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Salp swarm algorithm applied to optimal capacitor allocation problem in distribution network for annual cost savings

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ABSTRACT

Utilities have been forced to raise the overall efficiency towards a better position in radial distribution systems (DS). From the literature, it has been proved that reactive power compensation performs well in minimizing the P_{Loss} and enhancing the bus voltage profile within the permissible range in radial DSs. This work presents the salp swarm algorithm (SSA) to solve 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 annual financial benefits using the placement and sizing of capacitors optimally. This can however be achieved by minimizing the objective function composed of cost-based power loss and capacitor cost on radial DS considering three different load levels. The proposed technique has been tested on standard IEEE 69 and modified 12 bus systems. Computational results are compared with the results obtained by the previous published work and proved that SSA can minimize the P_{Loss} more effectively thereby financial benefit.

Keywords: Capacitor siting and sizing, Radial distribution system, Power loss minimization, Annual financial benefit, Salp swarm algorithm (SSA).

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1. INTRODUCTION

The most important issues that occur in the entire distribution systems (DS) are power loss (P_{Loss}) and poor voltage profile. Considering the developed countries in Europe and US, the power loss is 10% only. On the other hand, the average transmission &distribution of power losses are roughly 27% of the entire power generated in India (Ankaliki et al., 2012). Such a non-negligible amount of losses has a direct impact on economical aspects and the overall efficiency of distribution utilities. Further, it is mandatory to maintain an acceptable voltage profile for the end users. Therefore, methods for P_{Loss} reduction and bus voltage improvement are essential to achieve financial goals.

It is widely recognized that the installation of shunt capacitors reduces a portion of P_{Loss} of the DS, which in turn increases 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 Kilo Volt Ampere (KVA)demand, and feeder capacity release can be possible only when the capacitors are located at optimal locations with appropriate capacity. 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 cost of the capacitor vary in a discrete manner. To perform reactive power compensation using capacitors, many researchers used two different objectives. Either minimization of P_{Loss} reduction cost against capacitor purchase cost or maximization of net annual economical profit. However, some of the authors still considered P_{Loss} reduction as the only objective (Suryakala and Rani, 2017). It is essential to consider economic-based criteria in the capacitor allocation problem in order to achieve the best solution. The selection of appropriate nodes and determination of optimal capacitor sizing are the two main steps to obtain the best result in the capacitor allocation problem.

P_{Loss} minimization as objective, optimal allocation and sizing of capacitors using Particle Swarm Optimization (PSO) and Enhanced PSO under three different load levels (80%, 100% and 120%) have been reported in Suryakala and Rani (2017). The PSO has been modified using levy flight (LF) method for updating the velocity of the particles. Allocation and sizing of capacitors at single to four optimal nodes have been performed in this paper. Optimal placement and sizing of capacitors at three optimal buses with the intention to reduce energy loss and capacitor purchase cost have been discussed by Youssef et al. (2018). In this work, the selection of potential buses for reactive power compensation has been obtained using two loss sensitivity factors (voltage loss sensitivity factors) and a reactive power loss sensitivity factor. Normalization is used to segregate the most potential buses, and optimal sizing of capacitors has been done using Salp Swarm optimization Algorithm (SSA). Energy loss cost and capacitor investment cost minimization as objective, capacitor placement, and sizing considering three / four optimal locations under three load levels using Slime Mould Optimization Algorithm (SMOA) have been discussed by Kien et al. (2021). IEEE 69 and Indian 85 bus test systems have been taken to validate the performance of SMOA and combined optimization approach (COA). power voltage sensitivity constant (PVSC) based determination of potential buses that require compensation and Nawaz et al. (2017) have presented optimal capacitor sizing using the analytical technique. Two test systems such as IEEE 69 bus and a practical Indian 130 bus test system are taken to verify the usefulness of the proposed method under three load levels. Apart from the capacitor purchase cost, energy loss reduction cost and capacitor installation cost have been included in the objective function. Sampangi and Jayabarathi (2020) utilized two optimization methods such as GWO and WCA to solve the optimal capacitor allocation problem in radial DSs. Six test systems including three Indian practical DSs were considered to prove the efficacy of the proposed methods in gaining the maximum network savings under three different load levels.

P_{Loss} reduction and voltage profile enhancement as objective, optimal sizing of the capacitor using cuckoo search algorithm (CSA) considering five different load levels (50%, 75%, 100%, 125% and 160%) has been proposed by Devabalaji et al. (2018). For the optimal selection of potential nodes for capacitor placement, the voltage stability index has been adopted. The emission constraint capacitor allocation problem in DS using a modified competitive swarm optimizer approach (MCOS) has been implemented by Das and Malakar (2021). In this paper, an environment-friendly and cost-effective solution procedure has been adapted to solve the optimal capacitor locations and sizing problem in radial power DS which is formulated as a two-stage Mixed Integer Non-Linear Programming problem. A new Relative Emission Index (REI) based formulation has been introduced to select the potential candidate buses for reactive power injection. Next, the identification of optimal places and capacity determination of the capacitors were done using a basic Competitive Swarm Optimizer (CSO) algorithm. To get a better and improved result, Opposition-based CSO (OCSO) has also been adopted. Optimal capacitor placement in the radial DS using FPA to reduce the total power loss and capacitor installation cost has been presented by Tamilselvan et al. (2018). Mahmoud and Lehtonen (2021) discussed optimal multiple capacitor allocation and sizing using two analytical closed-form expressions in radial DS to maximize the total cost reduction. These analytical expressions do not require iterative processes or optimization algorithms. Maximization of profit by minimizing the energy loss with the reduction in capacitor investment cost and reliability enhancement using the Sine Cosine Algorithm (SCA) has been proposed by Abdelsalam and Mansour (2019). In this work, LSF has been engaged to find the most sensitive buses for reactive power compensation.

Nevertheless, some of the drawbacks observed in capacitor allocation problems are the determination of optimal capacitor node and sizing independently could lead the result being trapped in local minima instead of global ones due to the calculation of the capacitor size based on the predetermined locations (Youssef et al., 2018; Devabalaji et al., 2018; Abdelsalam and Mansour, 2019). and also some of the papers have dealt the capacitor placement problem considering the capacitor treated as a continuous variable instead of discrete types (Nawaz et al., 2017; Das and Malakar 2021; Mahmoud and Lehtonen, 2021). On the other hand, available commercial capacitors are of discrete types. It has already been proved that continuous variable methodology might not yield optimal results.

In this study, SSA which is powerful in solving a 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, an 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. A single objective function comprising capacitor purchase cost with cost-based power loss reduction has been evaluated subject to maintaining all the constraints within its permissible limits. The proposed methodology has been tested and evaluated with the help of the standard IEEE 69 bus and a modified 12-bus test system using MATLAB coding. The purpose and contribution of this work is to yield a better solution for reactive power compensation. Hence as already discussed, sensitivity-based index has not been considered in this work. To verify the effectiveness of the proposed methodology, modified 12-bus test system (with increased load demand) has been taken which is new for reactive power compensation. Two ways of comparison, (IEEE 69-bus) have been given in Tables from 2 to 5. One is based on P_{Loss} reduction and the other is based on net cost savings.

The total paper has been arranged into 5 sections. Section 2 indicates the problem formulation, objective function, and basic load flow. Section 3 discusses in brief the proposed optimization method, mathematical model, and the application of SSA in the optimal allocation and sizing of capacitors. Section 4 reports about the results obtained followed by the discussions for both test cases. Section 5 concludes the paper.

2. PROBLEM OF STATEMENT

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

2.1 Objective Function

$$\text{Minimize Cost} = (K_{PL*}P_{TL}) + (K_{CP} * \textstyle\sum_{i}^{NC} Q_{ci}) \quad (1)$$

Subject to Equality Constraints

$$Q_{MS} - \sum Q_D + \textstyle\sum_{i}^{NC} Q_{C(i)} - Q_{TL} = 0 \quad (2)$$

Inequality Constraints

$$Q_{C(i)}^{min} \leq Q_{C(i)} \leq Q_{C(i)}^{max} \quad (3)$$

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

$$\textstyle\sum_{i}^{NC} Q_{C(i)} \leq (\sum Q_D + Q_{TL}) \quad (5)$$

Where $P_{TL} = \sum_{m=0}^{TNB} P_{LOSS(m,m+1)}$ and $P_{LOSS(m,m+1)} = \frac{P_m^2+Q_m^2}{|V_m^2|} * R_{(m,m+1)}$

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

$$Q_c^{max} = U.Q_c^0 \quad (6)$$

Thus, for each capacitor installation node, the sizes are 'U' times that of capacitor size (i.e) {Q_C^o, $2Q_C^o$, $3Q_C^o$, ..., UQ_C^o} where 'U' is an integer multiplier.

2.2 Distribution System Power Flow (DSPF)

To know the necessity of additional power requirements under seasonal periods, reactive power support, and bus voltage profiles within acceptable limits, a power flow (PF) study has been performed frequently. Though PF study is a common method applied to both transmission and distribution networks, the renowned matrix-based PF methods used for transmission network were unsuccessful in solving power balance equations due to the low X/R ratio and radial nature of the DS.

In this paper, a recursive function and a linked-list data structure designed power flow (Venkatesh and Ranjan, 2003) have been used which has the advantages of solving power balance equation for the radial nature of DN, low X/R network and also the ability to update easily to accommodate the reconfiguration technique.

3. PROPOSED METHODOLOGY

The key target of any optimizer is to find out the global optimal solutions that select the user suitability for the allocation. SSA is a population-based optimization algorithm (Mirjalili et al., 2017) for solving real-world problems known to be a powerful algorithm. It is inspired by the navigation and foraging behaviour of salps in oceans. Salps have a transparent barrel-shaped body that will move similar to jellyfish. The SSA resembles the behaviours of salps when they form a swarm called a salps chain. Salps in the chain are divided into either leaders or followers according to the individuals' (i.e., salps) positions in the chain. The salp at the front of the chain is the leader, and the rest of the salps are followers. The leader leads the swarm and the followers follow each other.

3.1 Mathematical Model for Salp Chains

Similar to other swarm-based algorithms, the position of salps is well defined in a m-dimensional search space where m is the number of variables of the problem to be solved. Thus, the location of all the salps are arranged and saved in a two-dimensional matrix designated as X. It is assigned that the position of the best salp called F, which is chased by the salps chain. During optimization, according to the instructions received from the leader for swallowing the best food (F), each salp position is updated in order to get a better solution (Mirjalili et al., 2017) So the salps chain has to move toward the global optimal, which changes over the range of iterations. The mathematical model to move the salps chain may be written as follows

$$x_j^1 = \{F_j + C_1((ub_j - lb_j)c_2 + lb_j)c_3 \geq 0 \text{ and } x_j^1 = \{F_j - C_1((ub_j - lb_j)C_2 + lb_j)c_3 < 0 \quad (7)$$

where x_j^1 is the location of the starting salp (i.e.) leader in the jth dimension. F_j is the place of the food source in the jth dimension which is the swarm's target. ub_j and lb_j indicate the upper and lower bound of the jth dimension respectively. C_1 to C_3 are the arbitrary numbers uniformly generated in the interval of [0,1], and the coefficient C_1 is the main controlling parameter of the SSA and is defined by

$$C_1 = 2e^{-\left(\frac{4l}{L}\right)^2} \quad (8)$$

$$x_j^i = \frac{1}{2}\left(x_j^i + x_j^{i=1}\right) \quad (9)$$

where l is the current iteration and L is the maximum number of iterations. The position of the followers is updated using the Equation (9). where $i \geq 2$ and x_j^i is the position of the i^{th} follower salp in the j^{th} dimension.

3.2 Application of SSA for the Chosen Problem

The steps involved in the SSA algorithm are discussed below:

Step 1: Initialize the search agents, the maximum number of iterations and the total number of dimensions which gives location and size of capacitors. Generate the initial search agents of a size considering all the constraints (2) – (6).

Step 2: Calculate the network parameters such as power loss using the DSPF discussed by Venkatesh and Ranjan, (2003) for each search agent generated. Calculate the fitness of initial salps using (1). Calculate the best search agent position using (7) for the first iteration.

Step 3: The value of C_1 gets updated for every iteration using (8), and the location of the follower salps is being updated using (9).

Step 4: Amend the salp based on the upper and lower boundary condition. Calculate the best value of the given objective function (fitness function)

Step 5: Check for the maximum number of iterations. Once maximum number of iterations reached, stop the operation and display the objective function value related to optimal capacitor node and sizing or else, repeat the steps 2 to 5. Fig. 1 shows the flow chart for the proposed method in positioning and sizing the capacitor.

4. RESULTS AND DISCUSSIONS

To prove the usefulness of the proposed optimization algorithm (SSA), in minimizing the P_{Loss} with enhancement in bus voltage and maximizing the cost saving, two radial power distribution test systems such as modified 12-bus and standard IEEE 69-bus system have been considered in this work.

The single-line diagram of both the test systems is shown in Figs. 2 and 3. 12-bus test system is an Indian 11kV single feeder system with loads in all the buses. The details of the network can be found in Das (1994). However, similar to Aman et al. (2012), the loads on each bus are multiplied by five (both active and reactive power). For IEEE 69 bus test system the kV base and MVA base have been taken as 12.66 and 100 respectively. 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 nodes that require compensation.

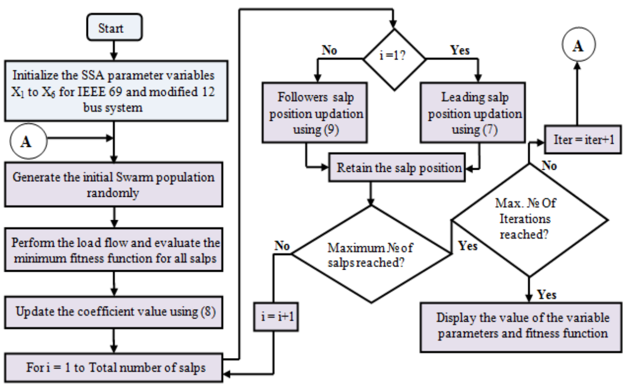

Fig. 1. Flow chart for the proposed algorithm – SSA

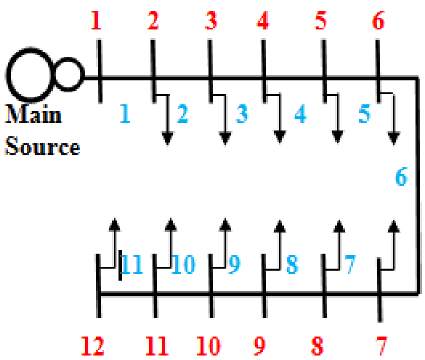

Fig. 2. 12 Bus test system (base case)

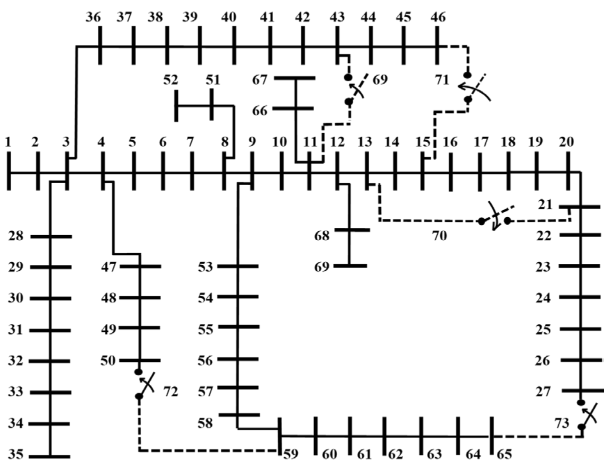

Fig. 3. IEEE 69 bus test system (base case)

In this work, the maximum number of nodes for capacitor installation is limited to three for both test cases. The algorithm parameters details such as agent size and number of iterations are selected as 800 and 100 respectively. The proposed algorithm with DSPF has been developed and carried out in MATLAB software and run on an i5 Intel processor based personal computer with 6 GB RAM. 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 analysis has been taken from (Kien et al., 2021).

4.1 Modified 12 Bus Test System

First radial test system is a modified 12-bus system which has 12 buses and 11 sectionalizing switches. This system supplies a real and reactive power demand of (1087.5 + j1012.5), (1631.3 + j1518.8) and (2175 + j2025) kVA under 50%, 75% and 100% load respectively. The real and reactive power loss without compensation is (153.0848 + j59.2462), (420.1375 + 161.9583) and (1090.7 + j416.8654) for 50%, 75% and 100% load conditions. The minimum bus voltages of this radial DN without compensation are 0.8443, 0.7387 and 0.5689 p.u. respectively at bus number 12. The P_{Loss} costs under BC are $25718.246, $70583.1 and $183237.6 /year.

Considering light load 50%, it has been observed from Table 1 that, the P_{Loss} has reduced by 48.84%compared to initial P_{Loss} consequent to the reactive power injection of 83.98% of the total reactive power supplied by the sub-station. The bus voltage has been enhanced by 5.1522%. The economical gain after reactive power injection is found to be 47.62% of the total P_{Loss} cost.

Under medium load condition, the P_{Loss} has reduced by 52.67% compared to BC. This has been achieved after the reactive power injection of 89.25% of the total QD, at three optimal nodes (4,7 and 10). From Table 1 it is obvious that the bus voltage has enhanced by 11.83% compared to BC. The economical gain after the compensation is seemed to be 52.16% of the total P_{Loss} cost.

Taking into consideration the heavy load 100%, by optimal allocation and sizing of capacitors at 5, 8 and 10, the power loss has suppressed by 61.64% compared to initial condition of the network. The bus voltage has improved by 32.27% with the reactive power penetration of 79.86%. The financial benefit after capacitor allocation is found to be 61.42% of the total P_{Loss} cost. Table 1 reveals the results obtained by the proposed method. Fig. 4 shows the graph of the bus voltages before and after compensation under three-load levels. From Fig. 4, it is visible that drastic fall in voltage for buses from 1 to 5 and 7 to 9 compared to other buses. However, after capacitor placement, the bus voltage has improved by 5.15%, 11.83% and 32.27%, respectively considering 50%, 75% and 100% load levels.

4.2 IEEE 69 Bus Test System

This test system has 69 buses and 68 sectionalizing switches which delivers apparent power under three different load levels (50%, 100% and 160%) are 2385.823, 4903.0477 and 8159.6766 kVA at 0.81845, 0.821365 and 0.8255 power factors respectively. The real and reactive power losses under initial conditions are (51.5822 + j23.54), (224.895 + j102.1155) and (652.2165 + j294.1142) kVA considering the above three load levels. The minimum bus voltages under initial conditions are 0.9567, 0.90919 and 0.8445 p.u. respectively. The BC P_{Loss} costs are $8665.81, $37782.36 and $109572.372 per year. Details of the results obtained by the proposed method are shown with comparative studies from Tables 2 to 5 under two categories. The first one is only P_{Loss} comparison (different cost-based objectives), and another is comparison of the results with other algorithms in the literature which has the same (almost) and similar cost based objective function such as P_{Loss} cost and capacitor cost minimization, constraints, and commercial capacitor data.

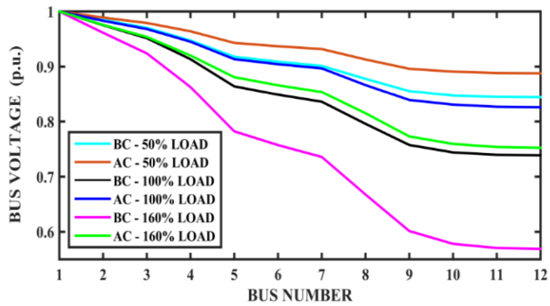

Fig. 4. Bus voltage profile – modified 12 bus

Table 2 reveals the performance of the IEEE 69-bus system under light load level. From Table 2, it is apparent that consequent to the reactive power compensation, the P_{Loss} has reduced by 33.55%, which is better than Nawaz et al. (2017); Devabalaji et al. (2018) by comparing the economical benefit achieved by SSA with other existing methods (Sampangi and Jayabarathi 2020; Kien et al., 2021), the cost-benefit almost equals GWO and WCA. However, it is apparent that SMOA achieves better performance compared to SSA, which is below 0.3%. Thus, the performance of SSA equals GWO and WCA.

From Table 3, by the addition of capacitors at three optimal locations, the P_{Loss} has decreased by 35.18% compared to the initial P_{Loss} value. The total capacitor value added to the network is around two third of the total reactive power demand of the network. However, with the application of SSA, the P_{Loss} has reduced to a lower value in comparison with the aforementioned methods, such as CSA, DA, SCA and EPSO. Around 0.1% of P_{Loss} reduction difference between OCSO and SSA is evidenced. Taking into consideration the bus voltage enhancement, an increase in bus voltage of 0.02221 p.u is noticed which is a 2.44% increase compared to the initial minimum bus voltage.

Table 1. Performance of SSA – modified 12 bus system – all the three load levels

Parameter details	50% load	75% load	100% load
P_{Loss} (BC) (kW)	153.0848	420.1375	1090.7
P_{Loss} (AC) (kW)	78.3155	198.8591	418.3909
% P_{Loss} reduction	48.842	52.6681	61.64
Capacitor nodes (KVAR)	300 (4) 300 (7) 300 (10)	450 (4) 600 (7) 450 (10)	900 (5) 600 (8) 450 (10)
V_{min} (p.u)	0.8878	0.8261	0.7525
P_{Loss} cost (BC) ($)/year	25718.246	70583.1	183237.6
P_{Loss} cost (AC) ($)/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
% Cost saving	47.61694	52.1585	61.4161

Table 2. Performance of SSA – 69 bus – light load – P_{Loss}& Cost based comparison

Parameter details	Analytical	C S A	S M O A	G W O	W C A	S S A
P_{Loss} (BC) (kW)	53.31	51.6	51.6	51.6	51.6	51.5822
P_{Loss} (AC) (kW)	36	34.45	34.14	34.40	34.45	34.2788
% P_{Loss} reduction	32.4	33.236	33.837	33.33	33.23	33.5453
Capacitor nodes	21, 61, 64	18, 61, 65	12, 18, 61	16, 60, 61	16, 59, 60	18, 61, 66
Capacitor size (kVAr)	80, 410, 170	150, 500, 150	150, 150, 600	150, 450, 150	150, 150, 450	150, 150, 600
V_{min} (p.u)	0.966	0.9675	-----	0.9663(65)	0.9659 (65)	0.9666 (65)
P_{Loss} cost (BC) ($)	------	------	8668.8	8668.8	8668.8	8665.81
P_{Loss} cost (AC) ($)	------	------	5735.52	5779.2	5787.6	5758.8384
Cost of capacitor ($/(kVAR-year))	------	------	282	263.85	263.85	282
Net savings ($)	------	------	2651.28	2625.75	2617.35	2624.9716
% Cost saving	------	------	30.584	30.28966	30.19276	30.29113

Table 4 presents the cost-based comparison for the same IEEE 69-bus system to study the maximum cost savings after reactive power compensation. Similar to Table 2, Table 4 also analyses the cost-related details based on P_{Loss} and capacitor investment costs. The results have been compared with the existing methods such as GWO, WCA, FPA, COA and SMOA. From Table 4, it is obvious that the proposed method maximizes the cost saving per year, which is 34.14% compared to the initial P_{Loss}. By comparing the cost saving achieved by SSA with other existing methods, the performance is better except SMOA. The difference between SMOA and SSA in achieving cost savings is 0.05% only. This may be due to an increase in capacitor purchase cost.

Table 5 indicates the performance of SSA in optimizing the capacitor placement and sizing under heavy load levels. From Table 5, it is clear that the P_{Loss} reduction achieved by SSA is better than other existing methods (except CSA), along with enhancement in the bus voltage profile. It is to be noted that the P_{Loss} reduction difference between CSA and SSA is around 0.65% only (Devabalaji et al., 2018). Considering the cost saving at heavy load level, it is obvious that the minimum and maximum cost saving difference between Sampangi and Jayabarathi (2020) and the proposed method are found to be 0.057% and 0.54% respectively. In spite of the increased capacitor purchase cost, the annual cost saving achieved by SSA is still better compared to Nawaz et al. (2017); Devabalaji et al. (2018); Sampangi and Jayabarathi (2020) and Kien et al. (2021). Fig. 5 shows the bus voltage profile under three load levels compared with the base case value. From Fig. 5, it is perceptible that severe reduction in bus voltage for buses from 4 to 27 and from 50 to 65 compared to other buses. On the other hand, after reactive power compensation, the bus voltage has enhanced by 1.035%, 2.443%, and 5.175% respectively considering light, medium, and heavy load levels.

Table 3. Performance of SSA – IEEE 69 bus – medium load – P_{Loss}-based comparison

Parameter Details	C S A	D A	S C A	EPSO	O C S O	S S A
P_{Loss} (BC) (kW)	225	225	224.96	225	224.8949	224.895
P_{Loss} (AC) (kW)	146.1	146	146.46	147.3	145.52	145.775
% P_{Loss} reduction	35.07	35.111	34.8951	34.5333	35.294	35.18086
Capacitor nodes	18, 61, 65	12, 21, 61	8, 12, 61	36, 63, 69	12 ,42, 50	61, 21, 12
Capacitor size (kVAr)	350, 1150, 150	201, 207, 1176	500, 500, 1150	450, 1350, 450	434, 400,1175	1200, 150, 450
V_{min} (p.u)	0.932	-----	0.931	0.9335	0.9317	0.9314

Table 4. Performance of SSA – 69 bus – 100% load – P_{Loss} and cost-based comparison

Parameter details	G W O	W C A	F P A	C O A	S M O A	S S A
P_{Loss} (BC) (kW)	225	225	225	224.96	225	224.895
P_{Loss} (AC) (kW)	146.74	146.73	145.86	146.269	145.78	145.775
% P_{Loss} reduction	34.78222	34.78666	35.17333	34.98	35.2	35.181
Capacitor nodes	16, 60, 61	16, 59, 60	11, 61, 22	17, 57, 61,	12, 18, 61	61,21,12
Capacitor Size (kVAr)	300, 900, 450	300, 450, 900	450, 1350, 150	300, 150, 1200	150, 300, 1200	1200, 150, 450
V_{min} (p.u)	0.9322 (65)	0.9312 (65)	0.933	0.93131	-----	0.9314
P_{Loss} cost (BC) ($)	37800	37800	37800	37793.28	37800	37782.36
P_{Loss} cost (AC) ($)	24652.32	24650.64	24504.48	24573.192	24491.04	24490.2
Cost of capacitor ($/(kVAR-year))	383.55	383.55	468.3	384	384	392.85
Net savings ($)	12764.13	12765.81	12827.22	12836.088	12924.96	12899.31
% Cost saving	33.76754	33.772	33.93444	33.96394	34.193	34.1411

Table 5. Performance of SSA – 69 bus – heavy load – P_{Loss} and cost-based comparison

Parameter details	Analytical	C S A	SMOA	G W O	W C A	S S A
P_{Loss} (BC) (kW)	643	652.5	652.42	652.42	652.42	652.2165
P_{Loss} (AC) (kW)	408	408.5	413.93	412.87	416.70	412.5627
% P_{Loss} reduction	36.5474	37.394	36.5546	36.71715	36.1301	36.74452
Capacitor nodes	21, 61, 64	18, 61, 65	12, 18, 61	16, 60, 61	16, 61, 62	19, 61, 66
Capacitor size (kVAr)	240, 1500, 600	600, 1800, 200	150, 300, 1800	600, 750, 1050	600, 900, 900	450, 1650, 450
V_{min} (p.u)	0.887	0.8839	------	0.8855(65)	0.8785 (65)	0.8882 (65)
P_{Loss} cost (BC) ($)	------	------	109606.56	109606.56	109606.56	109572.372
P_{Loss} cost (AC) ($)	------	------	69540.24	69362.16	70005.6	69310.5336
Cost of capacitor ($/(kVAR-year))	------	------	516.6	578.4	461.4	546.15
Net savings ($)	------	------	39549.72	39666	39139.56	39715.6884
% Cost saving	------	------	36.08335	36.18944	35.70914	36.24608

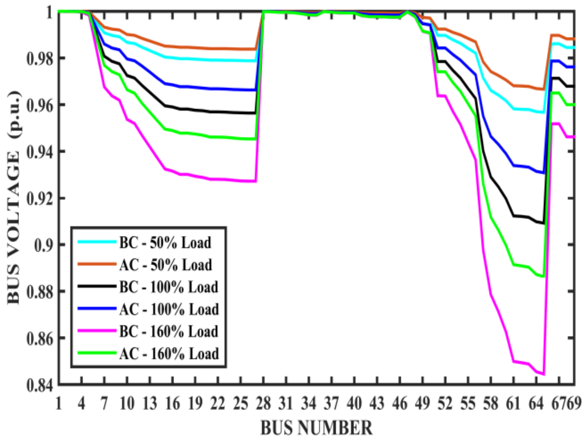

Fig. 5. Bus voltage profile – 69 bus

5. CONCLUSION

In this paper, a powerful swarm intelligence algorithm named SSA has been utilized to solve the cost-based objective function which is the combination of power loss cost with capacitor investment cost, so as to get more financial savings under three different load levels. The merits of adopting SSA for this problem have already been discussed. The proposed method has been successfully applied to a new modified 12-bus and the IEEE 69-bus test systems. Following are the key points which are worth noting.

1. No sensitivity factor-based optimal node selection for reactive power compensation has been adopted in this paper.
2. An overall P_{Loss} reduction (under three load levels) of around 48% to 62% with an economical gain of 47.6%, 52% and 61.4% have been achieved by reactive power compensation for modified 12-bus system and for standard IEEE 69 bus system the overall P_{Loss} reduction is found to be between 33.5% and 36.74% with an economic gain of 30.29%, 34.14% and 36.25%.
3. From the results, it is obvious that the difference in financial gain achieved between SSA and other algorithms is found to be almost equal except for SMOA (low and medium load level). However, the difference is minuscule.

The simulation results reveal that SSA yields better results compared to other methods in terms of P_{Loss} reduction.

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REFERENCES

Abdelsalam, A.A., Mansour, H.S. 2019. Optimal allocation and hourly scheduling of capacitor banks using sine cosine algorithm for maximizing technical and economic benefits. Electric Power Components and Systems, 47, 1025–1039.

Aman, M.M., Jasmon, G.B., Mokhlis, H., Bakar, A.H.A. 2012. Optimal placement and sizing of a DG based on a new power stability index and line losses. International Journal of Electrical Power & Energy Systems, 43, 1296–1304.

Ankaliki, S.G., Kulkarni, A.D., Katti, S.I. 2012. Hierarchical compensation technique for loss minimization in distribution systems. IOSR Journal of Engineering (IOSRJEN), 2, 356–362.

Das, D., Nagi, H.S., Kothari, D.P. 1994. Novel method for solving radial distribution networks. IEE Proceedings-Generation, Transmission and Distribution, 141, 291–298.

Das, S., Malakar, T. 2021. An emission constraint capacitor placement and sizing problem in radial distribution systems using modified competitive swarm optimiser approach. International Journal of Ambient Energy, 42, 1228–1251.

Devabalaji, K.R., Yuvaraj, T., Ravi, K. 2018. An efficient method for solving the optimal sitting and sizing problem of capacitor banks based on cuckoo search algorithm. Ain Shams Engineering Journal, 9, 589–597.

Kien, L.C., Nguyen, T.T., Pham, T.D., Nguyen, T.T. 2021. Cost reduction for energy loss and capacitor investment in radial distribution networks applying novel algorithms. Neural Computing and Applications, 33, 15495–15522.

Mahmoud, K., Lehtonen, M. 2021. Direct approach for optimal allocation of multiple capacitors in distribution systems using novel analytical closed-form expressions. Electrical Engineering, 103, 245–256.

Mirjalili, S., Gandomi, A.H., Mirjalili, S.Z., Saremi, S., Faris, H., Mirjalili, S.M. 2017. Salp swarm algorithm: A bio-inspired optimizer for engineering design problems. Advances in Engineering Software, 114, 163–191.

Nawaz, S., Sharma, M.P., Gupta, A. 2017. Optimal allocation of capacitor bank in radial distribution system using analytical approach. International Journal of Electrical and Computer Engineering, 7, 748.

Sampangi, S.K., Jayabarathi, T. 2020. Optimal capacitor allocation in distribution networks for minimization of power loss and overall cost using water cycle algorithm and grey wolf optimizer. International Transactions on Electrical Energy Systems, 30, e12320.

Suryakala, D., Rani, D.S. 2017. Optimal placement of capacitors for loss reduction in distribution system using EPSO. International Journal of Control Theory and Applications, 10, 727–741.

Tamilselvan, V., Jayabarathi, T., Raghunathan, T., Yang, X.-S. 2018. Optimal capacitor placement in radial distribution systems using flower pollination algorithm. Alexandria Engineering Journal, 57, 2775–2786.

Venkatesh, B., Ranjan, R. 2003. Data structure for radial distribution system load flow analysis. IEE Proceedings-Generation, Transmission and Distribution, 150, 101–106.

Youssef, A.R., Kamel, S., Ebeed, M., Yu, J. 2018. Optimal capacitor allocation in radial distribution networks using a combined optimization approach. Electric Power Components and Systems, 46, 2084–2102.