A Novel Technique for Optimal siting and Rating of Shunt Capacitors Placed to the Radial Distribution Systems

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Abstract. *The overall efficacy of power distribution is reduced through power loss in distribution systems owing to branch resistance. For providing quality power to customers, power losses must be diminished, and voltages must be enhanced. This paper introduces a novel improvement for the traditional Salps Swarm Algorithm (SSA) called Enhance SSA (ESSA) for selecting Optimal Shunt Capacitor Ratings and their Locations (OSCRL). ESSA is viewed as an enhanced version of SSA with the aim of improving the SSA's poor performance. A multi-objective function was designed in this work for reducing real power loss and Total System Cost (TSC), as well as, improving feeder voltage profile and maximizing Net Savings (NSs) per year under security restrictions. For validating and evaluating the proposed ESSA technique, a practical* 33*-bus local Iraqi and standard IEEE* 69*-bus Radial Distribution Systems (RDSs) were used as test systems through utilizing MATLAB. The experimental results attained by the proposed ESSA are compared with other approaches currently available in the literature for addressing OSCRL problem. The experimental results prove the efficacy and supremacy of the ESSA to other literature algorithms with respect to diminishing power loss as well as TSC, reinforce bus voltage profile and increase NSs per year for multiple RDSs.*

Keywords

MATLAB, power loss, radial distribution systems, Salps Swarm Algorithm, shunt capacitors.

1. Introduction

The distribution system's efficiency depends on how efficient electricity is distributed to customers. Even though they are designed in a mesh topology, most distribution networks are structured in a radial configuration [1]. The Radial Distribution System (RDS) operation improves safety scheme alignment, lowers short circuit current fault levels, simplifies fault troubleshooting, and allows for longer distribution feeder line extensions [2]. The distribution current amount is significantly greater than the magnitude of voltage of power grids which is much poorer [3]. As a result of this effect, there is a higher power loss as well as more voltage drop. As a result, distribution networks in several developing countries around the world have suffered and continue to suffer from overloading and are being run at or near their full operational restrictions because of unplanned growth induced by continued increases in power load from existing and newly connected users with more responsive demands [4].

According to research results, the impacts of the aforementioned reasons resulted in significant power losses of around 13 % of total produced power, lowering its reliability in fulfilling the minimum requirements of perfect distribution networks, that are: sufficient voltage magnitude, long-term reliability, and adequate power availability subject to a load [5], [6] and [7]. Other studies have found that 80 % of power outages were caused through unsafe disruptions at distribution parts of power networks, whereas other scholars have labeled distribution systems as the primary cause of power outages [8], [9] and [10]. In recent years, engineers and scientists have become increasingly concerned about avoiding power loss and extreme voltage profile degradation with a faster and less expensive strategy for ensuring optimal and efficient RDS. For reducing power loss and raising minimum voltage, several approaches have been suggested. Local Shunt Capacitors (SCs), among other methods, are one of the comparatively less costly methods that were used over time [11] and [12]. SCs are injected reactive power capable of significantly enhancing system overall outputs including power factor, voltage profile, and significantly reducing power loss which results in significant savings of energy and reductions in cost [13]. Shunt Capacitors (SCs) supplying lag reactive power reduce branch currents and reactive power demand all the way up to generation sources, reducing branch loss and increasing voltage[14].

As SCs are installed, the best location(s) and size(s) must be assessed; otherwise, incorrect placing and rating would not only reduce the benefits but will also jeopardize the whole power network's control mechanism. As a result, it is necessary to decide the optimal capacitors volume and their place to use for network compensation to achieve the desired results while still meeting system constraints [15]. It is worth noting that the most important and irreplaceable part of incorporating and improving RDS with SCs is determining the optimal values and positions for installation for maximizing the possible benefits [16]. Because of its various topological characteristics, the OSCRL problem in RDS is complex and difficult when considered as an optimization issue, attracting the interest of scientists to investigate further.

Numerous authors from around the world have tried to place SCs in RDS. Numerous methods and technologies have been proposed in recent years for deducing the OSCRL. Al-Ammar EA et al. introduced a hybrid algorithm called Fuzzy-Dragonfly Method (FDM) with Power Loss Index (PLI) for SC placement utilizing IEEE standard 34-bus as a test case network [17]. PLI has been used for predicting possible SC installation sites, while a hybrid algorithm, determined the exact sizes and locations. As compared to other conventional algorithms, FDM obtained remarkable power loss reduction while significantly improving voltage profile. A Gravitational Search Algorithm (GSA) provide with the SC allocation in [18], while the same work was done by a Teaching-Learning-Based Optimization (TLBO) in [19]. In [20], a two-stage technique for SC positioning and rating was utilized on IEEE 15-, 69-, and 118-node RDS. The Flower Pollination Algorithm (FPA) has been implemented for finding the values and locations for SC installation, while PLI has been used for determining possible sites where SCs will be located. The results of this work have been compared to those of other optimization techniques, and in every case, the projected solution resulted in lower loss and cost, along with a better voltage profile and net savings. SCs can also be used in RDS for lessening the incidence of harmonics; the Harmony Search Algorithm (HSA) has been utilized for this purpose in [21]. Another publication investigated the Intersect Mutation Differential Evolution (IMDE) technique for SCs sizing and positioning on IEEE 33- and 69-node RDS with an emphasis on reducing power loss and enhancing voltage profile in reference [22]. When the findings were compared to those of other recently created algorithms, it was discovered that IMDE outperforms them.

The algorithms listed above appear to have been effective. However, since power loss is subject to non-linear equality constraints, they cannot guarantee achieving the optimum solution. Several previous research has some flaws, including the economic benefits not being identified as a significant target in the objective functions, and the SCs construction and operating costs not being defined with the capacitors' overall cost. Furthermore, the voltage and reactive power limitations have not been verified, and capacitor purchasing cost was assumed to be a fixed cost/kVAR, resulting in additional costs that are higher than normal costs. After examining the advantages and disadvantages of previous approaches to SC placement on RDS, this work aims to develop on the efforts of earlier researchers in terms of OSCRL for diminishing power loss and total cost including SCs costs as well as reinforcing voltage profile and net savings. So, in this research a novel and efficient method called ESSA is projected. It has a few parameters, making the algorithm simpler for implementing and find an optimal solution faster. Furthermore, the implementation of ESSA to solve the problem has not yet been addressed, as evidenced by the literature review. This encourages the implementation of the ESSA to address this problem.

So, this motivates to use a novel ESSA herein for lessening power loss in addition Total System Cost (TSC) including SCs cost and maximizing Net Savings (NSs) per year as well as raising node voltage profile by deducing OSCRL in various RDS. The ESSA is a simple and effective enhancement for balancing the search and use of the SSA algorithm. The Backward Forward Sweep (BFS) is applied in power flow analysis for determining RDS parameters such as, currents, power loss, voltage, and the power flow in each line among other things. The proposed ESSA method has been validated using two different test networks, namely the real 33-bus local Iraqi RDS and IEEE 69-bus RDS. To demonstrate ESSA's capability for solving the OSCRL problem, the findings were compared to those produced by other techniques currently available in the literature. According to the acquired results, the offered SSA-based method can solve the OSCRL problem in a competitive manner in terms of accuracy and utility.

2. Problem Formulation

2.1. Load Flow Calculation

Load flow is the foundation of power system analysis, since it allows network engineers for understanding the status of power grids at steady state for taking appropriate steps that will promote active scheduling, effective program operation, proper system control, and desirable optimization methods [23]. RDS produce meshed systems, unbalanced loads and high R/X ratios, among other issues. As a result, the power flow in RDS is measured using a new algorithm named Backward Forward Sweep (BFS) method [24]. Figure 1 depicts a sample RDS as a Single Line Diagram (SLD).

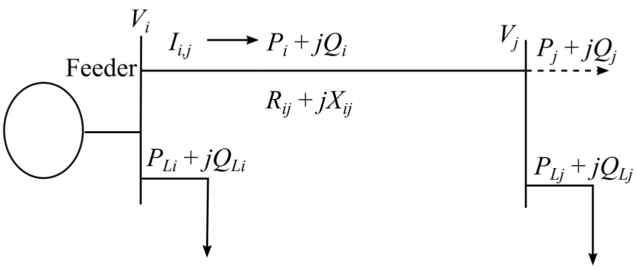

Fig. 1: SLD of a RDS.

Using BFS, the active (P_i) and reactive (Q_i) power flow among buses i and j can be determined as follows:

$$P_i = P_j + P_{Lj} + R_{i,j} \frac{(P_j + P_{Lj})^2 + (Q_j + Q_{Lj})^2}{|V_j|^2}, \quad (1)$$

$$Q_i = Q_j + Q_{Lj} + X_{i,j} \frac{(P_j + P_{Lj})^2 + (Q_j + Q_{Lj})^2}{|V_j|^2}, \quad (2)$$

where P_i and P_j refer real power at nodes i and j. Q_i and Q_j refer reactive power at nodes i and j. P_{Lj} and Q_{Lj} are active and reactive power at node j. $R_{i,j}$ and $X_{i,j}$ denote resistance and reactance at nodes i and j. V_j represents the voltage at node j.

The actual power loss $P_{\text{loss}(i,j)}$ in the branch segment connecting node i and node j can be measured as following:

$$P_{\text{loss}(i,j)} = R_{i,j} \frac{(P_j)^2 + (Q_j)^2}{|V_j|^2}. \quad (3)$$

Through adding every one of the independent branches' losses ($P_{\text{loss}(i,j)}$), the total power loss ($P_{T,\text{loss}}$) in the RDS can be determined as shown in Eq. (4):

$$P_{T,\text{loss}} = \sum_{i=1}^{n-1} R_{i,j} \frac{(P_j)^2 + (Q_j)^2}{|V_j|^2} = \sum_{i=1}^{n-1} P_{\text{loss}(i,j)}. \quad (4)$$

2.2. Objective Function

The OSCRL problem is presented as a multi-objective optimization issue. The main goals of OSCRL are for lessening the total power loss ($P_{T,\text{loss}}$) and the Total System Cost (TSC), which leads to increasing the bus voltage profile, and maximizing Net Savings (NSs) per year. In the following section, we'll go over how to formulate the objective function and how to deal with constraints.

1) Minimize Power Loss

The following equations can be used to explain this objective:

$$F_1 = \min\left(P_{T,\text{loss}}\right), \quad (5)$$

$$F_1 = \min\left(\sum_{i=1}^{n-1} P_{\text{loss}(i,j)}\right). \quad (6)$$

2) Minimize Total System Cost

The power loss cost, capacitor purchase costs C_P, capacitor installation costs $C^j_{I_c}$, and capacitor operating costs $C^j_{O_c}$ are all included in the cost objective F_2. Under strict operational restrictions, the cost objective F_2 is achieved via diminishing the Total System Cost (TSC) resulting from power loss costs $P^{\text{wCom}}_{T,\text{loss}}$ after installing SCs and total SCs costs C_{TC}). The following equations can be used to explain this objective:

$$C_P = \sum_{c=1}^{\text{nc}} \left(Q^j_c \cdot C^j_c\right), \quad (7)$$

$$C_{TC} = C_P + \sum_{c=1}^{\text{nc}} \left(C^j_{I_c} + C^j_{O_c}\right), \quad (8)$$

$$\text{ELC}^{\text{wCom}} = \left(C_{\text{Energy}} \cdot \text{Time} \cdot P^{\text{wCom}}_{T,\text{loss}}\right), \quad (9)$$

$$\text{TSC} = \text{ELC}^{\text{wCom}} + C_{\text{TC}}, \quad (10)$$

$$F_2 = \min\left(\text{TSC}\right), \quad (11)$$

where C_{Energy}, nc and Q^j_c are the energy loss cost in kWh, the number of capacitors and the size of capacitor (kVAR). ELC^{wCom} denotes the energy loss cost with SCs. Table 1 contains the cost variables and specified time, while [25] contains the identified capacities and corresponding purchase costs for the chosen SCs.

Tab. 1: Cost variables values [8].

Parameter	Value
$C^j_{I_c}$ ($ per location)	1600
$C^j_{I_c}$ ($ per location per year)	300
C_{Energy} ($ per kWh)	0.06
time (h)	8760

2.3. Constrains

1) Equality Constrains

Power flow constraint: for keeping a balance among generation and demand, active and reactive power flow limits, that reflect equality limits, may be created. The following equations describe these constraints [26]:

$$P_g = \sum_{i=1}^{\text{nbr}} P_{\text{loss}}(i) + \sum_{j=1}^{n} P_L(j), \tag{12}$$

$$Q_g = \sum_{i=1}^{\text{nbr}} Q_{\text{loss}}(i) + \sum_{j=1}^{n} Q_L(j) - \sum_{k=1}^{N_{\text{SC}}} Q_{\text{SC}}(k), \tag{13}$$

where P_g and Q_g denote generating bus real and reactive power, nbr is number of branches. $P_{\text{loss}}(i)$ and $Q_{\text{loss}}(i)$ represent real and reactive power loss at line i. $P_L(j)$ and $Q_L(j)$ express actual and reactive power loads at node j. N_{SC} is number of SC placed in the RDS and $\sum_{k=1}^{N_{\text{SC}}} Q_{\text{SC}}(k)$ refers the SC value (kVAR) placed in the RDS.

2) Inequality Constrains

- Voltage constraints: all of the buses' voltage magnitudes ($V_{i,j}$) must be held within their min. ($V_{\min} = 0.90$) and max. ($V_{\max} = 1.05$) restrictions:

$$V_{\min} \leq |V_{i,j}| \leq V_{\max}. \tag{14}$$

- Branch current constraints: the line's current (I_{line}) must not surpass its maximum values ($I_{\text{line max}}$):

$$|I_{\text{line}}| \leq |I_{\text{line max}}|. \tag{15}$$

- Capacitor location constraint: in a simulation method, the best SC position is between node number two (Node_2) and the total number of nodes ($\text{Node}_{\text{Total}}$):

$$\text{Node}_2 \leq \text{Node}_{\text{Total}}. \tag{16}$$

- Capacitor number constraint: this restriction limits the number of capacitors that can be used in the RDS. According to Eq. (7), the number of SC positions (L_n) is much less than or equal to the maximum number of SC positions ($\text{NSC}_{\max}$), with one SC allowable per node:

$$L_n \leq \text{NSC}_{\max}. \tag{17}$$

- Compensation constraint: each candidate node's injected reactive power must be less than their appropriate reactive power.

- Total compensating constraint: the total reactive power injection by SC $\left(\sum_{k=1}^{N_{\text{SC}}} Q_{\text{SC}}(k)\right)$ introduced in the RDS must not exceed the total reactive load power $\left(\sum_{j=1}^{n} Q_{L_{\text{Total}}}(j)\right)$:

$$\sum_{k=1}^{N_{\text{SC}}} Q_{\text{SC}}(k) \leq \sum_{j=1}^{n} Q_{L_{\text{Total}}}(j). \tag{18}$$

- Capacitor's capacity constraint: Reactive power (Q_{SC}) injection in kVAR through the chosen SC must be held within their max. ($Q_{\text{SC}_{\max}}$) and min. ($Q_{\text{SC}_{\min}}$) limits, as shown in Eq. (19):

$$Q_{\text{SC}_{\min}} \leq Q_{\text{SC}} \leq Q_{\text{SC}_{\max}}. \tag{19}$$

2.4. Multi-Objective Formulation

Since the OSCRL is recorded as a multi-objective optimization problem, it is constructed for this work by incorporating Eq. (6) and Eq. (11). The opposing multi-objectives are translated to single objectives using priori approach in which weights are assigned to objective functions. The equation for the overall single objective F_t is as follows:

$$F_t = (W_1 \cdot F_1 + W_2 \cdot F_2), \tag{20}$$

$$W_1 + W_2 = 1, \tag{21}$$

where W_1 and W_2 denote the weighting factors.

2.5. Net Savings/Year Formulation

The two main objectives of OSCRL are for diminishing total power loss ($P_{T,\text{loss}}$) and Total System Cost (TSC), which leads for increasing bus voltage profile, and maximizing Net Savings (NSs) per year. NSs per Year is the difference in the total cost without compensation ($\text{ELC}^{\text{woCom}}$), (i.e. base case) and the Total System Cost (TSC) with compensation [27], as shown in the following equations:

$$\text{ELC}^{\text{woCom}} = C_E \cdot T \cdot P_{T,\text{loss}}^{\text{woCom}}, \tag{22}$$

$$\text{TSC} = \text{ELC}^{\text{wCom}} + C_{\text{TC}}, \tag{23}$$

$$\text{NSs} = \text{ELC}^{\text{woCom}} - \text{TSC}. \tag{24}$$

3. Optimization Process

3.1. Traditional SSA

The traditional Salp Swarm Algorithm (SSA) was formulated in 2017 [28]. The SSA is induced through the swarming movement of salps, which live in oceans and form salp chains. Salp fishes are transparent fish that move in water as the water is pumped through their body allowing them to propel forward. As shown in Fig. 2, salps form long chains by bonding together. There are two sections to the salp chain: leaders and followers. The chain's leader is at the top, and its location can be adjusted as follows:

$$X_1^j = \begin{cases} F_j + C_1 \cdot \left(\left(\mathrm{ub}_j - \mathrm{lb}_j \right) \cdot C_2 + \mathrm{lb}_j \right), & C_3 \geq 0 \\ F_j - C_1 \cdot \left(\left(\mathrm{ub}_j - \mathrm{lb}_j \right) \cdot C_2 + \mathrm{lb}_j \right), & C_3 < 0 \end{cases}, \tag{25}$$

where X_1^j and F_j refer the leader and food position, ub_j and lb_j are upper and lower limit. C_2 and C_3 are the random numbers within $[0, 1]$. The parameter C_1 is a vital factor in the SSA and is defined:

$$C_1 = 2e^{-\left(\frac{4l}{L}\right)^2}, \tag{26}$$

where l and L refer the current and max. iterations. The follower position is updated by Eq. (27):

$$X_i^j = \frac{1}{2}\left(X_i^j + X_{i-1}^j \right), \tag{27}$$

where X_i^j represents the followers location.

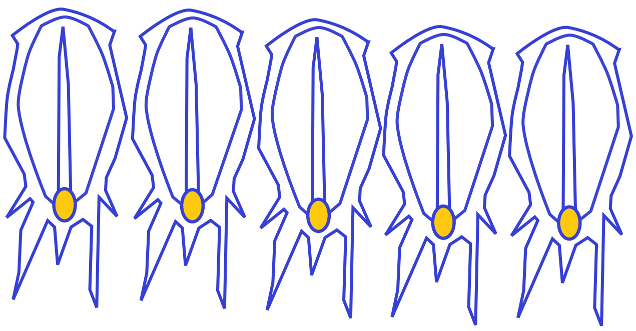

Fig. 2: Salp chain.

3.2. ESSA

Despite the success and effectiveness of SSA, there are still some problems in traditional SSA, which need to be tackled such as low precision and local extremum. To avoid the above problems and achieve better convergence and high precision solutions, the traditional SSA can be updated and enhanced by introducing new factors to the traditional SSA as well as new upgraded techniques for the position of the leader and the followers. These newly introduced factors form a novel improvement for the SSA named ESSA through balancing the exploration and extraction methods [29]. The leaders oversee finding food location F_j as shown in Eq. (25), and then moving toward the food place using the squared exponential covariance parameter C_1 as shown in Eq. (28). As in the Gaussian model, the factor C_1 is the most main factor that regulates the leader agent's quest for food. If the followers oversee food analysis and assisting the leaders with decision-making, Eq. (27) can be redeveloped as shown in Eq. (29):

$$C_1 = 2e^{-\left(\frac{4r_1 l}{L}\right)^2}, \tag{28}$$

$$X_i^j = r_2 \cdot \left(X_i^j + X_{i-1}^j \right), \tag{29}$$

where r_1 denotes an integer random within $[0, 50]$ and r_2 is a random value within $[0, 1]$. Table 2 contains the final parameter selection for the ESSA, which is the best option in this analysis after many trials and errors. The flowchart in Fig. 3 depicts the optimization method for the ESSA-based OSCRL.

Tab. 2: ESSA parameters.

Parameters	Al-Fuhood 33	IEEE-69
population size (N_s)	10	10
iterations (L)	250	250

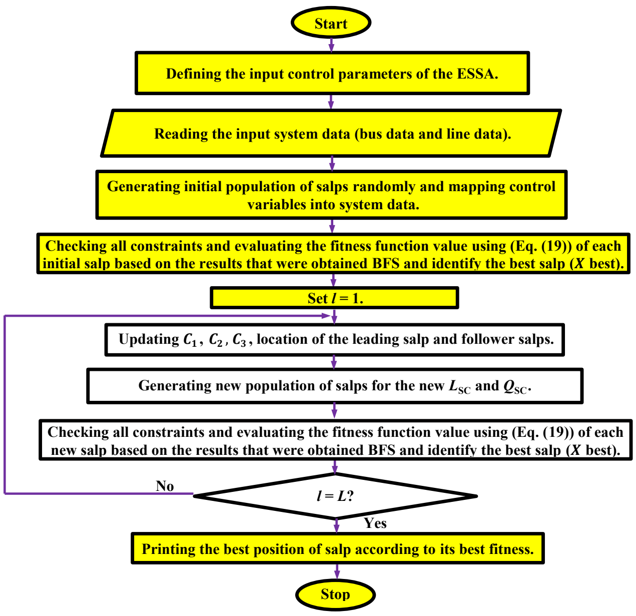

Fig. 3: Flowchart of ESSA applied for solving OSCRL problem.

4. Results and Discussion

For this experiment, the RDSs of practical 33 local Iraqi and standard IEEE-69 nodes were investigated for assessing the accuracy and efficacy of the suggested ESSA methodology in terms of diminishing power loss and cost. The ESSA technique for handling optimal SC positioning and sizing is implemented through MATLAB. For solving the equations recursively and modify the voltage profile, the BFS power flow technique is used. The ESSA has been compared to some algorithms that have been reported in the literature.

4.1. Results of Local Iraqi 33 Node RDS

A real 33-bus local Iraqi RDS is used to test the presented ESSA for examining the efficiency of the offered ESSA method for practical system. The district of Al-Fuhood is about 65 km south of the Thi-Qar city. The feed own secondary power station has 12 feeders, one of which is used for feeding a rural area (the farms feeder), which is one of the worst instances in terms of power loss and voltage stability, and thus has been chosen. This system has 33 nodes with 11.5 kV base voltage. This system's line and bus data is shown in [30]. Table 5 in the App. A also contains this detail. This RDS is exposed in Fig. 4. Before using SCs, a power flow measurement is performed by using FBS; the minimum bus voltage $V_{\min}$ at node 26 is 0.889 p.u., which is not within permissible voltage limits (i.e. below 0.9), and the active power loss $P_{T,\text{loss}}$ is about 441.06 kW. As a result, the Energy Loss Cost without compensation ($\text{ELC}^{\text{woCom}}$) is \$113,876. Low voltages at the end nodes, induced by high inductive loads, characterize this radial method. For improving the low voltage, SCs are linked to the nodes for providing part of the reactive power demand, decreasing flow of current and loss at the terminal end.

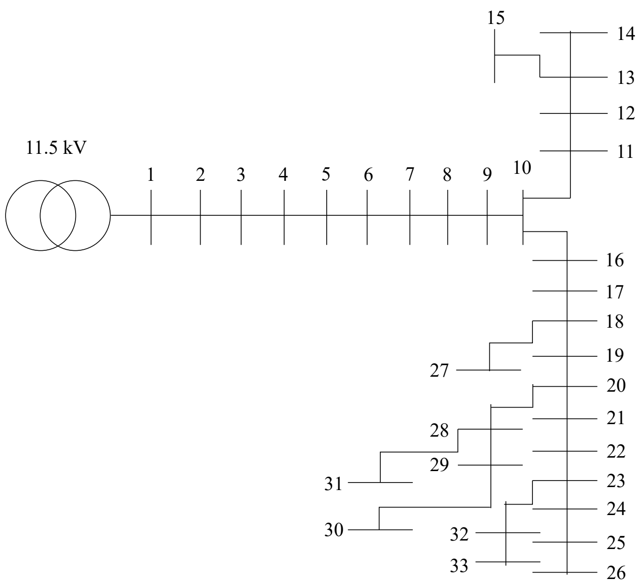

Fig. 4: Al-Fuhood 33-bus RDS [30].

The proposed ESSA and traditional SSA are investigated as an optimization technique to achieve the optimal SCs position and capacity, as seen in Tab. 3. Moreover, these results are compared to those of conventional SSA. After compensation, ESSA outperforms the base case. The projected ESSA accomplishes the best result for power loss $P_{T,\text{loss}}$ (257.80 kW), as well as the Total System Cost (TSC) is minimized from \$231,821.13 to \$141,454.68 after choosing buses 9, 20 and 24 to install three SCs with values: 150, 150, and 300 kVAR, which are more minimal when compared to traditional SSA. Furthermore, the base case's minimum voltage $V_{\min}$ is 0.898 p.u., which is located at node #26, while after compensation's the minimum voltage $V_{\min}$ is 0.9454 p.u., which really is greater than the base case $V_{\min}$. The Net Savings (NSs) achieved by the proposed ESSA algorithm after compensation is \$118,272.55 per year, reflecting a percentage savings of 51.01 %, which is really the largest savings of traditional SSA, according to the results in Tab. 3. ESSA's dominance is ensured by its high efficiency, which includes the smallest active power and energy losses, as well as the largest NSs in the real local Iraqi RDS.

Figure 5 displays the voltage profile of 33-bus local Iraqi RDS without and with compensation, all buses showing a considerable improvement with compensation (after installing SCs). Finally, under the real RDS, it is seen that the proposed ESSA is more successful than the conventional SSA solution.

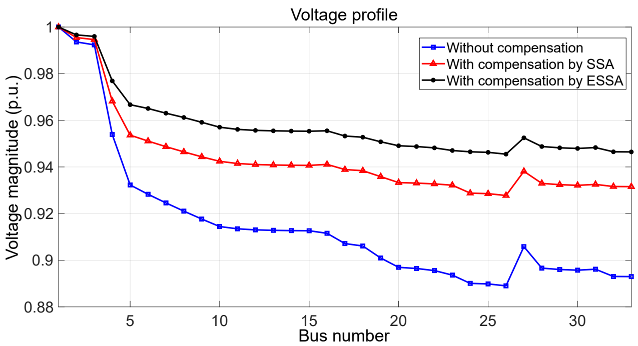

Fig. 5: Voltage profile without SCs (base case) and with SCs for the 33-bus local Iraqi RDS.

4.2. Results of IEEE-69 Node RDS

The 69-bus network, which consists of main feeders, 7 branches, 69 buses and 68 edges which can be seen in Fig. 6, is used to test the efficacy of the offered ESSA on a large scale of RDS. The network data is available in [31] with total real (P_L) and reactive (Q_L) power demands of $P_L = 1.896$ MW and $Q_L = 1.347$ MVAR. $V_{\text{base}} = 12.66$ kV and $S_{\text{base}} = 100$ MVA are the network's base values. Devoid of using SCs, the base case power loss ($P_{T,\text{loss}}$) and Energy Loss Cost without compensation ($\text{ELC}^{\text{woCom}}$) for this network are 224.96 kW and \$118,239, and the minimum bus voltage ($V_{\min}$) at node 65 is 0.9092 p.u.

For reducing power loss and cost, optimization using ESSA and various comparative approaches is utilized to identify the optimal SCs place and their capac-

Tab. 3: Simulation and statistics of the 33-local Iraqi RDS (Al-Fuhood RDS).

Items	Base case	SSA	ESSA
year	-	2021	2021
L_{SCs} (bus no.)	-	16, 18, 23	9, 20, 24
Q_{SCs} (kVAR)	-	300, 450, 1050	150, 150, 300
$V_{\min}$ (p.u.)	0.898	0.9277	0.9454
total kVAR	-	1800	600
$P_{T,\text{loss}}$	441.06	282.3	257.8
(A) C_{TC} (\$)	-	6158.25	5955
(B) ELC (\$)	231,821.13	148,376.88	135,499.68
$(C = A + B)$ TSC (\$)	-	154,535.13	141,454.68
$(D = 231{,}821.13 - C)$ NSs (\$)	-	77,286	118,272.55
$P_{T,\text{loss}}$ reduction (%)	-	35.99	41.54
$(E = D/231{,}821.13)$ savings (%)	–	33.33	51.01

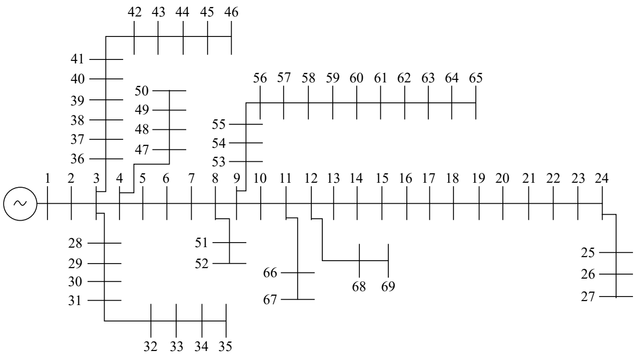

Fig. 6: IEEE 69-bus RDS.

itance. The findings of these approaches are summarized in Tab. 4, which also provides comparisons of the suggested ESSA with conventional SSA and other algorithms. The nodes identified as 54, 60, and 13 are optimal for installing SCs, with corresponding capacities of 450, 150, and 300 kVAR, respectively, according to optimization by using proposed ESSA method as depicted in Tab. 4. With compensation devices, the power loss $P_{T,\text{loss}}$ is diminished from 224.96 kW to 142.1 kW. As shown, the proposed ESSA solution results in the minimum amount of loss of all the other approaches. Furthermore, the compensation rises the worst (minimum) voltage at bus #65 ($V_{\min_{65}}$) to 0.9501 p.u. This is higher than the base case ($V_{\min}$) of 0.9092 p.u. Also, after compensation, as recorded in Tab. 4, the proposed ESSA decreased the TSC from \$118,239 to \$80,681.61 with SCs cost, resulting in a Net Savings (NSs) of \$37,557.39 per year, corresponding to a percentage of 31.76 % which is the highest savings (NSs) among all approaches. In contrast to the traditional SSA and other methods, the proposed ESSA has the minimum actual power and energy losses, as well as maximum net savings.

Figure 7 displays the voltage profiles of the IEEE 69-bus without OCP (before compensation) and with OCP (after compensation); all the buses' profiles are much improved with OCP (after compensation). Other techniques cannot match the ESSA's efficiency and precision when it comes to SCs allocation and sizing. Finally, from the simulation results, the proposed ESSA is more successful than the conventional SSA and other techniques in literature.

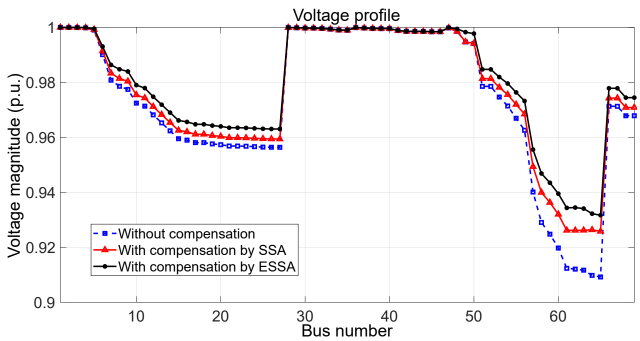

Fig. 7: Voltage profile without OCP (base case) and with OCP (with SCs) for the 69-bus IEEE RDS.

5. Conclusions

Since the Optimal Capacitor Allocation (OCA) problem is difficult and necessitates the use of a powerful and efficient optimization method, a novel ESSA has been implemented in this report to address it. The conventional SSA's exploration and exploitation strategies are improved by adding new variables that update the position of the leader and followers to avoid some drawbacks and achieve better convergence, and precise solutions. These introduced factors form a novel improvement for the SSA named ESSA by balancing the exploration and extraction methods.

This article presents a strategy for producing Optimal Shunt Capacitor Ratings and their Locations (OSCRL) in various RDSs using a novel ESSA optimization tool. The BFS algorithm is used to compute power flow. The IEEE 69-bus RDS and a real 33-bus local Iraqi RDS are used to prove the application of the suggested ESSA approach. The results indicate that positioning the SCs optimally results in reduced cost and power loss ($P_{T,\text{loss}}$), increase Net Savings (NSs),

Tab. 4: Simulation and statistics of the IEEE-69 RDS.

Items	**Base case**	**GSA [18]**	**MSA [32]**	**AWOA [33]**	**SSA**	**ESSA**
year	-	2015	2018	2021	2021	2021
L_{SCs} (bus no.)	-	26, 13, 15	21, 12, 61	49, 50, 61	57, 62, 63	54, 60, 13
Q_{SCs} (kVAR)	-	150, 150, 1050	150, 450, 1200	150, 150, 1050	450, 300, 900	450, 150, 300
V_{min} (p.u.)	0.9092	09519	0.9324	0.9032	0.9500	0.9506
total kVAR	0	1350	1800	1350	1650	900
$P_{T,\mathrm{loss}}$	224.96	145.9	145.41	144	143.5	142.1
(A) C_{TC} ($)	-	6089.4	6092.85	6089.4	6083.55	5993.85
(B) ELC ($)	118,239	76,685.04	76,427.49	75,686.4	75,423.6	74,687.76
$(C = A + B)$ TSC ($)	-	82,774.44	82,520.34	81,775.8	81,507.15	80,681.61
$(D = 118{,}239 - C)$ NSs ($)	-	35,464.56	35,718.65	36,463.2	36,731.8	37,557.39
$P_{T,\mathrm{loss}}$ reduction (%)	-	34.14	35.36	35.98	36.21	36.83
$(E = D/118{,}239)$ savings (%)	-	29.99	30.20	30.83	31.06	31.76

and rose bus voltage profile. The ESSA approach has been compared to other strategies such as GSA, MSA, AWOA, and SSA; the comparisons revealed that the ESSA achieves the minimal power loss ($P_{T,\mathrm{loss}}$) and Total System Cost (TSC), along with reinforcing the voltage profile for all suggested RDSs, and ESSA's Net Savings (NSs) per year outperform the other methods. The ESSA discovery and extraction capabilities are responsible for the enhanced performance.

Depending on the ESSA approach's success in solving optimal SCs allocation issue, it can be concluded that the developed ESSA is a strong prudent technique for tackling the optimal SCs positioning and rating issue in RDSs. Future work may include the implementation of ESSA to various aspects of power networks.

Author Contributions

O.M.N. contributed substantially to the development of the ESSA algorithm by using MATLAB program and obtain the data of the local Iraqi grid.

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Appendix A
Data of Local Iraqi RDS

Tab. 5: Data of system for the 33-local Iraqi RDS (Al-Fuhood RDS).

Branch no.	Sending bus	Receiving bus	Branch data			Load at receiving end bus	
			R (Ω)	X (Ω)	Length (m)	P_L (MW)	Q_L (MVAR)
1	1	2	0.07125	0.08697	300	0.200	0.150
2	2	3	0.01425	0.01739	60	0.200	0.150
3	3	4	0.4512	0.5508	1900	0.200	0.150
4	4	5	0.2612	0.3188	1100	0.200	0.150
5	5	6	0.0456	0.0666	230	0.200	0.150
6	6	7	0.0475	0.0579	200	0.320	0.240
7	7	8	0.0475	0.0579	200	0.200	0.150
8	8	9	0.0475	0.0579	200	0.320	0.240
9	9	10	0.0475	0.0579	200	0.200	0.150
10	10	11	0.0593	0.0724	250	0.320	0.240
11	11	12	0.0356	0.0434	150	0.320	0.240
12	12	13	0.0237	0.0289	100	0.320	0.240
13	13	14	0.0475	0.0579	200	0.200	0.150
14	13	15	0.0712	0.0869	300	0.200	0.150
15	10	16	0.0593	0.0724	250	0.200	0.150
16	16	17	0.095	0.1159	400	0.200	0.150
17	17	18	0.0237	0.0289	100	0.320	0.240
18	18	19	0.1425	0.1739	600	0.200	0.150
19	19	20	0.1187	0.1449	500	0.200	0.150
20	20	21	0.0237	0.0289	100	0.200	0.150
21	21	22	0.0475	0.0579	200	0.200	0.150
22	22	23	0.1187	0.1449	500	0.320	0.240
23	23	24	0.475	0.5798	2000	0.320	0.240
24	24	25	0.0712	0.0869	300	0.080	0.060
25	25	26	0.3325	0.4058	1400	0.200	0.150
26	18	27	0.0712	0.0869	300	0.320	0.240
27	20	28	0.0356	0.0434	150	0.200	0.150
28	28	29	0.1187	0.1449	500	0.200	0.150
29	29	30	0.1187	0.1449	500	0.200	0.150
30	28	31	0.1900	0.2319	800	0.200	0.150
31	23	32	0.1187	0.1449	500	0.200	0.150
32	32	33	0.0237	0.0289	100	0.200	0.150
Tie line data							
33	14	26	1.615	1.9713	6800	-	-
34	16	22	0.4512	0.5508	1900	-	-
35	4	30	1.2184	1.4872	5130	-	-
36	10	23	0.6294	0.7682	2650	-	-
37	6	33	0.9619	1.1741	4050	-	-