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Loss reduction and reliability improvement in distributed network using HF-SOA based optimal installation of DG, SCs and STF

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Abstract: In recent years, most of the research works related to Distributed Generation (DG), targeted on the loss minimization and reliability enhancement due to the existence of intermittent Renewable Energy Sources (RES). In this research work, this target is attained by an optimal installation of DG, shunt capacitors (SCs) and single tuned filter (STF) through a novel hybrid fuzzy based seagull optimization algorithm (HF-SOA) in a distributed power network. Compared to the literatures better harmonics mitigation is achieved in this research work due to the presence of STF. The proposed research problem is considered as multi-objective and a novel objective function that incorporates, minimization of power loss, harmonics and enhancement of voltage profile (VP) as well as system reliability is introduced in this research article. The fuzzy membership function is framed for each objective function parameter and the fuzzified membership functions are considered as an objective function for the SOA approach. Three case studies are conducted in both IEEE 33 and 69 radial networks to examine the influence of the HF-SOA algorithm in satisfying the proposed multi-objective function (MOF). In the case studies, the percentage loss, THD reduction, VP enhancement, cost reduction of DG and reliability improvement measured through expected interruption cost (ECOST) are analyses in detail. The coding of HF-SOA and analysis of the proposed work are resolved in the MATLAB R2022a Editor Software. The simulation results confirms that the proposed HF-SOA is superior than the with the recently published optimization approaches named genetic moth swarm algorithm (GMSA) and salp swarm optimization algorithm (SSA).

Keywords: Distributed Generation (DG); hybrid fuzzy based seagull optimization algorithm (HF-SOA); Power loss minimization; reliability improvement; seagull optimization algorithm (SOA); Shunt Capacitors (SCs)

Zmanjšanje izgub in izboljšanje zanesljivosti v porazdeljenem omrežju z uporabo optimalne namestitve DG, SC in STF na podlagi HF-SOA

Izvleček: V zadnjih letih je večina raziskovalnih del, povezanih z razpršeno proizvodnjo električne energije (DG), usmerjena v zmanjševanje izgub in povečanje zanesljivosti zaradi obstoja nestalnih obnovljivih virov energije (RES). V članku je ta cilj dosežen z optimalno namestitvijo DG, vzporenih kondenzatorjev (SC) in enojnega uglašenega filtra (STF) s pomočjo novega hibridnega optimizacijskega algoritma na osnovi fuzzije (HF-SOA) v distribuiranem elektroenergetskem omrežju. V primerjavi z literaturo je v tem raziskovalnem delu zaradi prisotnosti STF dosežena boljša ublažitev harmonikov. Predlagan problem je obravnavan kot večpredmeten, predstavljena je nova ciljna funkcija, ki vključuje minimizacijo izgube moči, harmonikov in izboljšanje napetostnega profila (VP) ter zanesljivosti sistema. Za vsak parameter ciljne funkcije je oblikovana mehka funkcija pripadnosti, mehke funkcije pripadnosti pa se obravnavajo kot ciljna funkcija za pristop SOA. Da bi preverili vpliv algoritma HF-SOA pri izpolnjevanju predlagane večobjektivne funkcije (MOF), so izvedene tri študije primerov v radialnih omrežjih IEEE 33 in 69. V študijah primerov so podrobno analizirani odstotki izgube, zmanjšanje THD, izboljšanje VP, zmanjšanje GD in izboljšanje zanesljivosti, merjeno s pričakovanimi stroški prekinitve (ECOST). Kodiranje HF-SOA in analiza predlaganega dela sta rešena v programski opremi MATLAB R2022a Editor. Rezultati simulacije potrjujejo, da je predlagani HF-SOA boljši od nedavno objavljenih optimizacijskih pristopov, imenovanih algoritem genetskega roja (GMSA) in algoritem optimizacije roja Salp (SSA).

Ključne besede: razpršena proizvodnja (DG); hibridni mehki optimizacijski algoritem (HF-SOA); minimizacija izgube moči; izboljšanje zanesljivosti; optimizacijski algoritem (SOA); vzporedni kondenzatorji (SC)

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1 Introduction

Nowadays, the conventional energy sources are replaced with the RES due to the increasing energy crisis and lack of availability of fossil fuels. Hence, the research platform widens by virtue of power quality (PQ) issues occurring in Radial Distributed Network (RDN) including intermittent RES. The crucial factors commonly considered in most of the earlier research works to mitigate PQ issues in RDN are power loss minimization, VP improvement and reliability improvement. To effectively meet these factors, the distributed generation system is suggested as an alternate solution instead of expanding the network infrastructure since, its limited commissioning time and its effectiveness in minimizing network losses. In recent research works, the SCs are installed along with distributed generation as it provides reactive power compensation for enhancing the VP. Hence, both real as well as reactive powers could be improved with the combination of distributed generation and SCs in RDN. However, the optimal selection and installation of DG and SCs is a challenging task since the cost of installation of distributed generation should overcome the energy losses. So many optimization approaches are being developed to optimize the siting and sizing of distributed generation and SCs and some of them are presented below:

Most of the earlier research articles reported so far aimed to optimize the sitting and sizing of DG only [1-3]. The optimal siting and sizing are commonly termed as optimal installation in this research article. The artificial intelligence (AI) based optimization algorithms which mimic the social behavior of living organisms were suggested to foreseeing the optimization installation of distributed generation. The particle swarm optimization (PSO) algorithm was proposed to predict the cost-effective installation of DG to reduce the power losses, and harmonics [4]. The artificial bee colony (ABC) algorithm was reported to optimize the size and installation node of DG by minimizing the multi-objective function such as cost, voltage drop and power loss in the network [5]. The Manta Ray Foraging optimization algorithm (MRFO) was suggested to diminish the network loss in RDN by optimal installation of DG in power network. The result analysis of MRFO was performed with 3, 69 and 85 bus system [6].

However, the presence of inductive components in power network induces lagging power factor which minimize the VP and increases the network losses. Hence, it is necessary to improve the power factor and VP by installing the SCs thereby reduce the network losses. Belkacem Mahdad and K. Srairi presented the adaptive differential algorithm-based optimization of siting and sizing of DG in presence of static VAR compensator (SVC) in RDN to reduce the cost and loss functions [7].

A fuzzy based optimal installation of DG using Genetic Algorithm (GA) to reduce real and reactive power supply as well as losses, stability index and enhancement minimum bus voltage was introduced by Srinivasa Rao Gampa et.al [8]. In this approach the fuzzy membership functions are framed based on the proposed objective function and the selection of nodes for distributed generation and SCs with different power factors were optimized with GA approach. The experimental analysis was performed in both 51 and 69 node RDN and successfully obtained the proposed objective function.

In the same manner, optimal integration of capacitor and DG using Bat Algorithm (BA) was proposed by Thangaraj Yuvaraj et.al which was aimed to reduce the power loss and stability improvement of the RDN. The load variations such as constant, industrial, residential and commercial were also considered as one of the main factors in that research work [9]. The experimental study in that article was performed in 33 and 69 node network and the superiority of the Bat Algorithm was proved over conventional methodologies.

The ant lion optimization (ALO) was suggested by Ahmed R. and Abul'Wafa to select the optimal node for the installation of DG and SCs based on the proposed multi-objective function [10]. The ALO algorithm was examined on the IEEE 118 node network and the installation of various RES and the SCs were optimized in that article. Amirreza Naderipour et.al have presented the spotted hyena optimizer (SHO) approach for optimizing the DG and SCs in a cost-effective manner. The SHO approach was tested in both island and grid connected mode with different modes of operation and power factors and the superiority was proved over grey wolf optimization (GWO) algorithm [11].

In similar manner, many research articles were published based on the optimal sizing and installation nodes of DG and SCs combination so as to reduce both real and reactive power losses [7, 12-14]. Commonly, in most of the article, the power loss minimization was considered as the fundamental objective function related to the proposed research arena. Furthermore, the minimization of installation and operating cost and enhancement of VP, system stability and reliability were also reported as effective objective functions in some of the research articles [9, 10, 15, 16].

Optimization techniques like Constriction Coefficient Particle Swarm Optimization (CPSO) are used to reduce the loss of renewable energy resources (RES) in distributed generation systems. By used this method, losses are reduced by 63.90 % [27]. To reduce voltage regulation issues, non-sorting dominated genetic algorithms (NSGAs) were employed to allocate battery energy storage systems and distributed energy resources optimally [28]. The Modified Shuffled Frog Leaping Algorithm (MSFLA) was proposed to minimize energy loss, operational costs, and energy not supplied by DG systems [29]. Using an AC optimal power flow (OPF) and genetic algorithm (GA) for 24 hours, [30] minimize investment and operation costs in renewable energy systems integrated with battery banks. In [31] an optimal allocation of DG and D-STATCOM within a distribution system using the Bat Algorithm, in which the loss sensitivity factor (LSF) is utilized to find the optimum location for distribution generation systems. The minimum loss obtained is 31.94 kW, which is 89.88 %.

In some of the recent articles the single tuned filters (STF) were also installed in the distribution network which consist of a series connected resistor, inductor and a capacitor. The number of harmonics presented in the network is measured with Total harmonics distortion (THD) and it is added as one of the prime factors in multi-objective function of the optimization problem. The comparative THD values of the network in the presence and absence of STF undoubtedly confirms that the THD is much reduced in the presence of STF [17].

A technical research growth was observed from the literature survey. Most of the earlier research works presented so far have initially targeted only on DG installation to minimize the power loss with analytical calculations. Subsequently, intelligent algorithms were proposed to optimize the installation of DG with a single objective function. Afterwards, the multi-objective functions were introduced which incorporated minimization of losses, harmonics, voltage drop, cost also to improve VP, stability as well as reliability. To provide the reactive power compensation and to enhance the VP the compensating devices such as static VAR compensator, shunt capacitor and DSTATCOM were then installed and their location are optimized along with DG.

2 Materials and methods

From the observations made from the literature study, the following research gaps are identified:

i. However, enormous optimization methodologies have been proposed so far to predict a suitable sizing and location of DG so as to compensate the suggested objective functions, the research works are still in progress on developing the novel metaheuristic approaches to reimburse the objective functions in a better way.
ii. Most of the articled focused only on optimal DG installation and very few articles include the presence of shunt capacitors.
iii. The multi-objective functions proposed in earlier literatures employed mainly with loss reduction and VP improvement and little effort has been expended on reliability enhancement and harmonic mitigation.

By reviewing the literatures related to the proposed research problem, and to overcome the research gap stated above the following augmentation are presented in the proposed research work:

According to the research gap, the contributions of the proposed work is described as follows;

- (i) A novel HF-SOA optimization algorithm is proposed in this research article to optimize the siting and sizing of GD, SCs and STF and better results are produced compared to GMSA and SSA approaches.
- (ii) The SCs also included in the power network and its influence on enhancing the VP and diminishing of power losses are proved in this article.
- (iii) The STF is installed in the power network and a novel multi-objective function that incorporates network loss minimization, harmonics mitigation, VP enhancement, reliability improvement and total cost minimization of DG is developed in this proposed research problem. The effectiveness of the proposed algorithm is also experimented in standard IEEE 33 and 69 node networks with three case studies and its dominance is confirmed over genetic moth swarm algorithm (GMSA) [18] and salp swarm optimization algorithm (SSA) [19].

The content presented in this research work are structured as follows: Section 2 describes the distributed power network with 33 and 69 node RDN. Section 3 explains the system description of DG network. The problem formulation and the (HF-SOA) optimization approach proposed in this research work is apprized in section 4. The section 5 acquainted with detailed computational analysis performed in this paper out and their results and discussions. Finally, section 6 describes the conclusion of proposed work together with the future scope.

3 Distributed power network

3.1 System description

While integrating the intermittent renewable energy system in DG the distributed power network faces the problems such as voltage fluctuations, intensifies the network losses and increases the THD. Hence, the future development of power systems is mainly targeted to develop smart distributed power networks which attracts the focus of so many researchers to work towards it [20]. One of such attempts is made in this proposed research article by developing an optimization algorithm to foreseeing the siting and sizing of DG, SCs and STF. In this proposed research work, the solar photo voltaic (PV) and wind turbines are considered to be integrated in DG system and the SCs and STFs are shunted with the buses. The rating of SCs might be carefully chosen that the voltage rise problem not occurring in power system. In general, the optimization problems are experimented in reconfigured IEEE systems. In the similar manner, the proposed HF-SOA based installation of DG, SCs and STF is examined in 33 and 69 RDN which are illustrated in Fig 1 and Fig 2. Prepare the figures and tables according to these instructions

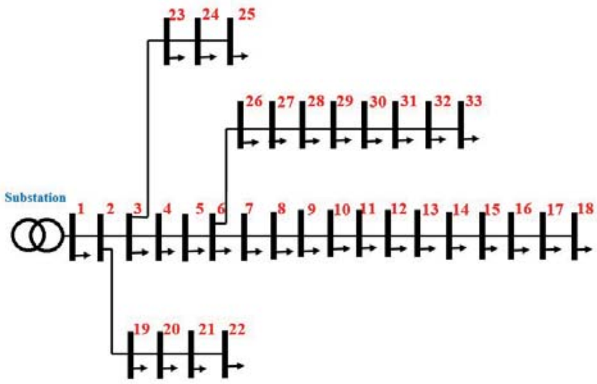

Figure 1: IEEE 33 node reconfigured RDN

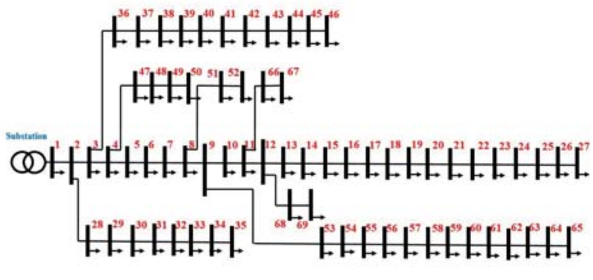

Figure 2: IEEE 69 node reconfigured RDN

When the RES is connected with the DG, the intermittent nature of RES and the power converter arrangements equipped with the utility grid makes nonlinear DG (NLDG) and generates harmonics in the power network system. Very few recent research works related to DG allocation are focused on harmonics mitigation using either active or passive filters [21, 22]. In the research work the single tuned filter (STF) is preferred which consist of series connected resistor, inductor and a capacitor. The THD is considered as the measuring factor for the harmonics analysis and it is included as the minimization function in the optimization problem to mitigate the harmonics.

4 Optimizing the size and allocation of DG with proposed AO algorithm

4.1 Problem Formulation

The optimal installation of DG, SCs and STF is the proposed research problem and the results are optimized with the HF-SOA approach. The multi-objective function is developed for this optimization problem that incorporates loss minimization, harmonics mitigation and VP improvement. The development of multi-objective function parameters and the constraints are described as below. The overall objective function for the proposed research problem is developed as stated below (0a,0b):

$$Obj_{fn} = min\sum\left(Obj1 + Obj3 + Obj5\right) + max\sum\left(Obj2 + Obj4\right) \quad (0a)$$

$$Obj_{fn} = \sum_{i=1}^{N} w_n\left(\min\left(P_{TL} + \text{THD} + Cost_{DG}\right) + max\left(R_{index} + V_P\right)\right) \quad (0b)$$

Where, $Obj1$ represents the power loss minimization (P_{TL}), $Obj2$ represents the reliability index (R_{index}), $Obj3$ represents the Harmonics minimization (THD), $Obj4$ represents the Voltage profile improvement (V_p), and $Obj5$ represents the overall cost of the DG system. w_n indicates the weighting factor used to emphasize the importance of lowering each term of the objective function, $w_1 = 0.4$, $w_2 = 0.1$, $w_3 = 0.1$, $w_4 = 0.4$, and $w_5 = 0.1$ attributed to power loss, reliability index, THD minimization, Voltage profile and overall cost of the DG system.

4.1.1 Power loss minimization (Obj 1):

The power loss (P_L) minimization is the parameter is commonly considered in most of research work related to DG installation. The optimal sizing and allocation of DG alone supports only for the real power losses and the installation of SCs along with DG assist for reactive power compensation in addition. The active and reactive power losses between i and $i + 1$ are denoted in (1) and (2) moreover, the voltage and power losses for real power and reactive power could be evaluated as illustrates in equations (3) and (4), respectively.

$$P_{i+1} = P_i - P_{L(i+1)} + R_i \frac{P_i^2 + Q_i^2}{V_i^2} \quad (1)$$

$$Q_{i+1} = Q_i - Q_{L(i+1)} + X_i \frac{P_i^2 + Q_i^2}{V_i^2} \quad (2)$$

Whereas, P_i and P_{i+1} are the real power at the sending as well as receiving end, Q_i and Q_{i+1} are the reactive power at the sending as well as receiving end, $P_{L(i+1)}$ and $Q_{L(i+1)}$

are the real and reactive power losses at the receiving end and V_i is the voltage at the sending end.

$$V_{i+1}^2 = V_i^2 - 2\left(R_i \cdot P_i + X_i \cdot Q_i\right) + (R_i^2 + X_i^2)\frac{P_i^2 + Q_i^2}{V_i^2} \quad (3)$$

$$P_{L(i,i+1)} = R_i * \frac{P_i^2 + Q_i^2}{V_i^2} \quad (4)$$

Whereas, R_i and X_i are the resistance and reactance of the transmission line. The total loss of the distributed power network is represented in equation (5). The n represents the number of nodes in the network.

$$P_{TL} = \sum_{i=1}^{n-1} P_{L(i,i+1)} \quad (5)$$

4.1.2 Reliability Index (Obj 2):

The reliability index is one of the essential terms that might be considered during the development of objective function. In this research work, the economical oriented reliability parameter which describes the ratio between the expected interruption cost in the presence and absence of DG, SCs and STF respectively (6) is considered as one of the parameters in the objective function.

$$R_{index} = \frac{ECOST_{DG,SCs,STF}}{ECOST} \quad (6)$$

Where, expected interruption cost (ECOST) is an effective tool in system planning which decides the adequate level of reliability for users. Accordingly, the ECOST without the installation of any DGs and capacitors ($ECOST_i^{without\ DG,Cap}$) is evaluated as follows:

$$ECOST_i^{without\ DG,Cap} = \sum_{i=1}^{N_{bus}} Load_{avg_i} \times C_i \times \lambda_i^{uncomp} \quad (7)$$

$$ECOST_i^{without\ DG,Cap} = \sum_{i=1}^{N_{bus}} Load_{avg_i} \times C_i \times \lambda_i^{uncomp} \quad (8)$$

Where, $Load_{avg_i}$ is the average load in KW, C_i is the interruption cost and $\lambda_{i_{new}}$ is the modified rate of failure after the capacitor placement, λ_i^{uncomp} is the without DG and capacitor installation case.

Following optimal DG and capacitor installation, the cost benefit from reduced ECOST can be expressed as following Eq. (9):

$$ECOST_{CB} = ECOST_i^{without\ DG,Cap} - ECOST_i^{with\ DG,Cap} \quad (9)$$

The installation of capacitor has a direct influence on the reliability as it moderates the rate of failure. The current induces due to the capacitor placement reduces the temperature as well as the loss of transmission line. Active and reactive power requirements in distribution networks can be met by the utilization of DGs and capacitor allocation. The losses efficiently decrease as a result of a reduction in current magnitude. Due to this, higher temperatures have a less destructive effect on the reliability indices of both overhead and underground lines. Distribution feeder components will have a lower failure rate as a result of these impacts. If the i^{th} feeder is not equipped with DGs and capacitors, it has an uncompensated failure rate of λ_i^{uncomp} In feeder laterals with fully compensated active and reactive current components, failure rate drops to λ_i^{comp} . It can be observed that if the active and reactive elements of the current are not compensated, the failure rate will be linearly related to the level of compensation. The change in real and reactive currents due to the capacitor placement is measured by the compensation coefficient $\propto_i$ (10). The I_{real}, and I_{reac} in equation (10) represents the real and reactive current components respectively.

$$\propto_i = \frac{I_{reac}^{new}}{I_{reac}^{old}} * \frac{I_{real}^{new}}{I_{real}^{old}} \quad (10)$$

Moreover, the modified rate of failure after the capacitor placement ($\lambda_{i_{new}}$) could be derived as shown below (11).

$$\lambda_{i_{new}} = \propto_i \left(\lambda_i^{uncomp} - \lambda_i^{comp}\right) + \lambda_i^{comp} \quad (11)$$

4.1.3 Harmonics minimization (Obj 3):

The harmonics minimization is computed through Total Harmonic Distortion (THD) presented in the signal (12) [23].

$$THD = \sum_{i=1}^{N} \left(\frac{1}{V_{1i}} \sqrt{\sum_{h=2}^{H} V_{hi}^2} \right) \quad (12)$$

Whereas, V_{1i} is the fundamental bus voltage, V_{hi} is the order of harmonics at i^{th} bus.

4.1.4 Voltage profile improvement (Obj 4):

In DG system the power generated from the various distributed energy sources are linked to the common distributer. The sudden change in load conditions affects the VP. Hence, the improvement of voltage profile is considered as one on the objective in this research work which is stated in equation (13).

$$Voltage\_profile = \sum_{i=1}^{N} \left(\frac{V_i - V_i^{spec}}{V_i^{max} - V_i^{min}} \right)^2 \quad (13)$$

Whereas, V_i is the i^{th} bus voltage, V_i^{spec} is the specified voltage magnitude (1.0 p. u) and V_i^{max}, V_i^{min} are the i^{th} bus minimum and maximum voltage respectively.

4.1.5 Cost minimization for the DGs (Obj 5):

Different types of DG have different costs. There will be a variation in the total cost of the DGs as the size and number of the DGs change. To minimize the cost of the DG, the objective can be formulated as follows:

$$Cost_{DG} = \left[\frac{Cap_c * Capacity * K_{DG_i}}{lifetime * 8760 * LF}\right] + \left[\left(C_{Fuel} + C_{O\&M}\right) * K_{DG_i}\right] \tag{14}$$

Where, $Cost_{DG}$ is the DGs' overall cost, Cap_c is the capital cost of DG system, LF is the load factor K_{DG_i} is the size of the ith DG, C_{Fuel} is the size of the ith DG system, and $C_{O\&M}$ is the operation and maintenance cost of DG system.

4.2 Hybrid Seagull Optimization Algorithm (HF-SOA)

4.2.1 Fuzzification of objective function parameters

This research work is targeted to foreseeing the optimal installation of DG, SCs and STF by satisfying the objective function stated above Eq. (0). In HF-SOA approach initially the fuzzification of this multi- objective function is performed corresponding to the membership functions selected. In this proposed problem the trapezoidal membership function is commonly chosen for fuzzification of all the fitness function parameters such as loss, the VP, ECOST and THD. The membership functions for the proposed research problem are illustrated in Fig3.

(i) Fuzzification of Power loss:

The power loss is stated in equation (5). The active power loss index (APLI) is evaluated as the ratio between the active power loss in the presence $(APL_{DG,SCs,STF})$ and absence (APL) of DG, SCs and STF (15).

$$APLI_{index} = \frac{APL_{DG,SCs,STF}}{APL} \tag{15}$$

Using the trapezoidal membership function depicted in Fig 3a, the APLI is fuzzified as described in the fuzzy set (16) given below.

$$\mu_{APLI} = \begin{cases} 1 \; for \; APLI \le APLI_{min} \\ \dfrac{APLI_{max} - APLI}{APLI_{max} - APLI_{min}} \; for \; APLI_{min} < APLI \le APLI_{max} \\ 0 \; for \; APLI > APLI_{max} \end{cases} \tag{16}$$

Where, $APLI_{min}$ and $APLI_{max}$ are the minimum maximum limits of power loss index. This minimum limit depends on the utility requirement and for the proposed problem the maximum value is chosen as 1.

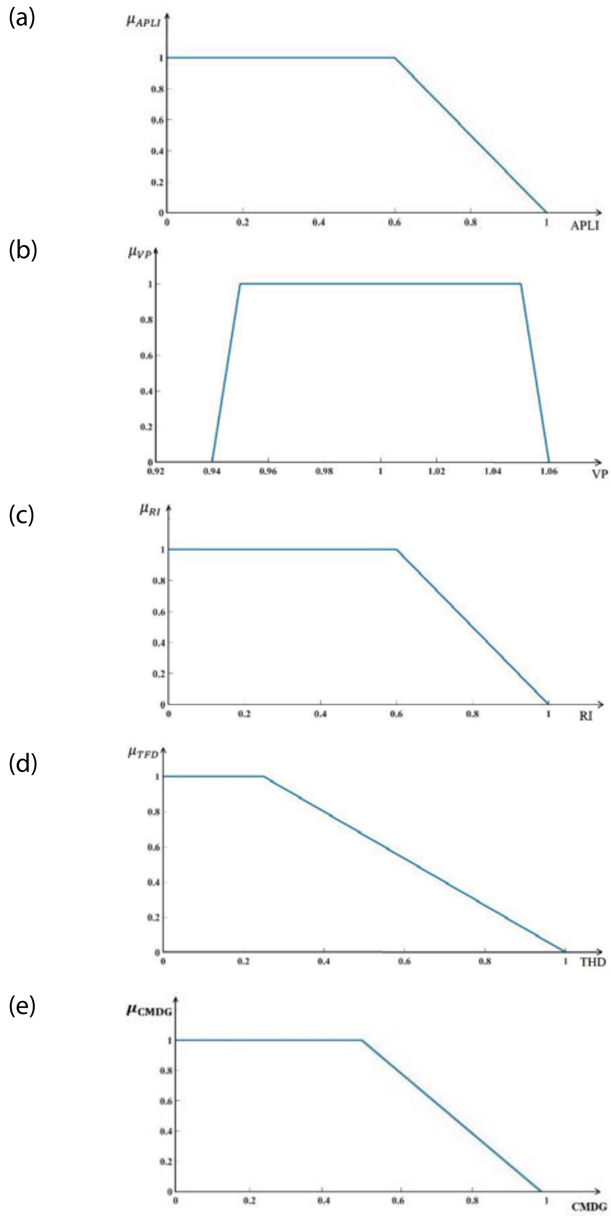

Figure 3: Fuzzy membership function for the objective function parameters

(ii) Fuzzification of minimum and maximum voltage profiles (VPs):

The VP is stated in equation (13). Using the trapezoidal membership function the VP is fuzzified as described in the fuzzy set (17) given below.

$$\mu_{VP} = \begin{cases} 0 & for\, VP \le VP_{L1} \\ \dfrac{VP - VP_{L1}}{VP_{min} - VP_{L1}} & for\, VP_{L1} \le VP \le VP_{min} \\ 1 & for\, VP_{min} \le VP \le VP_{max} \\ \dfrac{VP_{L2} - VP}{VP_{L2} - VP_{max}} & for\, VP_{max} \le VP \le VP_{L2} \end{cases} \tag{17}$$

Where, VP_{L1} and VP_{L2} are the minimum and maximum VP limits of the membership function and VP_{min} and VP_{max} are the primary and secondary limits represented in Fig 3b. These limits are chosen as VP_{L1} =0.94, VP_{min} =0.95, VP_{max} =1.05 and VP_{L2} =1.06 respectively.

(iii) Fuzzification of Reliability Index (RI):
The RI describes the ratio between the expected interruption cost in the presence and absence of DG, SCs and STF respectively which is stated in equation (6). Using the trapezoidal membership function depicted in Fig 3c, the RI is fuzzified as described in the fuzzy set (18) given below.

$$\mu_{RI} = \begin{cases} 1 \; for \; RI \le RI_{min} \\ \dfrac{RI_{max} - RI}{RI_{max} - RI_{min}} \; for \; RI_{min} < RI \le RI_{max} \\ 0 \; for \; RI > RI_{max} \end{cases} \tag{18}$$

Where, RI_{min} and RI_{max} are the minimum maximum limits of reliability index and their values are chosen as 0.6 and 1.0 for the proposed research problem.

(iv) Fuzzification of total harmonics distortion (THD):
The THD describes the harmonics presented in the bus voltage and it is stated in equation (12). This research work aimed to mitigate the harmonics to a minimum value Using the trapezoidal membership function depicted in Fig 3d, the THD is fuzzified as described in the fuzzy set (19) given below.

$$\mu_{THD} = \begin{cases} 1 \; for \; THD \le THD_{min} \\ \dfrac{THD_{max} - THD}{THD_{max} - THD_{min}} \; for \; THD_{min} < THD \le THD_{max} \\ 0 \; for \; THD > THD_{max} \end{cases} \tag{19}$$

Where, THD_{min} and THD_{max} are the minimum maximum limits of harmonic distortion and their values are chosen as 0.25 and 1.0 for the proposed research problem.

(v) Fuzzification of Cost minimization for the DGs (CMDG)
As shown in Fig 3(e), the DG cost function has been modeled as a fuzzy function. The cost minimization presented in the bus voltage and it is stated in equation (14). Eq. (20) represents the fuzzy membership function of the cost that is under or equal to the permissible cost as follows:

$$\mu_{\text{CMDG}} = \begin{cases} 1 & CMDG \le CMDG_{min} \\ \left(\dfrac{CMDG_{max} - CMDG}{CMDG_{max} - CMDG_{min}} \right) & CMDG_{min} \le CMDG \le CMDG_{max} \\ 0 & CMDG \ge CMDG_{max} \end{cases} \tag{20}$$

Where, $CMDG_{min}$ and $CMDG_{max}$ are the minimum and maximum DG cost.

4.2.2 Seagull Optimization Algorithm (SOA)
SOA is the most persuasive recently developed metaheuristic algorithm which is framed from the inspiration of hunting behavior of the bird Seagulls which are technically known as Laridae. It follows two significant strategies called exploration and exploitation to catch the prey. In this research, the proposed SOA algorithm is used to tune the membership function of fuzzy rules. The effectiveness of SOA algorithm has been proved in various engineering studies [23, 24]. The elucidation of hunting strategies of this algorithm with its mathematical modelling is presented in this section.

Migration (exploration):
In migration, the mathematical modelling of the particle movement is developed in a grouping pattern with respect to each other by satisfy the following three steps.

- Avoiding collision- To avoid collisions, while moving to the new position C_s) the current position ($\vec{P_s}(x)$) of particles are multiplied with the variable *A* (21). The variable *A* is represented in equation (10). The f_c represented in equation (22) regulate the frequency of retaining *A* which is decreased from f_c to 0.

$$\vec{C_s} = A \times \vec{P_s}(x) \tag{21}$$

$$A = f_c - \left(x * \left(\frac{f_c}{Max_{iteration}} \right) \right) \tag{22}$$

- Move towards optimal solution- In this step, the particles are moving towards its neighbor with best fitness value (23). Where, the $\vec{M_s}$ represent new particle position after moving towards best solution, $\vec{P_{bs}}(x)$ is the particle best solution and $\vec{P_s}(x)$ is the current position of particle. The *B* is represented in equation (16). The *rd* in equation (24) states the random number between 0-1.

$$\vec{M_s} = B \times (\vec{P_{bs}}(x) - \vec{P_s}(x)) \tag{23}$$

$$B = 2 \times A^2 \times rd \tag{24}$$

- Stay nearer to the particles with best fitness-In this step the position of particles is updated according to the best position (25).

$$\overrightarrow{D_s} = \left| \overrightarrow{C_s} + \overrightarrow{M_s} \right| \tag{25}$$

Attacking (exploitation):
In this process the Seagulls makes a spiral movement in the air to reach the prey. The best positions with optimal fitness values are finally achieved in this position with respect to the distance of each particle from the best fitness position and their movement in x, y and z plane (26).

$$\overrightarrow{P_s}(x) = \left(\overrightarrow{D_s} \times x' \times y' \times z' \right) + \overrightarrow{P_{bs}}(x) \tag{26}$$

Finally, the optimal solutions are reached in SOA with a smooth transition between exploration and exploitation moves.

5 Results and discussions

The optimal installation of DG, SCs and STF is the research problem and the solution is optimized using an effective proposed HF-SOA algorithm to predict the proposed fitness functions (objective function). The novel fitness function suggested in section 3.1 (1) is used for this optimization problem. With deterministic demand of load and DG system, the present article presents optimum location and size of DG in radial distribution network (RDN) to reduce network loss. The DG in this study is selected by Locating the bus in the network with the highest level of sensitivity. The study examines the placement of three DGs in both networks. Loss sensitivity analysis is used to determine the location of DG, one bus at a time, by selecting the most sensitive. The next sensitive bus is determined after employing DG at the selected bus. In order to find the next sensitive bus, the process is repeated once again. Therefore, DGs are placed in the respective RDNs based on the loss-sensitive buses in the network. For both 33-bus and 69-bus RDNs, the procedure identifies the loss-sensitive buses. A detail performance study of locating the DG, SCs and STF in standard IEEE 33 and 69 RDN which are depicted in Fig 1 and Fig 2 is conferred in this section. In each IEEE RDN under consideration, three case studies are acquired to perform the proposed optimization problem such as installation of DG alone, installation of both DG and SCs and installation of DG SCs and STF using the software MATLAB R2022a. Whereas, the term installation in this section represents both siting and sizing of energy components presented in this research work.

5.1 Analysis of HF-SOA in IEEE 33 RDN

The computational analysis of RDN is normally tested in reconfigured IEEE test systems. In this research study, two IEEE test systems with 33 and 69 nodes are considered for analysis purpose. The schematic layout of standard IEEE 33 bus considered in this research study is shown in Fig 1. The DG system considered in this research work includes 25MW of grid capacity with the fuel cost of 0.044 $/ /kWh, 1 MW of solar PV with the installation as well as operation and maintenance cost of 3985.0121 $/ /kWh and the 5 MW of wind turbine (WT) with the installation as well as operation and maintenance cost of 1822.0095 $/ /kWh [19, 26]. The optimal installation of DG, SCs and STF are analyzed with three case studies as follows:
Case 1: Optimal installation of DG alone
Case 2: Optimal installation of DG and SCs
Case 3: Optimal installation of DG, SCs and STF

(i) Case 1
The optimal DG installation alone is performed in this case using the HF-SOA algorithm, by averting harmonic parameter (Obj 3) in objective function (1) without violating the constraints. The harmonic load flow was simulated using MATLAB as a statistical method to account for uncertainty of input values. This problem represents the input data as random values from some specified, measured range. To work with and create a database for the proposed algorithm, the load flow method has been modified. A classical harmonic flow also takes into account the effect of background harmonics in the network. For HF-SOA, SSA and GMSA approaches, harmonic load flows are applied to systems with DG in three cases. To estimate different DG production losses, voltage drops, and THD online, the proposed HF-SOA is used. The optimized solutions are denoted in Table 1. These solutions confirms that the loss reduction obtained with the proposed HF-SOA is 68.31% with reference to the base case (without DG installation), which is higher than the results of SSA and GMSA approaches. Similarly, the maximum and minimum VP of the network is obtained as 0.9991 p.u and 0.9742 p.u correspondingly which is also higher than the results of the literature [18, 19]. Hence, the results confirms that the suggested HF-SOA algorithm outperforms SSA and GMSA approaches with, higher VP and less losses while installing the DG in bus numbers 13, 17, 24, 30 and 32 of an IEEE 33 bus networks, with the corresponding sizes denoted in Table 1.

Table 1: Case 1: Comparative analysis of optimal DG installation - IEEE 33 bus network

Optimization techniques	V_{min} (p.u)	V_{max} (p.u)	DG size (kW) and Placement (Bus Number)	Power Loss (kW)	Loss of reduction (%)
Base case	0.903	0.997	-	210.98	-
Proposed HF-SOA	0.9732	0.9991	541.32 (13), 301.20 (17), 978.74 (24), 505.54 (30), 407.61 (32)	66.84	68.31
SSA [19]	0.9686	0.9988	753.6 (13), 1100.4 (23), 1070.6 (29)	71.456	66.12
GMSA [18]	0.9725	0.9988	445.4 (29), 399.1 (10), 439.4 (15), 495.3 (25), 495.3 (26), 461.8 (32)	67.97	67.78

ii) Case 2

The SCs are also installed along with DG system in the same 33 node system and their installation criterions are optimized with the proposed HF-SOA algorithm in this case. The objective function preferred in case 1 is used for this case also. The optimal siting and sizing of DG as well as SCs are foreseeing by the HF-SOA and the resultant solutions are illustrated in Table 2. This table reveals that the network losses are considerably diminished to 7.56 kW (96.41%) with the proposed HF-SOA algorithm, which is precisely lesser than the power losses developed by SSA and GMSA approaches. Moreover, the total operating cost of the RDN with the proposed algorithm is evaluated as 236.51 $/h which is less than the operating cost of SSA (238.8 $/h). The minimum and maximum VPs are also enhanced to 0.9946 p.u and 1.0012 p.u which are comparatively higher than the alternate approaches depicted in Table 2 [18, 19]. Hence, it is confirmed that the HF-SOA could effectively reduce the power losses, operating cost, and maximize the VP compared to SSA and GMSA approaches while analyzing the DG and SCs installation in IEEE 33 network.

(iii) Case 3

The STF is installed along with DG and SCs in this case to support for harmonics mitigation. Whereas, the STF contains series connected resistor, inductor and capacitor and the configurations are directly referred from earlier research articles [17] such as C_m=29.8572μF, L_m=7.7793mH, R_m=0.2056Ω respectively. Fig 4 shows the waveform and harmonic spectrum of the source voltage waveform with a THD of 15.2314%, dominated by the 8th, 10th, and 12th harmonics. The THD of the source voltage and the perfor-

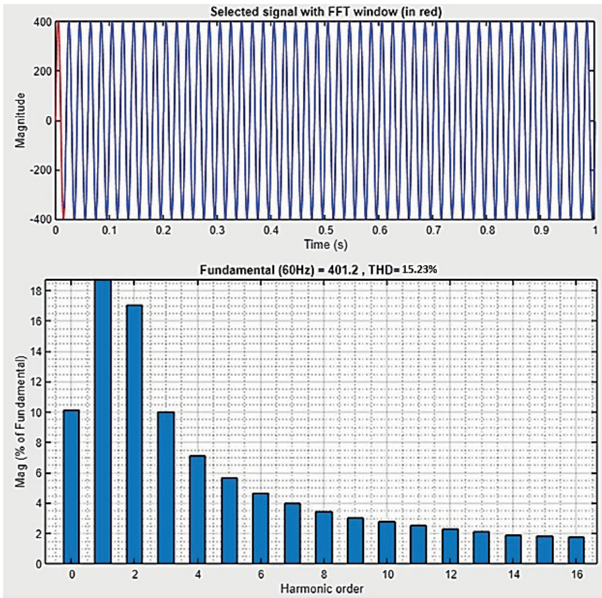

Figure 4: Source voltage waveform and its harmonic spectrum when passive filter connected

Table 2: Case 2: Comparative analysis of optimal DG and SCs installation - IEEE 33 bus network

Optimization techniques	V_{min} (p.u)	V_{max} (p.u)	Optimal DG installation (kW)	Optimal SCs installation (kVAr)	Power Loss (kW)	Loss of reduction (%)
Base case	0.903	0.997	-		210.98	-
Proposed HF-SOA	0.9946	1.0012	392.14 (13), 738.12 (24), 999.87 (29), 451.43 (32)	350 (13), 300 (23), 450 (29), 500 (32)	7.5651	96.41
SSA [19]	0.9918	1.0010	746.6 (13), 1078.9 (23), 1049.2 (29)	300 (13), 600 (23), 1050 (29)	11.8	94.41
GMSA [18]	0.9938	1.0010	418.2 (24), 474.8 (28), 478.6 (32), 448.7 (11)	600 (30), 350 (11), 450 (31), 150 (14)	7.94	96.24

mance can be improved by appending the passive filter into the existing passive filter system.

The optimal installation of filter in IEEE 33 RDN to minimize the objective function (1) that includes THD component is performed with the HF-SOA algorithm in this study. The solutions are presented in Table 3. This table reveals that the optimal location of STF is identified as bus 8 and the minimum and maximum THD values are obtained as 2.3221 and 4.3287 respectively. The graphical bar chart representation of THD level in each bus is depicted in Fig 5. The minimum and maximum THDs in the presence and absence of STF in bar chart are highlighted in brown and blue color in Fig 5. Similarly, the power loss also reduced by 96.48% with respect to the base case after the STF installation, which is comparatively higher than the power loss in base case and IEEE 33 network with only DG and SCs. In similar manner the minimum and maximum VPs are also enhanced after the installation of STF. The ECOST is also reduced from 316.58 $/h to 252.23 $/h which is nearly reduced to 20.64% with reference to the base case (without DG, SCs and STF) which ensures the reliability of operation after the installation of DG, SCs and STF. All the results clearly reveal that the proposed HF-SOA approach could effectively mitigate the harmonics after the installation of filter.

The comparative VPs of Case 1 Case 2 and Case 3 optimized with HF-SOA are shown in Fig 6(a) which evidently illustrates that the VP has been considerably improved in Case 3 and Case 2 related to Case 1. Hence, it is confirmed that, the VP is considerably enhanced after the installation of SCs as well as STF. The fig in 6(b) illustrates the reduction in the cost of DG system based on the analysis of the HF-SOA, the GMSA, the SSA and the base case of different cases in IEEE 33 RDN. As a result, the proposed method has a better performance than the existing.

The convergence of the proposed HF-SOA is examined with the five samples of power loss convergence characteristics for all the three cases. Here, the sample is considered as DG size and bus number in a test system. The power loss plot over consecutive iterations for five samples for Case 1, 2 and 3 are illustrated in Fig 7. It is evident from this figure that, fast convergence could be obtained with the proposed HF-SOA approach with minimum power loss in all the cases. The power loss at Case 3 is comparatively lower than other two cases. Hence, it is confirmed that fast convergence with least fitness values could successfully obtained with the proposed algorithm.

The Power losses, VP as well as the THD values for the three cases with and without filter are compared using

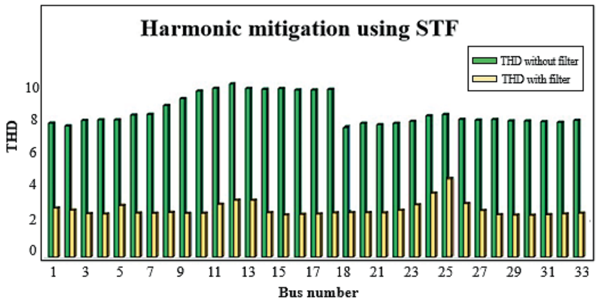

Figure 5: Percentage THD of bus voltage in IEEE 33 RDN

(a)

(b)

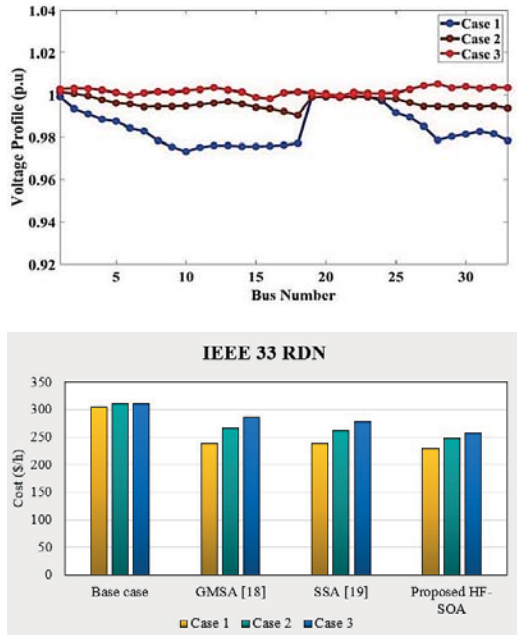

Figure 6: Comparative analysis of different cases in IEEE 33 RDN of (a) VP (b) DG cost

Table 3: Case 3: Comparative analysis of optimal DG, SCs, STF installation - IEEE 33 bus network

Condition	V_{min} (p.u)	V_{max} (p.u)	Filter Location	THDmax	THDmin	Power Loss (kW)	Loss of reduction (%)
Base case	0.9036	0.9971	-	15.2314	10.5269	210.98	-
With DG and SCs	0.9946	1.0010	-	9.6967	7.2924	7.5651	96.41
With DG, SCs and STF	0.9987	1.0052	8	4.3287	2.3221	7.4278	96.48

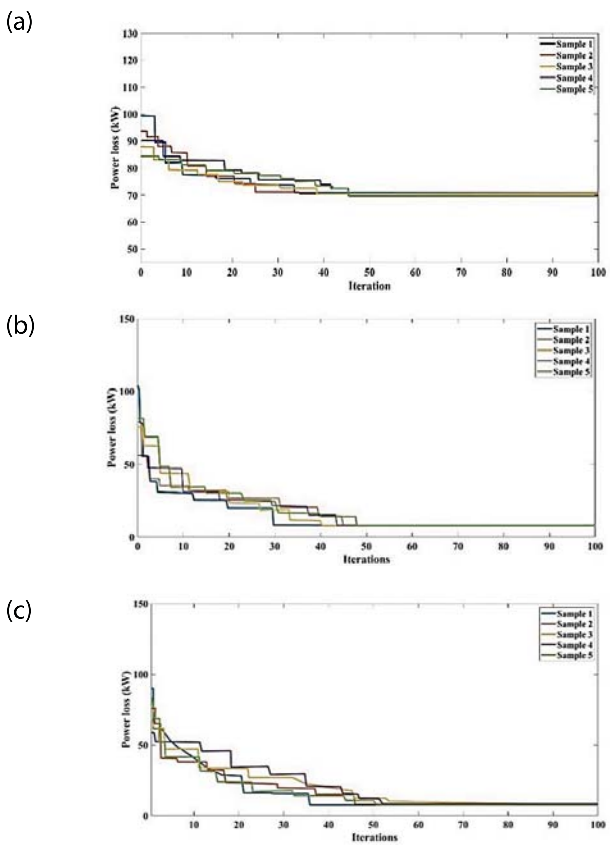

Figure 7: Power losses convergence - IEEE 33 bus system (a) Case 1(b) Case 2 (c) Case 3

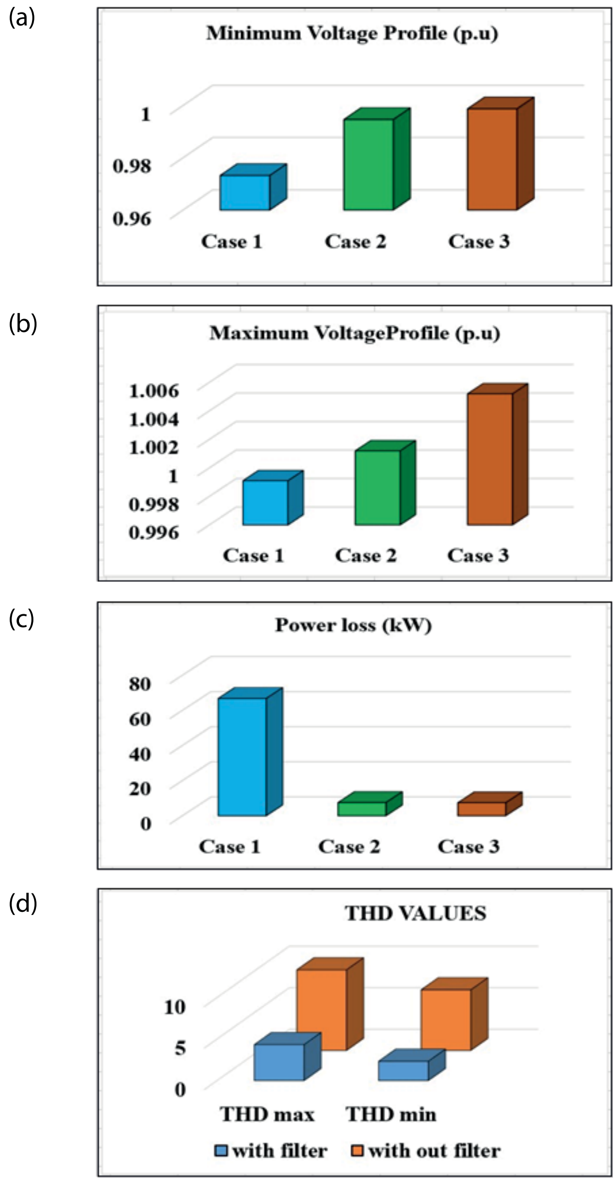

Figure 8: Comparative analysis of objective function parameters in three cases of IEEE 33 bus (a) Minimum voltage profile (b) Maximum voltage Profile (c) Power loss (d) THD values

Case 1: Optimal installation of DG alone
Case 2: Optimal installation of DG and SCs
Case 3: Optimal installation of DG, SCs and STF

bar chart analysis as illustrated in Fig 8. It is evidently clear from Fig 8(a) and Fig 8(b) that the minimum and maximum VPs are enhanced in Case 3 after the installation of DG, SCs and STF in IEEE 33 bus network related to Case 1 and 2. In similar manner, the Fig 8(c) reveals that the power loss is also considerably reduced in Case 3 compared to Case 1 and 2. Meanwhile, the comparative analysis of VP illustrated in Fig 8(b) evidently reveals that the presence of both SCs and STF could effectively minimize the THD values. Hence, the Fig 8 ensures that the presence of SCs and filters in power network could diminish the harmonics, losses and improve the VP. In similar manner, maximum THD values with and without filter is presented in Fig 8(c) clearly confirms the need of filter installation in power network for the purpose of harmonic mitigation.

5.2 Performance analysis on IEEE 69 RDN

The installation of DG, SCs and STF in 69 RDN shown in Fig 2 are optimized in this section using HF-SOA. Similar to the section 4.1 three cases are framed to examine the effectiveness of proposed HF-SOA algorithm in foreseeing the installation of DG, SCs and STF integrated in an IEEE 69 network.

The objective functions considered in the three cases of IEEE 33 bus study is considered in IEEE 69 bus also.

(i) Case 1
The installation of DG system in a 69 RDN is optimized in this case using the proposed HF-SOA approach and the solutions are represented in Table 4 which, reveals that the optimized siting of DG in IEEE 69 RDN using proposed HF-SOA approach are 17, 21, 42, 61 and 62 respectively. Meanwhile, the percentage reduction in

power losses is also stated as 70.25% which is higher than the SSA and GMSA algorithms. In the same way the minimum and maximum VPs are also improved to 0.9732 and 0.9991 respectively which is higher than the results of GMSA and SSA algorithms [18, 19]. Table 4 ensures that the proposed HF-SOA outperforms the earlier published articles. Hence, the dominance of the proposed HF-SOA is confirmed in this case study.

(ii) Case 2
Both DG and SCs are integrated in IEEE 69 bus system in this case, and their size as well as locations are optimized with HF-SOA algorithm. The resultant solutions are shown in Table 5. This table reveals that the optimal locations of DG in IEEE 69 bus system are 17, 23, 61 and 63 and the locations of SCs are 16, 35, 23 and 61, respectively. It is also revealed that the percentage power loss reduction (97.79%) is high in proposed approach compared to GMSA approach. The minimum and maximum VPs are also enhanced to 0.9986 and 1.0021using the proposed hybrid algorithm, which is higher than the results documented earlier in the literature [18, 19]. From this case study, the dominance of HF-SOA over SSA and GMSA in optimizing the siting and sizing of DG and SCs in IEEE 69 bus system is evidently proved.

(iii) Case 3
The installation of STF along with DG and SCs in IEEE 69 RDN is discussed in this case for effective mitigation of harmonics. The STF with same configurations as discussed in IEEE 33 case study is considered in this case also. The bar chart representation of THD in each bus in this optimization process is depicted in Fig 9 which demonstrates that the optimal location of STF is identified as bus 37 and the minimum and maximum VP values are obtained as 0.9987 and 1.0032 respectively. The minimum THDs with and without STF in the bar chart representation are highlighted in brown and blue color in Fig 9. For detailed analysis the minimum and maximum THD values are from this figure and listed in Table 6. This table clearly describes that the harmonics are mitigated after the installation of STF in the bus number 37 which is optimized with the proposed intelligent algorithm. It is also revealed from the table that, the minimum and maximum THD values of the power network without DG, SCs and STF are 9.5126 and 17.2562 and this value has been reduced by 77.22 % and 49.92 % after the installation of DG and SCs which is further reduced to 84.49 % and 73.32 % after the installation of STF. In addition, the losses of the network also minimized by 97.83 % compared to base case. The ECOST is also reduced from 421.65 $/h to 314.23 $/h which is nearly reduced to 25.47% related to the base case. Thereby, the reliability is also ensured. This case study confirms the dominance of proposed HF-SOA approach over SSA and GMSA in terms of power loss, harmonics minimization and VP and reliability improvement.

The comparative voltage profiles of the three cases optimized using proposed HF-SOA approach is depicted in Fig 10 (a). This figure clearly describes that the VP is

Table 4: Case 1: Comparative analysis of optimal DG installation - IEEE 69 bus network

Optimization techniques	V_{min} (p.u)	V_{max} (p.u)	DG size (kW) and Placement (Bus Number)	Power Loss (kW)	Loss of reduction (%)
Base case	0.909	0.999	-	224.98	-
Proposed HF-SOA	0.9802	1.0010	341.32 (17), 524.65 (21), 387.23 (42), 542.34 (61), 687.32 (62)	66.9314	70.25
SSA [19]	0.9789	1.0003	380 (17), 527 (10), 1718 (60)	69.41	69.14
GMSA [18]	0.9725	0.9988	359.8 (53), 282.2 (67), 100.1 (42), 281.07 (62), 307.04 (60)	67.79	69.87

Table 5: Case 2: Comparative analysis of optimal DG and SCs installation - IEEE 69 bus network

Optimization techniques	V_{min} (p.u)	V_{max} (p.u)	Optimal DG installation (kW)	Optimal SCs installation (kVAr)	Power Loss (kW)	Loss of reduction (%)
Base case	0.909	0.999	-	-	224.98	-
Proposed HF-SOA	0.9986	1.0021	592.14 (17), 320.89 (23), 951.77 (61), 851.65 (63)	420 (16), 490 (35), 650 (23), 750(61)	4.9623	97.79
SSA [19]	0.9971	1.0010	358 (19), 518 (10), 1673.5 (60)	600 (11), 600 (48), 1200 (60)	4.837	97.85
GMSA [18]	0.9976	1.000	346.5 (69), 383.2 (18), 446.4 (62), 360.7 (58)	450 (50), 150 (48), 450 (61), 1200 (23), 150 (10)	5.093	97.74

Table 6: Case 3: Comparative analysis of optimal DG, SCs, STF installation - IEEE 69 bus network

Condition	Vmin (p.u)	Vmax (p.u)	Filter Location	THDmax	THDmin	Power Loss (kW)	Loss of reduction (%)
Base case	0.909	0.999	-	17.2562	9.5126	224.98	-
With DG and SCs	0.9986	1.0021	-	8.6426	2.1669	4.9623	97.79
With DG, SCs and STF	0.9987	1.0032	37	4.6032	1.4748	4.8656	97.83

considerably increased in third case compared to other two cases. Further, the convergence analysis of HF-SOA is also examined with IEEE 69 bus network by examining the most fundamental parameter of objective function called power loss for the three cases. The figure in 10(b) illustrates the reduction in the cost of DG system based on the analysis of the HF-SOA, GMSA, SSA and the base case of different cases in IEEE 69 RDN. As a result, the proposed HF-SOA method has a better performance than the existing.

The power loss plot over consecutive iterations for five samples for Case 1, 2 and 3 are illustrated in Fig 11. This figure ensures the earliest convergence of proposed

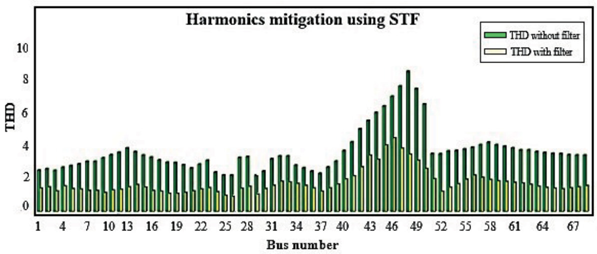

Figure 9: Percentage THD of bus voltage in IEEE 69 RDN

(a)

(b)

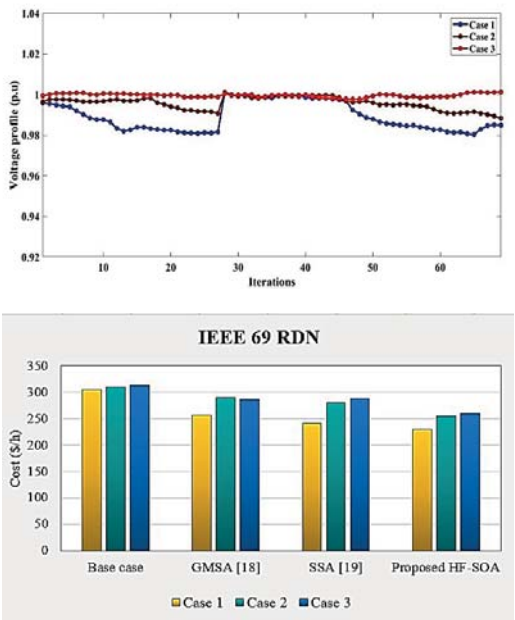

Figure 10: Comparative analysis of different cases in IEEE 69 RDN of (a) VP (b) DG cost

algorithm with minimum fitness value. In addition, it is also observed that the fitness value of power loss in Case 3 is less when compared to other two cases. Hence, the convergence ability of the HF-SOA approach is proved while optimizing the installation of DG, SCs and STF in the 69 RDN.

The comparative analysis of minimum and maximum VPs and power losses for the three cases as well as the THD values with and without filter are presented with the bar chart representation as depicted in Fig 12. Fig 12(a) and Fig 12(b) describes that the minimum and maximum VPs are enhanced in Case 3 after the installation of DG, SCs and STF in IEEE 69 bus network related to Case 1 and 2. In similar manner, it is understood from Fig 12(c) that the power loss is also considerably reduced in Case 3 compared to Case 1 and 2. In the same way, the Fig 12(d) confirms the mitigation of har-

(a)

(b)

(c)

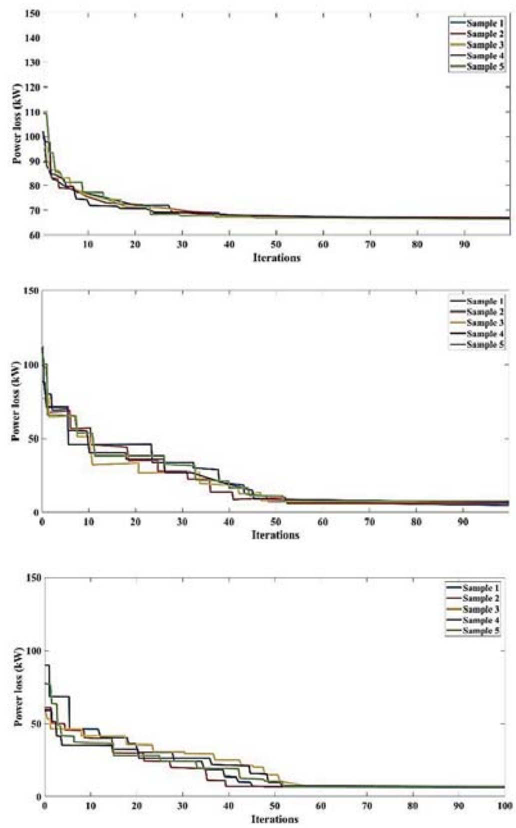

Figure 11: Convergence of power losses in IEEE 69 bus system (a) Case 1(b) Case 2 (c) Case 3

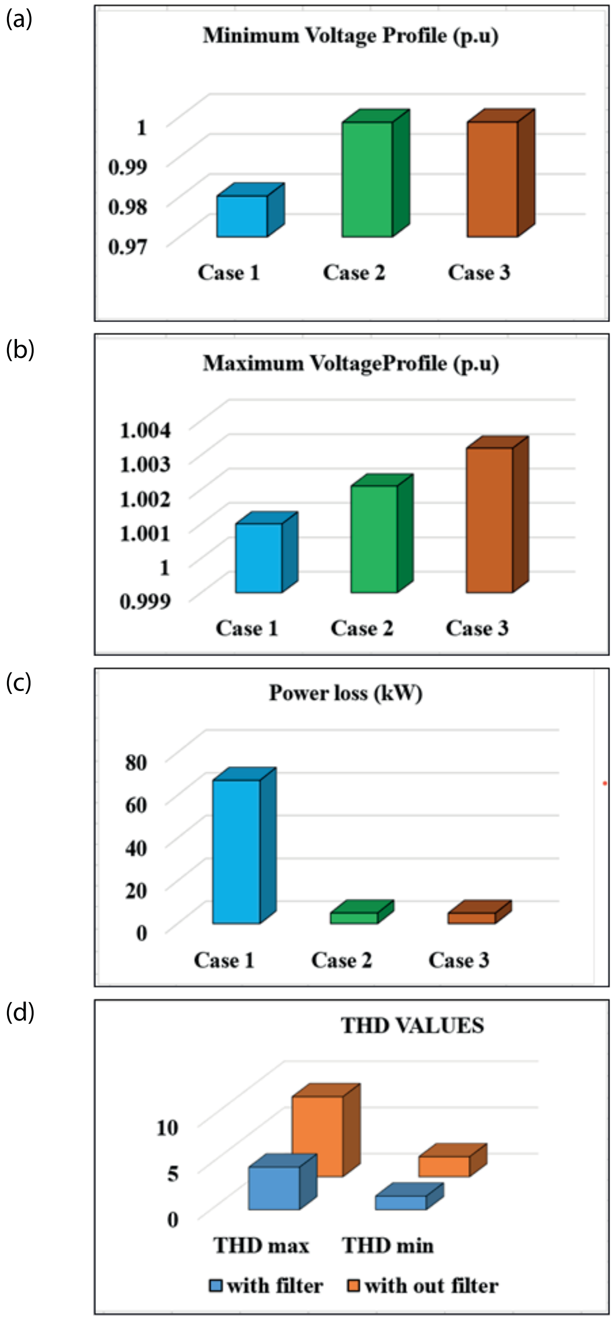

Figure 12: Comparative analysis of objective function parameters in three cases of IEEE 69 bus (a) Minimum voltage profile (b) Maximum voltage Profile (c) Power loss (d) THD values

monics after the installation of single tuned filter in Case 3. Hence the effectiveness of proposed HF-SOA in optimizing the siting and sizing of DG, SCs and STF is confirmed by this analysis.

6 Conclusion

A novel HF-SOA algorithm is proposed in this article to optimize the installation of DG, SCs and STF in a distributed network. The reduction of power losses, harmonics, and enhancement of VP and reliability are considered as the fundamental parameters in the proposed novel multi-objective function of this proposed research problem. Three case studies are conducted in standard IEEE network with 33 and 69 nodes, to examine the effectiveness of proposed intelligent algorithm. The results optimized with the HF-SOA in IEEE 33 bus system ensures that the power losses in Case 1, Case 2 and Case 3 are reduced by 68.31%, 96.41% and 96.48% respectively when compared to the base case. In the same way, the power losses are minimized by 70.25%, 97.79% and 97.83% compared to base case while optimizing with proposed intelligent algorithm. In addition, the minimum and maximum THD values are also reduced by 77.94% and 71.58% in IEEE 33 bus system and 84.49 % and 73.32 % in IEEE 69 bus system. The reliability enhancement is also proved with ECOST minimization which is reduced by 20.64% in 33 node and 25.47% in 69 node system. The effective VP enhancement is also achieved through the proposed intelligent algorithm. The results of convergence analysis revealed that earlier convergence could be obtained by the proposed HF-SOA approach with minimum power loss. Hence, with the proposed novel HF-SOA algorithm based on the novel fitness function, the optimal size and allocation of DG, SCs and STF are obtained successfully. This research work could be extended in near future with the following suggestions:

- In this research article, only the ECOST is considered in the objective function to improve the reliability however, the other cost parameters such as energy not supplied (ENS) could also be considered.
- In this article the filter parameters are referred from literature instead, they could be optimized along with siting of filters.

7 Acknowledgments

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8 Conflict of Interest

Authors do not have any conflicts.

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