactive power demand (QD) and the average range of capacitors.

Combined overall Power loss cost reduction and capacitor investment cost reduction as objective, reactive power optimisation using multi-verse optimizer (MVO) has been investigated in [19]. Besides, this work employs the partial and modified use of conventional LSFs. To reduce the search space, along with modified LSFs, MATLAB ‘is member’ and ‘any’ commands have been utilised. 10-bus, 33-bus, and 69-bus test systems are used to demonstrate the helpfulness of MVO. From [20], it is understood that the traditional LSF does not yield a realistic representation of the actual change in the Power loss. Reduction in Power loss, energy loss cost, and reduction in capacitor investment cost as objective, optimal allocation and sizing of capacitors in radial DSs using four algorithms, namely stochastic fractal search algorithm (SFSA), modified stochastic fractal search algorithm (MSFSA) 1 and 2 and the proposed MSFSA have been done in [20]. IEEE 33, PG&E 69, and Indian 85 bus test systems are taken to prove the efficacy of the proposed method. Reactive power injections at two, three, and four optimal nodes have been carried out to distinguish the power loss reduction. It is to be noted that the actual bus voltage profile improvement after optimisation has not been mentioned. Reduction in Power loss cost and costs related to the capacitor such as investment, installation, and operation as objective, reactive power compensation (four optimal locations) using mathematical remora optimisation algorithm (ROA) has been performed in [21]. The Power loss of the network lines index PLNLI has been considered to identify the most critical nodes for reactive power compensation. Allocation and sizing of Type-I DGs after reactive power compensation at two optimal locations have also been evaluated in [21]. IEEE 33 and PG&E 69 bus test system has been taken to prove the efficacy of the proposed method. Enhanced modified particle swarm optimisation (EMPSO) as an optimisation tool, evaluation of capacitor allocation, and sizing in radial DSs considering three objective functions have been performed in [22]. Capacitor allocation has been done in two phases. Identification of potential nodes for capacitor placement using LSF has been taken as the first phase, and in the second phase, the optimal locations have been chosen by NMPSO. In both phases, optimal sizing has been done by EMPSO. The first objective function dealt with Power loss reduction against capacitor integration. At the same time, the second objective function dealt with the energy loss reduction-based integration of capacitors. The difference between the second and third objective functions is the time duration. Second and third objective functions considered single and three load levels, respectively. EMPSO has been evaluated using standard 15 bus, IEEE 33 bus, and PG&E 69 bus test systems. It is to be noted that the selection of nodes for capacitor integration is typically three only. On the other hand, [22] considered five nodes for reactive power compensation, which is abnormal. Considering more nodes for payment and high reactive power penetration (more than 100%) will reverse the objective of the work, and there is a possibility of profit decrease and saturation in bus voltage enhancement as well.

Power loss minimisation and economic saving as objectives, optimal allocation and sizing of capacitors using a reformulation of the same mixed integer non-linear programming MINLP model through a mixed-integer second-order cone programming (MISOCP) has been performed in [23]. On the other hand, the major drawback is that it has already been proved that the mathematical-based optimisation methodology yields poor performance compared to meta-heuristics optimisation methods. Minimising energy loss cost and capacitor investment cost as objective, placement, and capacity determination of capacitors at three / five optimal nodes using a multi-verse optimizer (MVO) as an optimizing tool has been proposed in [24]. This paper discusses the importance of reactive power compensation at the source and load sides. 34 and Indian 85 bus test system has been taken for evaluation.

The authors generally consider power loss reduction and capacitor purchase costs as the main parameters [9-18]. However, [11,15,17,18,21,24] considered installation and O&M cost in addition to the above parameters. Many authors utilised sensitivity-based identification (LSF, VSF, VLSF, QLSF) of weak buses for capacitor installation [11,15,17,22]. However, from [18,25,26], it is understood that SI may not always indicate the appropriate location for reactive power compensation and also leading to the underutilisation of the optimising tool since it is used only for capacitor sizing.

From the above previously published papers, it is understood that the main objective is to increase the overall gain by reducing the total Power loss with capacitor investment cost. LSF-based weak node identification for reactive power injection will not yield a good result. Optimizing optimal nodes and appropriate capacitor sizing using the meta-heuristic algorithm may help get a better result.

In this study, sensitivity factor-based detection of feeble buses for reactive power injection has been avoided; instead, the algorithm has to search for both optimal nodes and sizing of capacitors, and also the capacitor sizes are taken in discrete steps (multiplication of 150 KVAr). Archimedes optimisation algorithm (AOA) has been engaged to solve the objective function due to its several advantages, which have been discussed in section 3. A single objective function comprising capacitor purchase cost with cost-based Power loss reduction has been evaluated with the condition that all the network constraints from Equations 2 to 5 should get satisfied. Indian 10-bus, modified 12-bus, IEEE 69-bus, and 94-bus Portugal DSs are used to verify the proposed method.

The purpose and contribution of this work are to yield a better solution for reactive power compensation using capacitors. A modified 12-bus test system with increased load demand (5 times) has been considered, which is new for reactive power compensation.

3. Problem Formulation

3.1. Distributed System Power Flow (DSPF)

To evaluate the performance of DSs under seasonal periods, a power flow (PF) study is an essential tool that needs to be performed frequently under steady-state operating conditions. Due to the DS's low X/R ratio and radial character, the renowned matrix-based PF methods used for the transmission network were ineffective. In this paper, the PF method developed in [8] has been utilised in order to solve the DS efficiently.

3.2. Objective Function

The main target of this problem is to find the best solution for Power loss and AFB by reactive power optimisation using capacitors in the DSs with the condition that network constraints must be satisfied. The objective function has been divided into two parts. From Equation (1), it is apparent that the denominator discusses the total cost saving pertaining to solving Power loss reduction due to reactive power compensation. The numerator reveals the capacitor investment cost. The various cost parameters discussed above are as follows:

$$\text{Minimise Cost} = \frac{(K_C \times \sum_{l}^{TCN} Q_{C(l)})}{(K_{P_{Loss}} \times (TP_{Loss}^{IC} - TP_{Loss}^{AO}))} \tag{1}$$

Subject to Equality Constraints

$$Q_{MS} - \sum Q_D + \sum_{l}^{TNC} Q_{C(l)} - TQ_{Loss}^{A0} = 0 \tag{2}$$

Inequality Constraints

$$Q_{C(l)}^{\min} \leq Q_{C(l)} \leq Q_{C(l)}^{\max} \tag{3}$$

$$\sum_{l}^{TNC} Q_{C(l)} \leq (\sum Q_D + TQ_{Loss}^{A0}) \tag{4}$$

$$V_{(i)}^{\min} \leq V_i \leq V_i^{\max} \tag{5}$$

where

$$TP_{Loss} = \sum_{m=0}^{TNB} P_{LOSS(m,m+1)} \quad \text{and} \quad P_{LOSS(m,m+1)} = \frac{P_m^2 + Q_m^2}{|V_m^2|} \times R_{(m,m+1)}$$

K_{PLoss} is the cost per KW of P_{Loss} ($/KW);
K_c is the capacitor investment cost ($/KVAr);
T_{PLoss} represents the total active $P_{Loss\,s}$(KW);
TQ_{Loss} represents the total reactive Q_{Loss} (KVAr);
IC is the initial condition of the DS;
AO indicates after optimisation;
TNC is the total number of nodes that require reactive power compensation
Q_{ci} is the reactive power support given at bus *'i'* (KVAr);
Q_{MS}, Q_D represents the primary source of reactive power supply and reactive power demand (KVAr);
TNB indicates the total number of buses in the DS.
$V_{(i)}$ is the bus voltage at i^{th} bus.

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. It is understood that large-capacity capacitors have lower prices. The available capacitor sizes are typically taken as

$$Q_C^{\max} = A \times Q_C^0 \tag{6}$$

Thus, for each capacitor installation node, the sizes are 'A' times that capacitor size (i.e.) {Q_C^0, AQC^0} where 'A' is an integer multiplier

3.2. Solution Methodology (AOA)

Hashim et al. propose a population-based metaheuristic optimisation algorithm termed AOA inspired by the law of physics named Archimedes' principle [27]. To find globally optimal solutions, AOA retains inhabitants of solutions and inspects a vast area. Hence this work considers AOA as an optimisation technique (OT) to solve the capacitor allocation problem and anticipates that AOA maintains a noble balance between exploration and exploitation. Like other population-based optimisation techniques, AOA begins the search procedure with initial solution vectors (SV) with random volumes, densities, and accelerations. Also, each object is set with its arbitrary location in the fluid. During the evaluation process, AOA updates the thickness and volume of everything in every iteration. The acceleration is updated based on the condition of its collision with any other adjacent object. The updated new SVs (density, volume, acceleration) replace the existing positions. The mathematical model of AOA is discussed below.

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

$$\mathrm{ob_d} = \mathrm{BL}_d^{\min} + [rand \times (\mathrm{BL}_d^{\max} - \mathrm{BL}_d^{\min})]; \quad \mathrm{d}=1,2,3......\mathrm{N} \tag{7}$$

where $\mathrm{ob_d}$ is the $\mathrm{d^{th}}$ object in an SV of N objects. $\mathrm{BL^{min}}$ and $\mathrm{BL^{max}}$ are the search agent's minimum and maximum values, respectively. Rand is an M-dimensional vector that randomly generates numbers between 0 and 1.

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

$$\mathrm{ac_d} = \mathrm{BL}_d^{\min} + [rand \times (\mathrm{BL}_d^{\max} - \mathrm{BL}_d^{\max})] \tag{8}$$

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

$$\mathrm{de_d}^{IT+1} = \mathrm{de_d}^{IT} + [rand \times (\mathrm{de}_d^{\mathrm{bt}} - \mathrm{de}_d^{\mathrm{IT}})] \; \& \; \mathrm{vo_d}^{IT+1} = \mathrm{vo_d}^{IT} + [rand \times (\mathrm{vo}_d^{\mathrm{bt}} - \mathrm{vo}_d^{\mathrm{IT}})] \tag{9}$$

Where $\mathrm{vo^{bt}}$ and $\mathrm{de^{bt}}$ are the volume and density connected with the best object established.

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

$$TO = \exp\left[\frac{IT - IT_{\max}}{IT_{\max}}\right] \tag{10}$$

where IT and $\mathrm{IT_{max}}$ represents the current iteration and maximum iterations, respectively. In the same way, the density decreasing factor 'g' also helps AOA achieve global to local search concerning time using Equation (11).

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

where $\mathrm{g^{IT+1}}$ decreases over time, allowing converging in previously recognized promising good value. Appropriate control of this variable must be confirmed to balance the exploration and exploitation process well.

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

$$ac_d^{IT+1} = \frac{de_{MR} + vo_{MR} \times ac_{MR}}{de_d^{IT+1} \times vo_d^{IT+1}} \tag{12}$$

Where d_{ed}, v_{od}, and acd are the density, volume, and acceleration of object 'd'. The parameters such as 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 to 0.5 conforms to the exploration during one-third of iterations. However, if the TO value is more important than 0.5, no collision between the objects occurs, hence updating the object's acceleration for iteration IT+1 using Equation (13).

$$ac_d^{IT+1} = \frac{de^{bt} + vo^{bt} \times ac^{bt}}{de_d^{IT+1} \times vo_d^{IT+1}} \tag{13}$$

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

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

$$ac_{d-nor}^{IT+1} = \mathrm{b} \times \frac{ac_d^{IT+1} - ac_{min}}{ac_{max} - ac_{min}} + k \tag{14}$$

Where 'b' and 'k' are the normalization range, set to 0.9 and 0.1, respectively. The LHS of eqn. (14) regulates the % step that each agent will change. The acceleration value 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 the exploitation phase. Under the typical case, the acceleration factor starts with a larger value and moves towards a lower value with time.

Process 6: If the object 'd' is in the exploration phase, the updating has been done using Equation (15), and if the object 'd' is in the exploitation phase, then updating has been done using Equation (16)

$$x_d^{IT+1} = x_d^{IT} + P_1 \times rand \times ac_{d-nor}^{IT+1} \times \mathrm{g} \times (x_{rand} - x_d^{IT+1}) \tag{15}$$

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

where 'T' increases concerning time, is 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 using Equation (XVII)

$$P = 2 \times \text{rand} - P_4 \tag{17}$$

The AOA optimisation process begins with producing a random set of candidate solutions (populations) according to their given value. Assign the P1, P2, P3, and P4 values as 2, 6, 2, and 0.5, as mentioned in [27]. Amid the direction of reiteration, acceleration, density, and volume of MR, access the attainable positions of the immediate ideal solution (Equations (7) and (8). Each answer re-establishes its function from the optimally obtained solution with the help of 'TO' and 'g' (Equations (9) – (11)). Exploration and exploitation (Equations (12) to (16)) of the parameters are expanded directly. Candidate solutions look to separate from the near-optimal solutions. Update 'F' after calculating 'P' (Equation (17)). Inevitably, the AOA calculation is halted by coming to the fulfillment of the convergence measure. Figure 1 reveals the block diagram of the entire process.

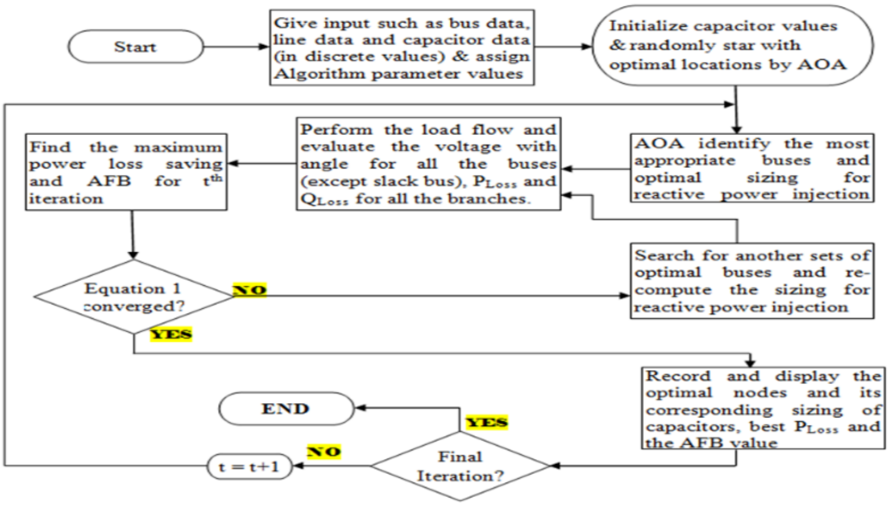


Figure 1. Block diagram – Reactive power compensation optimisation using AOA

4. Results

To demonstrate the usefulness of AOA in Power loss reduction and progress in node voltage with an increase in AFB, four radial power DSs, such as 10-Bus, modified 12-bus, IEEE 69-bus, and 94-bus Portuguese DSs, are considered for assessment. Figures 2 to 5 show the bus arrangement for all four test systems under IC.

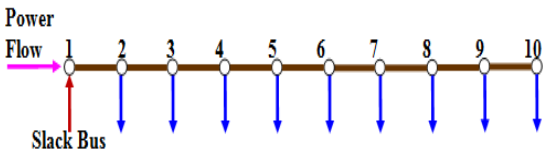


Fig. 2. Indian 10-Bus system (IC)

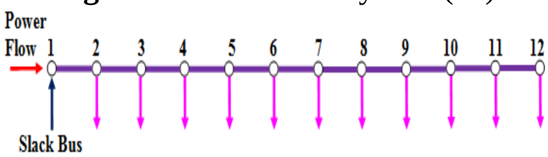


Figure 2. Indian 12-Bus system (IC)

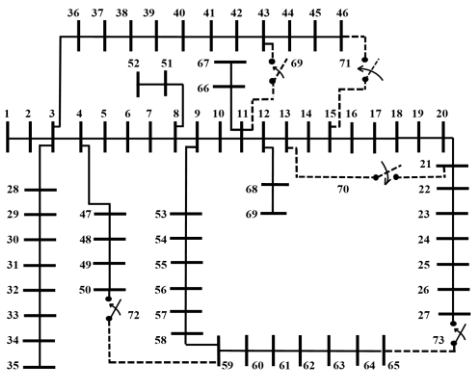


Figure 3. IEEE 69-Bus system (IC)

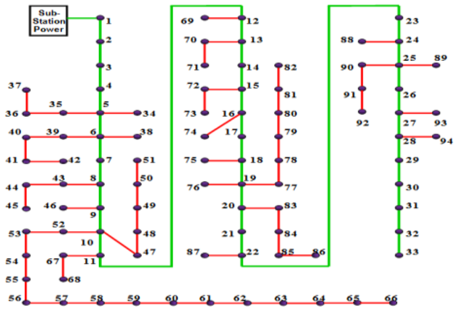


Figure 4. Portugal 94-Bus system (IC)

4.1. Test System Details

The first test system is a well-known single-feeder Indian DS operating at 23 KV with considerable loads in all the nodes. The details about this DS can be seen in [9]. Like the 10-bus system, the 12-bus test system is also a single-feeder Indian 11 KV system with loads in all the buses. Further, details of this network can be found in [28]. However, similar to [29], the AP demand on each bus is multiplied by five. 12.66 KV and 100 MVA are taken as KV $_{(base)}$ and MVA $_{(base)}$ for the renowned 69-bus DS. The details about 69-bus DS can be taken from [11]. For all the test cases, bus number 1 has been considered a substation bus/slack bus whose bus voltage is fixed as 1 p.u. The remaining buses are considered load buses, and capacitors will be installed in any potential nodes requiring compensation. The total number of compensation buses decides the loss reduction (P_{Loss} and Q_{Loss}). However, there is a limitation to the installation of capacitors in a DS. Injection of reactive power more than the required number of nodes and through non-optimal buses will increase the Power loss economically. Hence, this paper chooses capacitor installation at four optimal nodes for the 10-bus system and three optimal nodes for the remaining test systems. Algorithm parameter details such as the total population and iteration number have been taken as 800 and 100, respectively. DSPF-embedded AOA has been done using MATLAB coding. To find out the net AFB, the Power loss cost has been taken as $168/kW/year, and the cost related to prevailing capacitor sizes ($/KVAr) has been taken from [15].

4.2. Indian 10- Bus System

The first test system is a single-feeder 10-bus Indian system whose data can be viewed in [9]. Fig. 2 shows the structure of 10-bus Indian DS, which has 10 nodes and nine branches. 23 KV and 100 MVA have been taken as KV $_{(base)}$ and MVA $_{(base)}$, respectively. The total AP demand is (12368+j4186) KVA. The real and reactive Power loss and minimum bus voltage under IC are (783.7784+j 1036.5) KVA and 0.8375 p.u. (@ bus 10) respectively. The total Power loss cost under IC is $131674.7712.

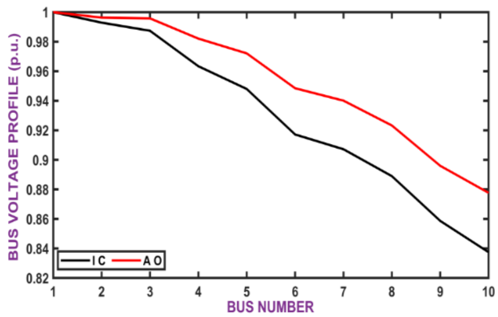
Table 1 shows that the Power loss has been reduced by 12.75787% compared to IC by optimally injecting 96.895% of the total reactive power (QD + Q_{Loss}(AO)) at four buses. The minimum node voltage has enriched from 0.8375 p. u to 0.8877 p.u. which is around 6% compared to IC. The enhancement in node voltage after compensation is uniformly distributed in all the nodes. Considering the cost factor, the power loss (Δ P_{Loss}) change is $16798.89. After considering the capacitor purchase cost, the net AFB is around 12.1% compared to the IC of Power loss of the DS. Table 1 shows that the AOA minimises Power loss in an enhanced way compared to [9-12]. The AFB achieved by AOA is $1909.74 greater than [9]. However, the benefit gained between AOA and [10] is minuscule. The minimum bus voltage profile after compensation is greater than [12]. However, the minimum bus voltage improvement equals SSA [10] and less than FPA [11]. Though [19] achieves a better result in Power loss reduction than the proposed method, the number of compensation nodes is six. Moreover, the reactive power compensation given is 2.4367 times greater than the total reactive power demand of the system. Figure 6 shows the graph of the bus voltages before and after compensation. Since it is a single feeder, the bus voltage profile faces a drastic fall in voltage from buses 1 to 10. However, after capacitor placement, the bus voltage has improved by 6%.

Table 1. Performance of AOA over other methods – 10-Bus DS

Parameters	E S [12]	F P A [12]	F P A E S [12]	F P A [11]	S S A [10]	CBGA [9]	MVO [19]	A O A
P_{Loss} (AO) /P_{Loss} (BO) (KW)	694.4 / 783.7	695 / 783.7	694.4 / 783.7	688.28 / 783.77	683.8012 / 783.7784	691.99 / 783.79	675.6971 / 783.7895	683.785 / 783.7784
% P_{Loss} reduction	11.3947	11.318	11.39467	12.1834	12.7558	11.7123	13.79	12.75787
Optimal Capacitor Size	1200 (5) 1100 (6) 500 (9) 200 (10)	1200(5) 1200(6) 300 (9) 200(10)	1200 (5) 1100 (6) 500 (9) 200 (10)	1500 (5) 300 (7) 600 (9) 1100 (10)	2400 (5) 1050 (6) 450 (8) 300 (10)	2100 (4) 1950 (5) 1950 (6) 750 (10)	4050 (3) 2100 (4) 2100 (5) 1200 (6) 450 (9) 300 (10)	2400 (5) 1050 (6) 450 (7) 300 (10)
V_{min}(p.u.)	0.86	0.86	0.86	0.9509	0.8877	------	0.9	0.8877
P_{Loss} cost – AC ($/Year)	116659.2	116760	116659.2	115631.04	114878.60	116254.32	113517.113	114875.88
Capacitor Cost ($/Year)	-------	-------	-------	-------	866.25	1399.5	1887	866.25
Net AFB ($/Year)	-------	-------	-------	-------	15929.92	14022.9	16272.5232	15932.64
% AFB	-------	-------	-------	-------	12.098	10.6495	12.3579	12.09999

4.3. Indian Modified 12-Bus System

The second radial test system is a modified 12-bus system with 12 nodes and 11 branches with loads in all the nodes. The KV (base)and MVA (base)are 11 KV and 100 MVA, respectively. This system supplies an AP demand of (2175+j2025) KVA. The Apparent Power loss and minimum bus voltage under IC are(1090.7+j416.8654) KVA and 0.5689 p.u. @ bus no.12 respectively. The Power loss cost under IC is $183237.6.



Figue 6. Bus voltage profile – 10-Bus DS

The Power loss has reduced from 1090.7 KW to 418.3909 KW, 61.64015% compared to IC. This has been achieved after the reactive power injection of 98.57% of the total (QD + $Q_{(Loss(AO))}$) at three optimal nodes {1050 (4), 600 (7), and 600 (10)}. The minimum bus voltage observed is 0.7525 p.u.

@ bus number 12, which is 0.1836 p.u. increase compared to IC. The improvement in bus voltage is found to be around 32.273%. Considering the cost factor, the change in the Power loss cost (ΔP_{Loss}) cost is $112947.93, and the capacitor purchase cost is $503.4. Thus, the total AFB is found to be 61.3654% compared to the IC of the DS. Figure 7 shows the graph of the bus voltages before and after compensation. Fig.7 shows a drastic voltage drop for buses from 1 to 5 and 7 to 9 compared to other buses. However, after capacitor placement, the bus voltage has improved by 31.306%.

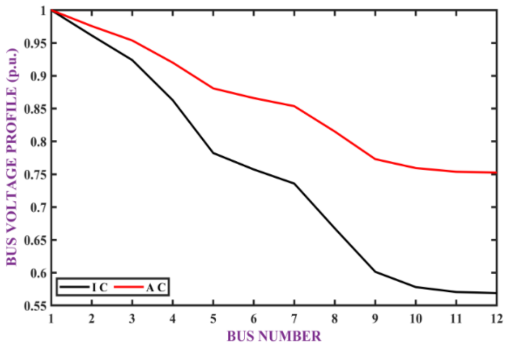


Figure 7. Bus Voltage profile – Modified 12-Bus DS

4.4. PG&E 69- Bus DS

The next DS is a renowned system with 69 nodes, 68 main switches, and five tie-switches formed as loop branches, as exposed in Fig. 4.

Table 2. Performance of AOA over other methods– IEEE 69-Bus DS

Parameters	GWO [13]	WCA [13]	FPA [14]	COA [15]	SMOA [16]	MSFS [20]	AOA
P_{Loss}(IC) / P_{Loss}(BO)(KW)	146.74 / 225	146.73 / 225	145.86 / 225	146.269 / 224.96	145.78 / 225	145.1297 / 225	145.775 / 225
% P_{Loss} reduction	34.78222	34.78666	35.17333	34.98	35.20888	35.4979	35.211
Capacitor Size (KVAR) / Nodes	300 (16) 900 (60) 450 (61)	300 (16) 450 (59) 900 (60)	450 (11) 150 (22) 1350 (61)	300 (17) 150 (57) 1200 (61)	150 (12) 300 (18) 1200 (61)	406.55 (11) 246.59 (19) 1236.45 (61)	450 (12) 150 (21) 1200 (61)
V_{min} (p.u)	0.9322 (65)	0.9312 (65)	0.933	0.93131	-----	0.93	0.9314
P_{Loss} cost (AC) ($)	24652.32	24650.64	24504.48	24573.192	24491.04	24381.79	24489.36
Cost of Capacitor ($/(KVAR-year))	383.55	383.55	468.3	384	384	-----	392.85
Net AFB ($)	12764.13	12765.81	12827.22	12836.088	12924.96	-----	12917.79
%AFB	33.76754	33.772	33.93444	33.96394	34.193	-----	34.1782

This test system KV (base) and MVA (base) of this test system are 12.66 KV and 100 MVA, respectively. This DS supplies a total AP demand of (4027+j 2797.115) KVA. The total AP and minimum bus voltage profile under IC is (225+j 102.115) KVA and 0.90918 p.u. respectively. The Power loss cost under IC is $37800.

From Table 2, it is evident that the Power loss has reduced by 35.181% after optimal reactive power support of 64.352% of the total ($Q_D + Q_{(Loss(AO))}$) at three optimal nodes. The bus voltage has enhanced from 0.90918 to 0.9314 p.u. The change in the Power loss cost is $13312.2, and the net AFB after considering the capacitor cost is 34.178%. Table 2 shows that the Power loss reduction achieved by AOA is better than [13-16]. The minimum and maximum AFB differences between AOA and other methods [13-15], as discussed in Table 2, are $81.702 and $153.66. However, the difference in Power loss reduction and net AFB achieved by AOA and [16] is minuscule. This is because of the increased capacitor cost. The Power loss reduction difference between [20] and the proposed method is around 0.5% only. This may be due to increased reactive power compensation. Fig. 8 reveals the bus voltage profile of the IEEE 69-bus system. The enhancement in node voltage between AOA and other methods [13-16] is minuscule. Yet AOA's minimum bus voltage profile after compensation is less than GWO [13] and FPA [14]. From Fig. 8, it is evident that the bus voltage has improved well in the maximum number of load buses.

4.5. Portugal 94-Bus System

The final test system taken for evaluation is a real 94-bus Portugal DS with 94 nodes, 93 branches, and 22 laterals. The $KV_{(base)}$ and $MVA_{(base)}$ are 15 KV and 100 MVA, respectively. This real test system's line and load data can be viewed in [11]. The total AP demand is (4797+j2323.9) KVA. The total AP Power loss and minimum bus voltage under IC are (361.67636+j 503.7688) KVA and 0.85413561 p.u. @ bus no. 33 respectively.

Table 3. Performance of AOA over other methods – real Portugal 94-Bus DS

Parameters	GA [17]	PSO [17]	TLBO [17]	MTLBO [17]	PSO [18]	AOA
P_{Loss} (AO) (KW) / P_{Loss} (IC) (KW)	279.1 / 362.858	301.5 / 362.858	278.98 / 362.858	269.91/ 362.858	271.777 / 362.858	268.386 / 362.8578
% P_{Loss} reduction	23	16.91	23.1	25.63	25.10	26.035
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)	750 (20) 250 (25) 800 (58)	750 (10) 750 (20) 900 (58)
V_{min} (p.u)	0.9094	0.9124	0.9039	0.9065	0.8485	0.9065
P_{Loss} cost (AC) ($)	46888.8	50652	46868.64	45344.88	45658.536	45088.848
ΔP_{Loss} Cost ($)	14071.344	10308.144	14091.504	15615.264	15301.608	15871.296
Cost of Capacitor ($/(KVAR-year))	-----	-----	-----	-----	-----	578.7
% AFB	-----	-----	-----	-----	-----	25.0862

The total Power loss cost under IC is $60761.62848. From Table 3, it is observable that the Power loss has reduced from 362.8578 to 268.386 KW, which is 26.035% compared to the IC after reactive power injection of 97.71615% of the total ($QD + Q_{Loss\,(AO)}$), at three optimal nodes. The difference in bus voltage enhancement is found to be 0.0523644 p.u. After reactive power compensation, the Power loss cost (ΔP_{Loss}) change is $15871.296. Thus, the net AFB, $15292.596, is more than 25%. By comparing the $P_{(Loss(AO))}$ with other methods [17,18], AOA achieves better performance. Figure 9 shows the graph of the bus voltages before and after optimisation. Fig. 9 shows that the enhancement in bus voltage is uniformly distributed in all the buses, and the overall voltage enhancement is identified as 6%. The minimum node voltage achieved by the proposed method is less compared to the genetic algorithm (GA) [17] and particle swarm optimisation (PSO) [17] and equals MTLBO [17].

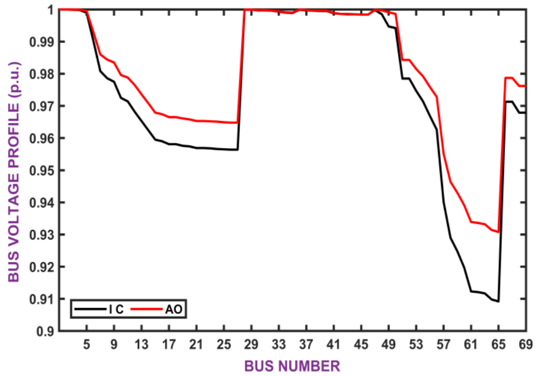


Figure 8. Bus voltage profile – IEEE 69-Bus DS

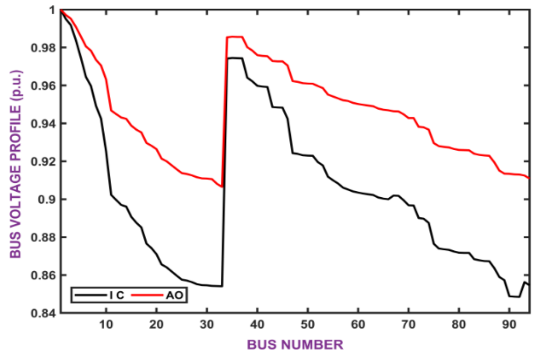


Figure 9. Bus voltage profile – Portugal 94-Bus DS

5. Discussions

As we have already seen, even without using SI, the proposed method yields better results than any other methods taken for comparison [9-18]. If the algorithm has optimal location and sizing, the AFB will be better than [9-18].

(i) Considering the Indian 10 Bus system, 100% reactive power support will yield 12.75787% of real power loss reduction. However, optimal results will not be achieved if the reactive power support is more [9] or less than adequate [11, 12]. It is noticeable that the difference between the result obtained by AOA and SSA [10] is found to be minuscule. FPA [11] achieves better voltage enhancement than any other method considering the bus voltage improvement. Understandably, the total reactive power support given to any DS should be at the search for most of the network's total reactive power demand (QD). On the other hand, CBGA [9] violates the previous statement by injecting 160% of the total QD. It is logical from [9] that over-compensation will reverse the objective of the work and will lead to financial loss.

(ii) The capacitor investment cost yielded by GWO, WCA, COA, and SMOA is almost the same, and the difference in capacitor size is only 150 KVAr. Though AOA recorded the least Power loss reduction after compensation compared to other methods, the % AFB is less than SMOA. This is because of the increased capacitor cost. The difference between AOA and other algorithms mentioned in Table 2 could be more manageable.

(iii) Regarding 94-bus Portugal practical DS, the change in power loss cost achieved by AOA due to reactive power compensation at three optimal nodes is more than GA, PSO, TLBO, MTLBO, and PSO [18], and the bus voltage also seems to be better. By analyzing the overall performance of the proposed method taking into consideration the above test systems, it is evident that AOA yields better performance. However, it is noticeable that, though AFB is imperative from an economic point of view, the performance of AOA in achieving voltage profile enhancement is found to be less. This study has not considered (i) Capacitor installation, operation, and maintenance costs and (ii) Load levels because of time and space constraints.

6. Conclusions

In this paper, a powerful physics-inspired intelligence algorithm named AOA has been utilised to solve the cost-based objective function for the capacitor placement problem: the combination of Power loss cost with capacitor investment cost to get more AFB. The merits of adopting AOA for this problem have already been discussed. The proposed method has been successfully applied to an Indian 10-bus, a new modified 12-bus, an IEEE 69-bus, and a real Portugal 94-bus test system. The following are the key points that are worth noting.

i. As already discussed, this paper has not considered the sensitivity-based index for identifying the most critical buses for reactive compensation. AOA must search for optimal location and sizing to yield the least cost value.

ii. The performance of the Single feeder 10-bus system, IEEE 69-bus system, and 94-bus Portuguese system have been analyzed and compared with the recent methods presented in the literature. The simulation results show that the difference in P_{Loss} reduction and AFB achieved by AOA are better and more significant. Hence AOA has been recommended to be another strong and efficient method for solving reactive power optimisation. Thus, AOA has been acknowledged as an effective optimisation tool for solving problems related to DSs.

Authors' Contributions

Srinivasan G: Conceptualization, Data collection, Running the MATLAB coding, taking the result, and partial manuscript preparation. Lavanya M: Conceptualization, Analysis, and Interpretation of Results and Review & Editing of the Manuscript.

Competing Interests

The authors declare that they have no competing interests.

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