IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 7, 2020, accepted December 21, 2020, date of publication December 28, 2020, date of current version January 6, 2021.

Digital Object Identifier 10.1109/ACCESS.2020.3047671

An Improved Sunflower Optimization Algorithm-Based Monte Carlo Simulation for Efficiency Improvement of Radial Distribution Systems Considering Wind Power Uncertainty

ABDULLAH M. SHAHEEN[1], EHAB E. ELATTAR[2], (Senior Member, IEEE), RAGAB A. EL-SEHIEMY[3], (Senior Member, IEEE), AND ABDALLAH M. ELSAYED[4]

[1]Electrical Engineering Department, Faculty of Engineering, Suez University, Suez 43533, Egypt
[2]Department of Electrical Engineering, College of Engineering, Taif University, Taif 21944, Saudi Arabia
[3]Electrical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh 33516, Egypt
[4]Electrical Engineering Department, Faculty of Engineering, Damietta University, Damietta 34517, Egypt

Corresponding author: Ragab A. El-Sehiemy (elsehiemy@eng.kfs.edu.eg)

This work was supported by the Taif University Researchers Supporting Project of Taif University, Taif, Saudi Arabia, under Grant TURSP-2020/86.

ABSTRACT All over the world, the operators of the power distribution networks (DNs) are still looking for improving the efficiency of their networks. The performance of DNs and lifetime of its component have been significantly affected by its capability of varying their topologies with accurate load gathering via smart grid functions. This paper investigates making use of the smart DNs features and proposes a model of handling the capability of re-allocating the capacitors integrating with configuring the DNs topology. Using the developed formulation, the efficiency of DNs can be improved not only by minimizing the operational costs related to the network losses but also by optimizing the investment costs associated with capacitor re-allocations. Also, various load patterns are employed in the developed formulation to imitate the daily load variations over a year. The improved sunflower optimization algorithm (ISFOA) is proposed in this paper to get the optimal solution of the presented problem. The standard IEEE 33-node feeder and practical 84-node system of Taiwan Power Company (TPC) are the considered test systems. Besides, the uncertainties due to a distributed generation of wind power are investigated via Monte Carlo simulation involved with the proposed ISFOA. Furthermore, to verify the ability of ISFOA to obtain better solutions compared with different recent optimizers, a statistical comparison is carried out based on a large scale 118-node distribution systems. The simulation results reveal that significant technical and economic benefits are obtained by applying the proposed algorithm with higher superiority and effectiveness.

INDEX TERMS Performance enhancement, multi-lateral distribution networks, network re-topology, capacitor re-allocations.

I. INTRODUCTION

Automation of distribution networks (DNs) is one of the most effective frameworks for improving their efficiency and enhancing the reliability of the power service as well [1]. Two main requirements are necessary for achieving the DNs automation which are the automatic switches and their secured communications. DNs and their related communication devices must be incorporated together to handle an effective automated DNs [2]. Thus, network reconfigurations can be immediately acquired in an optimized way. On the other side, power DNs represent the ultimate contact with consumers. They are continuously facing ever-growing load demand, leading to increased burden and bad performance with excessive branches loading [3]. The power losses in DNs represent a burden on electric utility, which reaching 13% of total generated power [4], [5]. It is important in effective DNs to reduce the dissipated energy as much as possible. Investigating and improving the DNs performance affects directly on the transmission and generation sectors as

The associate editor coordinating the review of this manuscript and approving it for publication was Siqi Bu.

well as providing luxury and consumers' satisfaction. Several methods have been followed to improve the efficiency of DNs such as capacitor banks (CBs), network reconfiguration, distributed generators (DGs), automatic voltage regulators (AVRs), etc. [6], [7].

Shunt capacitor is considered the common conventional enhancement devices for DNs. The achieved power loss minimization using single located capacitor bank was extended for multiple capacitor banks. Subsequently, optimization strategies were introduced to deal with capacitor optimal placement problem. Economic benefits of the capacitor banks depend mainly on capacitor optimal numbers and sizes as well as proper selection schemes to match load variations [8]. Over the past two decades capacitors' allocations and control have been studied using a range of heuristic methods such as ant-colony optimization algorithm [9], [10]; particle swarm optimization algorithm [11]; immune algorithm [12]; cuckoo search optimization algorithm [13]; genetic algorithm [14]; grey wolf algorithm [15]; plant growth algorithm [16]; gravitational search algorithm [17]; flower pollination algorithm [18]; teaching learning optimization algorithm [19]; bacterial foraging algorithm [20]; honey bee optimization algorithm [21]; combined fuzzy-heuristic techniques [22], [23]. These techniques solve the problem of best location and size imitating bees, birds, wasps, fish schools, etc. in order to reach the best solution. Optimal allocation of capacitor banks in DNs can fulfill many benefits once optimal sizing and sitting are obtained. Many researchers seek to maximize the advantages of using capacitor banks in DNs for performance enhancement either in technical or economic prospect [24], [25]. Hence, most of the objectives of interested researchers were in this regard such as minimum total cost [9]–[12], [15]–[18], [26], maximum annual net saving [5], [22]; distribution system voltage stability improvement [17]. Some of them were able to achieve these objectives either as a single objective function [10], [17], [24]–[26] or combined as a multi-objective [5], [9], [11], [12], [14], [15], [18]–[22].

Reconfiguration of DNs is one of the most effective means for power loss reduction, voltage profile improvement, load congestion management, and system quality and reliability enhancement. Generally, DNs are operated in a radial fashion. Distribution systems reconfiguration enables the DNs to re-struct its topology. This can be done by reconsidering the status of normally open/closed switches of sectionalizing and tie-switches. Reconfiguration of DNs can relieve load congestion and achieve secure and reliable operation of DNs during contingencies or under normal operating conditions [27], [28]. The reconfiguration problem can be either static or dynamic [29]. The static problem of the reconfiguration is still a complex, non-differentiable and combinatorial constrained optimization issue which is hard to be treated and gains more complexity by expanding over multiple time periods. Therefore, it is crucial to find a proper algorithm to solve the problem. Reconfiguration of DNs got deep investigation and great attention from researchers for enhancing the performance of DNs. Different techniques were introduced in previous literatures either using analytical or meta-heuristic algorithms. Interchange switch strategy [30], open-all switch strategy [31], close-all switch strategy [32] and sensitivities computation method [33] are the commonly used analytical methods for optimal reconfigurations. Improved Elitist–Jaya algorithm [34], feasibility-preserving evolutionary optimization [35], improved sine–cosine algorithm [36], tabu search algorithm [37], equilibrium optimization algorithm [38], grey wolf optimizer [39] and particle swarm optimization [7] are some examples of previously used meta-heuristic algorithms.

Most of the previous literatures were concerned with optimal capacitor placement or optimal reconfiguration of distribution systems without considering the other. Although the achievement of DNs enhancement with capacitor optimal placement or distribution system reconfiguration, but performance evaluation of distribution system and economic benefits of combined capacitor placement and distribution system reconfiguration not studied sufficiently [40]–[42]. The planners who interested in enhancing the DNs performance began to integrate the placement of enhancement devices with DNs reconfiguration [43]–[46]. There are only a few literatures studying cost minimization of DNs that applies distribution system reconfiguration and capacitor placement simultaneously. Ref [43] introduces a population-based ant colony search algorithm for optimal reconfiguration of DNs simultaneously with optimal capacitor banks allocation. Ref [44] introduces an improved branch exchange method by optimizing the sequence of loops selection for minimizing the energy losses. Then, a joint optimization algorithm is applied for combining this improved method of distribution system reconfiguration and optimal capacitor banks placement. A hybrid approach that combines network reconfiguration and capacitor placement using Harmony Search Algorithm (HSA) is proposed to minimize power loss reduction and improve voltage profile was proposed in [45]. Also, in [46], an improved binary particle swarm optimization method was proposed for optimal network reconfiguration and capacitor placement to reduce power loss.

Several of previous literatures were concerned with solving the optimal capacitors placement and reconfiguration of DNs problem at peak load only [9]–[11], [17]–[20], [23], [24]–[26]. Continuous daily and seasonally load variations cause many problems in modelling and calculations of distribution systems especially at light load values. As well, possibility of reverse power flow may lead to excessive energy losses [13], [47]. To get rid of these problems, some literatures are concerned with performance enhancement of distribution systems considering load variations [5], [12]–[14], [22]. There are additional modern and superior optimizers for the capacitor allocation on the distribution grid including variable load conditions and practical cases such as hybridization of particle swarm optimization besides a gravitational search algorithm [48], enhanced gravitational search algorithm [49], and spotted hyena algorithm [50].

This paper introduces a practical and economic solution methodology for performance enhancement of smart DNs with optimal integrated capacitors re-allocations, distribution reconfiguration and daily load variations. It represents several load patterns with daily load variations over a year horizon, which makes the proposed improvement more realistic and closer to reality. It supports the time of use tariff with different charge rates at different times of night or day. The introduced solution methodology, in this paper, uses a proposed improved variant of a novel nature-inspired optimizer based on sunflowers' motion. The sunflower optimization represents an iterative population-based optimizer for the sake of solving multi-dimensional problems. It mimics the sunflowers' movement for capturing the best orientation to the sun. Various recent implementations have been successfully executed for damage identification on composite plates [51], identifying the electrical parameters for photovoltaic cells [52], solving the optimal power flow [53], and parameter estimation of lithium-polymer batteries [54]. The main contributions of this paper can be summarized as follow:

- An improved sunflower optimization algorithm (ISFOA) is proposed. ISFOA develops the pollination rate and the mortality rate in an adaptive way to overcome the restrictions in the SFOA search capability due to being constants.
- The uncertainties due to the presence of distributed generation of wind power is investigated via Monte Carlo simulation involved with the proposed ISFOA.
- Furthermore, statistical comparison is carried out between the proposed ISFOA and different recent optimizers of harmony search, artificial bee colony, shark smell, cuckoo search, gravitational search, and salp swarm optimization on large scale 118-node distribution systems.
- The simulation results reveal that significant technical and economic benefits are obtained through the application of the proposed algorithm with higher superiority and effectiveness.
- The proposed methodology is applied for standard IEEE 33-node feeder, and practical 84-node system of Taiwan Power Company (TPC). Also, scalability of the proposed technique is tested on large scale 118-node distribution systems.

The rest parts of this work are organized as follows: Section II presents the proposed problem formulation. Section III introduces the basic and improved SFOA as well as its application for reconfiguration of DNs and capacitor re-allocations. Section IV presents the simulation results and results analysis and discussion. Overall conclusion is introduced in section V.

II. PROPOSED PROBLEM FORMULATION

The proposed problem is formulated as a sophisticated optimization problem to handle the readiness of re-locating and/or re-sizing the capacitors in re-configurable DNs. This developed formulation reinforces the minimization of the operational costs related to the network losses and optimizing the investment or untangling costs related to capacitor re-locations and re-sizing. These two objectives can be augmented in a single objective function as follows;

$$\mathrm{Min}\ O_f = \sum_{L=1}^{N_L} \left(\left\{ TD_L h_L \sum_{Br=1}^{N_{line}} Loss_{Br,L} \right\} + \left\{ \sum_{i=1}^{N_C} \left(e_i + c_i Q_{c_i} \right) \right\} + \left\{ \sum_{j=1}^{N_u} \left(u_j + c_j(-Q_{u_j}) \right) \right\} \right) \quad (1)$$

where, O_f ($/year) is the considered objective function that reinforces the minimization of the operational costs related to the network losses and optimizing the investment or untangling costs related to capacitor re-locations and re-sizing. The first term of this equation represents the total operational costs related to the network losses, where; TD_L is the time duration of each load level; h_L is the $/kWh cost of each load level; N_{Line} is the number of the distribution lines; $Loss_{Br,L}$ is the network losses in each distribution branch for each period of the load levels; N_L is the number of yearly load levels. The second and third terms are the costs ($/year) related to either investment for new installations of capacitors with size (Q_c) or savings for untangling capacitors with size (Q_u), where; e, u, and c are the installment ($), untangling ($), and purchase ($/kVAr) cost for each kVAr capacitor, respectively; N_C is the number of new installations; and N_u is the number of untangled capacitors.

This formulation searches for the optimal re-allocations of the existed capacitors, installing newer ones and optimal status of the switches for optimal re-configuration. In this formulation, daily load variations with several load patterns over a year horizon are simultaneously represented. Thus, the vector of the control variables (C_V) is as follows;

$$C_v = [\underbrace{SW_1 \ldots\ldots SW_{N_{sw}}}_{\text{Open switches}}, \underbrace{Lq_1 \ldots\ldots Lq_{N_q}}_{\text{Capacitor Re-locations}}, \underbrace{Qc_1 \ldots\ldots Qc_{N_q}}_{\text{Capacitor Sizes}}] \quad (2)$$

where, SW refers to the selected switches to be open (integer variable); N_{sw} is the total number of the must open switches that radially configure the distribution system; Lq is the candidate re-locations of the capacitor to be installed or untangled (integer variables); Qc is the regarded sizes to be installed or untangled (discrete variables); N_q is the total number of the capacitors to be installed or untangled.

Solving the objective function in (1) is subject to the following technical and operation constraints;

$$V_{n,L}^{min} \leq V_{n,L} \leq V_{n,L}^{max}, \quad n = 1, 2, \ldots, N_b, \quad L = 1, 2, \ldots, N_L \quad (3)$$

$$\left| S_{Br,L} \right| \leq S_{Br,L}^{max}, \quad L = 1, 2, \ldots, N_L, Br = 1, 2, \ldots, N_{Line} \quad (4)$$

$$1 \leq SW_i \leq N_{line}, \quad i = 1, 2, \ldots, N_{SW} \quad (5)$$

$$1 \leq Lq_j \leq N_b, \quad j = 1, 2, \ldots, N_q \quad (6)$$

$$0 \leq \mathrm{Qc_j} \leq \mathrm{Qc^{max}}, \quad j = 1, 2, \ldots, \mathrm{N_q} \tag{7}$$

$$\mathrm{N_q} \leq \mathrm{N_b} \tag{8}$$

$$\sum_{j=1}^{\mathrm{N_q}} \mathrm{Qc_j} \leq \sum_{n=1}^{\mathrm{N_b}} (\mathrm{Qd_n})_{\mathrm{min(L)}}, \quad \mathrm{L} = 1, 2, \ldots, \mathrm{N_L} \tag{9}$$

$$\mathrm{Pss_L} > \sum_{n=1}^{\mathrm{N_b}} (\mathrm{Pd_n})_{\mathrm{L}}, \quad \mathrm{L} = 1, 2, \ldots, \mathrm{N_L} \tag{10}$$

$$\mathrm{Qss_L} - \sum_{j=1}^{\mathrm{N_C}} \mathrm{Qc_j} > \sum_{n=1}^{\mathrm{N_b}} (\mathrm{Qd_n})_{\mathrm{L}}, \quad \mathrm{L} = 1, 2, \ldots, \mathrm{N_L} \tag{11}$$

where, V indicates the voltage magnitude; S and $\mathrm{S^{max}}$ refer to the power flow and the rating of the lines; Pss and Qss are the supplied active and reactive power from the substation; $\mathrm{N_b}$ refers to the total number of the nodes. The subscripts "min" and "max" refers to the minimum and maximum of each regarded variable.

This formulation represents an inequality bounds related to the voltage quality at each load demand at any period as in (3) while (4) handles the safe loading of each branch. Equations (5)-(7) bounds the control variables of the open switches, the locations of capacitor sizes to be installed or untangled, and their regarded sizes, respectively. Equation (8) specifies the number of capacitors to be installed or untangled not to exceed the total number of buses whilst (9) specifies the limits of total injected reactive power from the capacitors. Equations (10) and (11) guarantee powering all loads in the distribution network as the supplied power have to be greater than the loads aggregation. Added to that, the load flow balance for each load level should be preserved as the equality constraints.

To preserve the radial mode of the distribution network, a branch-bus incidence matrix is formed as in (12);

$$\mathrm{A_{ij}} = \begin{cases} 0, & \text{if line i isn't connected to bus j} \\ -1, & \text{if the line i enter to bus j} \\ 1, & \text{if the line i exits from bus j} \end{cases} \tag{12}$$

This matrix is a $\mathrm{N_b} \times \mathrm{N_{Lines}}$. Based on this matrix formation, if their determinant is zero, the network isn't radial and if it is 1 or -1, the network topology is radial [55].

Additionally, the presence of wind DGs can be connected to some buses with their rated power. Typically, wind speeds have probabilistic characteristics that can be interpreted using the Weibull Density Function (WDF) [56], [57]. Thus, for each hour, the WDF ($\mathrm{F_{wind}}$) for wind speed(s) can be expressed as:

$$\mathrm{F_{wind}}(s) = \frac{k}{c}\left(\frac{s}{c}\right)^{k-1} e^{-(\frac{s}{c})^k} \tag{13}$$

where, s indicates the random wind speed (m/s); c refers to the Rayleigh scale index ($c \approx 1.128 s_{av}$); s_{av} is the average speed dependent on historical speed data; k indicates the shape index (k=2). In real time operation, the correct value of the wind speed(s) is measured, and the output power of the wind turbine ($\mathrm{P_{wind}}$) is determined. Much of the time, the calculation speed is greater than the rated speed and less than the cut-off point, so the output power at the measured frequency ($\mathrm{P_{wind}}$) is determined as follows;

$$\mathrm{P_{wind}}(s) = \begin{cases} 0 & \text{if } s \leq s_{ci} \\ m_3 s^3 + m_2 s^2 + m_1 s + m_0 & \text{if } s_{ci} < s < s_r \\ \mathrm{P_{rated}} & \text{if } s_r < s < s_{co} \\ 0 & \text{if } s_{co} \leq s \end{cases} \tag{14}$$

where, s_{ci}, s_r and s_{co} are respectively the cut-in, rated, and cut-out speed of the turbine; m_0, m_1, m_2, m_3 are the coefficients defined on the basis of the curve fitting; $\mathrm{P_{rated}}$ is the nominal rating of the turbine.

III. PROPOSED ISFOA

A. BASIC SUNFLOWER OPTIMIZER

SFOA is one of the recent evolutions in soft computing algorithms which is inspired from the nature. The main notion of the SFOA is the simulation of the sunflowers' movement seeking for capturing the best following to the sun where this process is repetitious at the sunrise every morning. The cycle of a sunflower is always the same: every day, they awaken and accompany the sun like the needles of a clock. At night, they travel the opposite direction to wait again for their departure the next morning [51]. The law of radiation manages the cycle of a sunflower as;

$$\mathrm{Q_x} = \frac{\mathrm{P_x}}{4\pi \mathrm{r_x^2}} \tag{15}$$

where, $\mathrm{Q_x}$ is the heat intensity that received by each sunflower individual (x); $\mathrm{P_x}$ is the solar power and $\mathrm{r_x}$ is the distance between the best individual in the current population and each individual. Equation (15) shows the inverse square relationship between the radiated heat and the distance. Each sunflower adjusts its orientation towards the sun be expressed in (16);

$$\vec{s_x} = \frac{\mathrm{X^*} - \mathrm{X_x}}{\|\mathrm{X^*} - \mathrm{X_x}\|}, \quad x = 1, 2, \ldots, \mathrm{NP} \tag{16}$$

where $\mathrm{X}*$ is the best individual in the current population, $\mathrm{X_x}$ refers to each solution and NP is the specified size of the population. The sunflowers move across the sun is represented as follow.

$$\mathrm{d_x} = \lambda.\ \mathrm{P_x}\left(\|\mathrm{X_x} + \mathrm{X_{x\text{-}1}}\|\right).\ \|\mathrm{X_x} + \mathrm{X_{x\text{-}1}}\| \tag{17}$$

where, λ is a defined constant related to the inertial displacement of each sunflower; $\mathrm{P_x}(||\mathrm{X_x}+\mathrm{X_{x-1}}||)$ is the sunflower probability of the pollination.

In SFOA, the pollination is carried out in a random way through the least distance between each flower and the posterior flower. Consequently, the sunflower pollinates for a new position where the nearer sunflowers to the sun make smaller moves to support the local search improvement whereas the other sunflowers move normally. Based on the above, the update mechanism of each sunflower position is carried out via the sunflowers move (d_x) and their orientation (s_x) towards the sun as follows:

$$X_{x+1} = X_x + d_x \times s_x \tag{18}$$

The basic steps of the SFOA can be summarized as follows:

Step 1: Initialize NP, Pr, m, maximum iteration Max_w, the iteration counter (t=0), and the specified limits of C_V (2).
Step 2: Create the initial sunflower population ($X_x(w)$), randomly. Each sunflower is represented as in (2).Therefore, each sunflower is composed of simultaneous capacitor allocations with selected switches to be open.
Step 3: Evaluate the related fitness function (O_F) as in (1).
Step 4: Appoint the best sunflower ($X*$) with the least O_F.
Step 5: Check if Max_w is reached. If it is satisfied, extract $X*$ and end the program.
Step 6: Adjust the sunflower positions towards the sun (16).
Step 7: Calculate the orientation vector for each sunflower (15) and remove the worst m% sunflowers.
Step 8: Update the Pr% sunflowers according to (18), and the m% sunflowers by randomly creating them within their limits.
Step 9: Increase the counter increment (w=w+1). Then, go to step 3.

B. IMPROVED SUNFLOWER OPTIMIZER VIA NORMALIZATION PROCESS

The SFOA is very sensitive to the two specified parameters of the pollination rate (Pr) and the mortality rate (m). This high sensitivity does not guarantee the capability for finding the best sunflower. Also, the inertial displacement of each sunflower is defined as constant which restricts the searching behavior of the SFOA. These two restrictions don't support the search exploration of the SFOA. In this paper, two modifications are suggested to overcome the above-mentioned restrictions. The first modification proposes converting the pollination rate (Pr) from constant specified value into adaptive value as in (19);

$$Pr = 0.5 \times (1 - \frac{w}{Max_w}) \tag{19}$$

This equation describes the co-efficient vector (Pr) as a linear declined from 0.5 to 0 over the iterations.

The second modification proposes describing the inertial displacement (λ) adaptively for each sunflower as in (20);

$$\lambda = (U_b - L_b) \times (1 - \frac{w}{Max_w}) \tag{20}$$

where, U_b and L_b are the upper and lower bounds of the decision variables; w is the current iteration. Fig. 1 illustrates the flowchart of the proposed ISFOA.

Based on the above, the advantages of the proposed algorithm are as follows:

- The search space is passed through different directions based on two specified parameters which are the pollination rate (Pr) and the mortality rate (m).

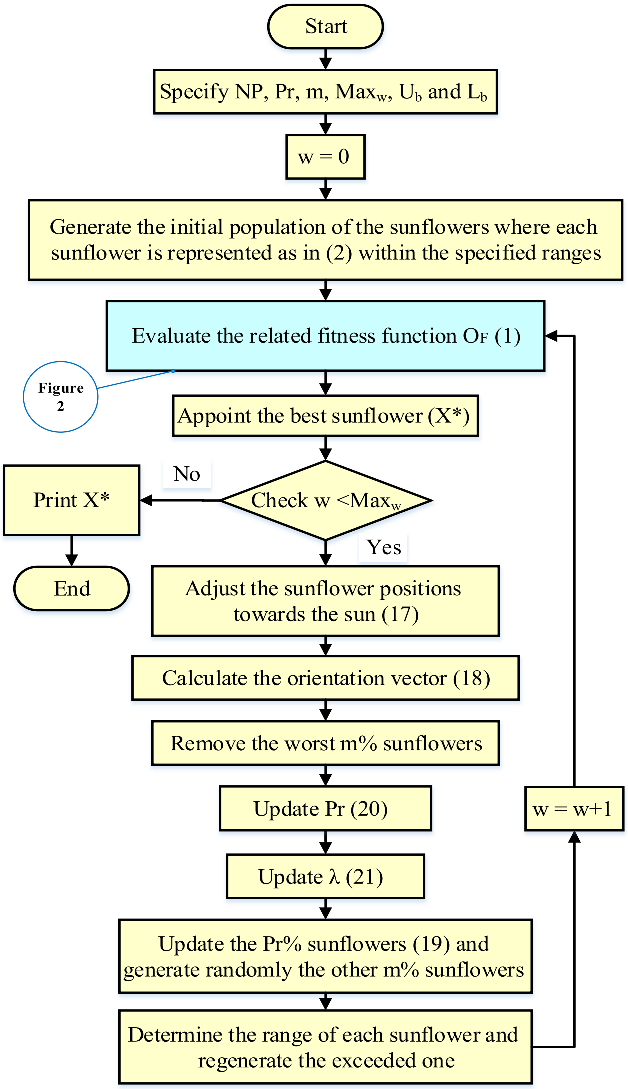


FIGURE 1. Flowchart of the proposed ISFOA for handling the proposed formulation.

- The first determines the percentage of the sunflower individuals that pollinates for new positions with smaller moves to support the local search improvement.
- The second determines the percentage of the sunflower individuals with worse fitness values that will be removed in each iteration.
- The adaptive parameter of the pollination rate helps the exploration phase of the SFOA by decreasing the local search dependability on the Best sunflower as illustrated in its update mechanism.
- The adaptive parameter of the inertial displacement is represented considering the diversified ranges of each decision variable. Related to the proposed formulation, the ranges are greatly varied where the ranges for the open switches and the capacitor re-allocations are very small compared to the capacitor sizes. Thus, the new adaptive description of the inertial displacement performs as a normalization process to the updating

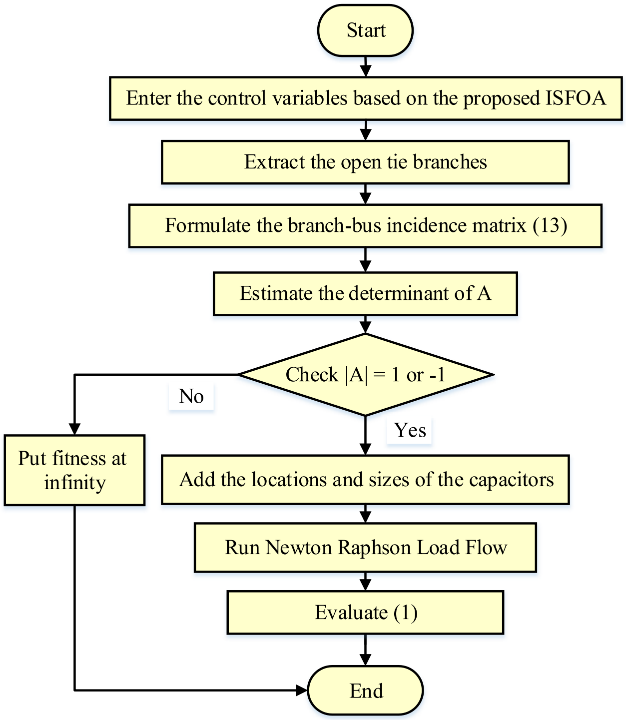


FIGURE 2. Evaluating the related fitness function.

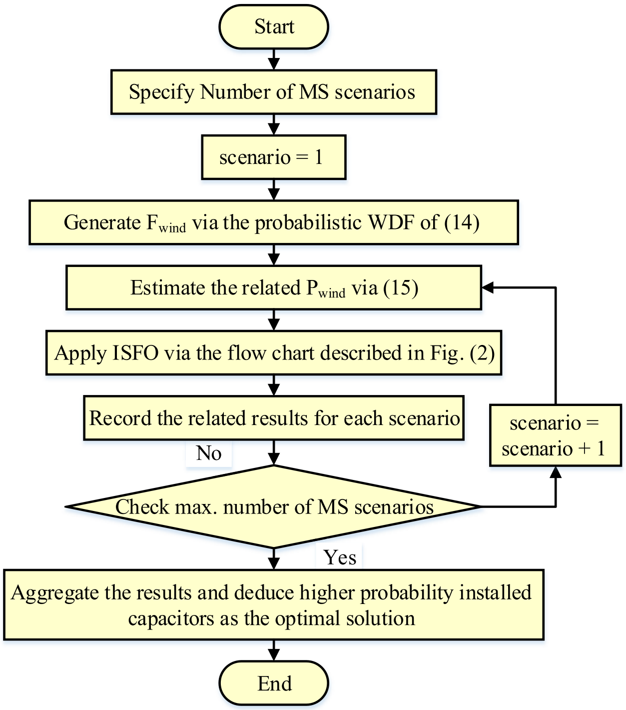


FIGURE 3. ISFOA structure incorporating wind power uncertainties.

mechanism which helps supporting the exploitation phase of the SFOA.

To describe in detail the solution procedure for joint reconfiguration and capacitor re-allocations, Fig. 2 shows a related flowchart. As shown, the proposed ISFOA creates based on its updating mechanism (Fig. 1) the control variables. The first type of the control variables represents the open tie branches, and the second type represents the capacitor locations and their corresponding sizes (2). After that, equation (12) is activated to formulate the matrix of branch-bus incidence (A) based on the open tie branches. Then, the determinant of A can be estimated. Then, a checking process is executed to the radial topology, where the network is radial if the determinant of A is equal to 1 or -1. Else, the network is not radial or islanded. Finally, the load flow, via Newton Raphson method, is performed for the radial condition and the fitness function (1) is calculated. The fitness function will be set at infinity if the network is not radial. So, the related solution will be discarded in the following iterations.

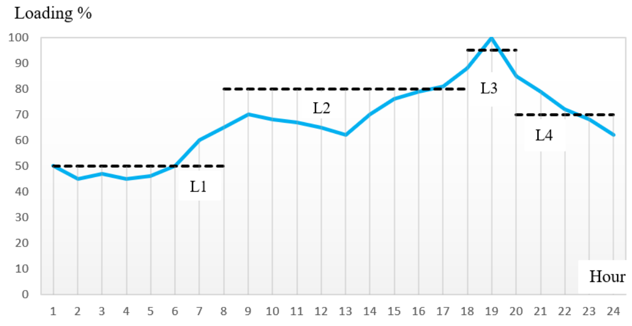
C. ISFOA FOR NETWORK RE-TOPOLOGY AND CAPACITOR RE-ALLOCATIONS INCORPORATING THE WIND POWER UNCERTAINTIES

Forecasting studies of the wind speed are executed through several forecasting techniques [58]–[60] and the output power of the wind turbine (P_{wind}) is determined. Despite the high efficiency of the forecasting techniques, it remains some uncertainties that may cause small deviations between the actual and the forecasted. In order to overcome the uncertainty in generated output power from the wind turbine, Monte Carlo Simulations (MS) is implemented, which requires random input variables depending on the probability density function (PDF) [61], [62]. And then all stochastic data can be computed. A probabilistic model is expected to use the MS. To fix the complexity of the Wind power model (represented by F_{wind}), random data is represented by a WDF which is the best suitable PDF to adapt the random scattered wind speed (13). It is distributed where the scale and shape parameters are taken of 10 and 3.1, respectively considering 20 samples of average measured wind speeds as deterministic data. The variability of wind power generation is selected at random within a ±5 per cent range. The more scenarios to be simulated the more accuracy of MS to be derived. Fig. 3 describes the structure of ISFOA application for network re-topology and capacitor re-allocations incorporating the wind power uncertainties.

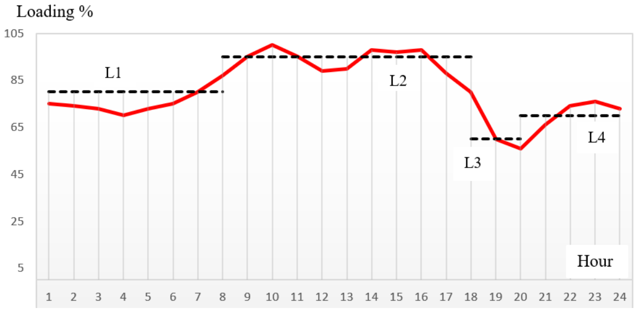
As shown, the maximum number of MS scenarios is firstly specified. Then, the WDF is generated to extract the output power from each wind turbine existed in the network. After that, the proposed ISFOA, that is previously detailed in Section III.B, is applied for each generated scenario. When all the MS scenarios are simulated, the accumulated probability based on the total installed capacitors is evaluated and the higher probability solution is deduced as the optimal one.

IV. SIMULATION RESULTS

In this section, the ISFOA and the conventional SFOA are applied on the IEEE 33-node feeder [63], and 11 feeder practical 84-node system [64]. Four loading levels with different load patterns are considered within a year horizon. This analysis is based on two exemplary load patterns which were taken from a practical Brazilian distribution utility [65].



a. Group-A



b. Group-B

FIGURE 4. Exemplary load pattern [65].

For each tested system, the distribution nodes are divided into two groups based on these two loading patterns. The first (Group-A) has the load curve that depicted in Fig. 4-a, while the second (Group-B) has the load curve in Fig. 4-b. All the distribution nodes are possible for locating the capacitors, so the capacitor sites are integers chosen from node 1 to N_b. Similarly, all the distribution lines have switches which are possible to be the opened tie line.

The capacitors are modelled as voltage dependent susceptance where their VAr injection is proportionally to the square of the node voltage [66]. This model demonstrates high accuracy compared to modelling it as negative reactive demand [7]. Added to that, the considered sizes of the capacitors are discrete values within the range [0-1800] kVAr with step 200 kVAr and the associated investment cost of the capacitors is 4 US\$/kVAr [67]. Their instalment and untangling costs are considered 150 and 100 US\$, respectively. The nodal voltage limits are 0.90 p.u. and 1.1 p.u [68]. The time duration of each load level and the related energy price, based on the concept of time of use tariff, are tabulated in Table 1 [67]. The simulation runs are performed using the proposed SFOA and ISFOA with 50 and 100 sunflowers for IEEE 33-node and practical 84-node system, respectively with maximum number of 200 iterations. MatlabR2017b is used to perform the simulations on a system with 8 GB of RAM and intel(R) Core (TM) i7-7200U CPU (2.5 GHz).

A. IEEE 33-NODE FEEDE

The first test system is the radial distribution feeder with 33-node, 12.66-kV rated, and total demand of 3.715 MW and 2.3 MVAr [63]. In this system, there are five open switches at lines from 33:37. Three capacitors are optimally considered, as referred in [9], at nodes 9, 19, and 25 with sizes of 450, 450, and 1050 kVAr, respectively. Fig. 5 depicts the system diagram. The distribution nodes (2:18) follow the load pattern of Group-A while the rest follow the load pattern of Group-B.

TABLE 1. Time duration of different load levels and the related energy price.

Loading level	L1	L2	L3	L4
Time (hr)	2920	3650	730	1460
Energy price (US\$/kW h)	0.06	0.06	0.108	0.06

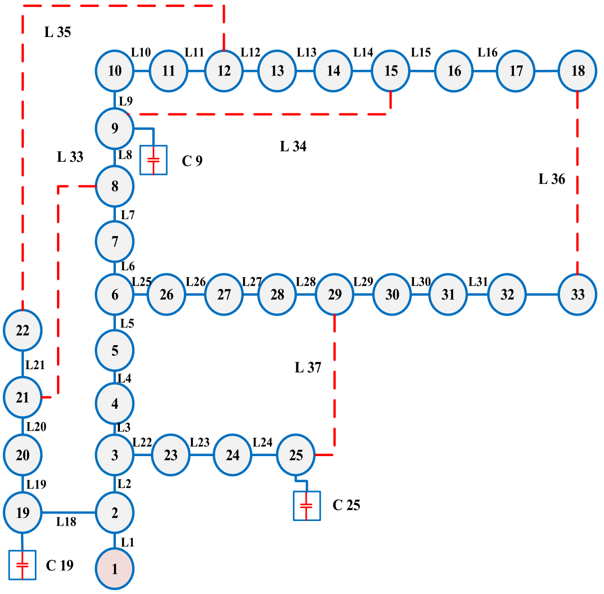


FIGURE 5. IEEE 33-node distribution system.

The proposed SFOA and ISFOA are applied for the proposed formulation. In addition, PSO [69] are also employed for comparative purposes. The related control variables are tabulated in Table 2. This table illustrates that the proposed ISFOA untangles the three existed capacitors and re-locating them at nodes 14, 25 and 30 with re-sizes of 200, 200 and 800 kVAr, respectively. The obtained re-allocations are conducted with the same configuration by opening the same switches at lines from 33:37.

Table 3 tabulates the obtained system performance assessment in terms of the economic and technical issues. From which, the proposed ISFOA is effectively achieves the least total costs of the operational losses and the capacitor costs which are minimized from initially 67828 US\$ to 44486 US\$. With this selected control variables, the power losses are greatly reduced from initially 82.053, 162.39, 117.40 and 98.56 kW to 57.997, 110.596, 84.852 and 66.378 kW at all loading levels (L1:L4), respectively.

Also, the minimum voltages are greatly improved from initially 0.9479, 0.92, 0.9194 and 0.9345 p.u. to 0.9614, 0.9359, 0.9353 and 0.9503 p.u. at all loading levels (L1:L4), respectively. In addition, the negative sign for the investment

TABLE 2. Optimal capacitor re-allocation of the 33-node system.

Items	Locations (Lq (node))				Sizes (Qc (kVAr))			
	Initial	PSO [69]	SFOA	ISFOA	Initial	PSO [69]	SFOA	ISFOA
Capacitor	9	8	7	14	450	600	400	200
	19	30	12	25	450	600	200	200
	25		30	30	1050		800	800
Open Switches (SW)	33	33	33	33				
	34	34	34	34				
	35	35	35	35				
	36	36	36	36				
	37	37	37	37				

TABLE 3. Performance evaluation of the 33-node system.

Items		Initial	PSO [69]	SFOA	ISFOA
Losses (kW)	L1	82.053	61.275	59.069	57.997
	L2	162.39	113.331	108.201	110.596
	L3	117.40	85.27	84.833	84.852
	L4	98.56	68.3634	67.109	66.378
Min. Voltage (p.u.)	L1	0.9479	0.9604	0.9639	0.9614
	L2	0.92	0.9377	0.9385	0.9359
	L3	0.9194	0.9372	0.9379	0.9353
	L4	0.9345	0.9521	0.9529	0.9503
Losses Costs (US$)		67828	48266	46612	46886
Sum of Qc (MVAr)		1.95	1.2	1.4	1.2
Capacitor Costs (US$)			-2400*	-1450*	-2400*
Total Costs (US$)		67828	45866	45162	44486

***The negative sign indicates that the proposed algorithm saves capacitors by untangling them from the DNs**

on capacitors refers to the regarded savings due to untangling 750 kVAr which can be re-installed in other systems. Furthermore, the convergence curve of the proposed ISFOA, SFOA and PSO is displayed in Fig. 6 where the proposed ISFOA demonstrates their capability in finding the global minimum of 44486 US$ compared to the PSO and SFOA which achieve total costs of 45866 and 45162 US$, respectively.

To consider the uncertainties of the wind power, three wind DGs are considered at optimal locations as previously mentioned per [70]. The installed nodes are 13, 24, and 30 with sizes of 813.4, 1094.6, and 1066 kW, respectively. By applying the ISFOA structure that is described in Fig. 3 where the maximum number of 400 MS scenarios is taken. Fig. 7 displays the related probabilities of the acquired solutions which are discriminated based on their size summation of the capacitors. As shown, high probability of 16, 19.8, 16.7 per cent is driven at sum of capacitor size within range of 1-1.4 MVAr where the maximum probability of 19.8 per cent at 1.2 MVAr where the regarding optimal solution is illustrated in Table 4. From this table, the optimal locations are 10, 29, and 33 with sizes 400, 600, and 200 kVAr, respectively where the must open tie lines are from 33:37.

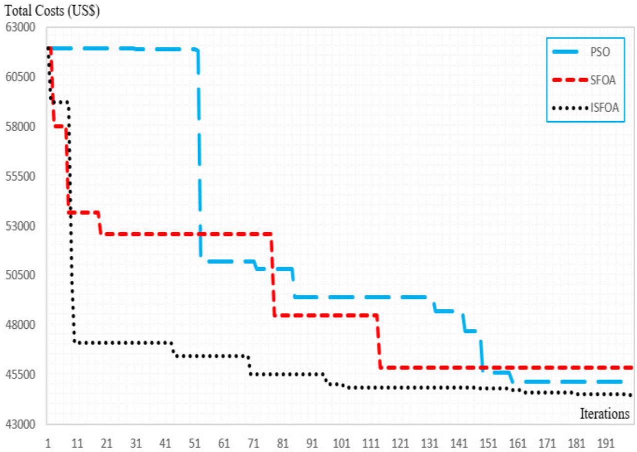


FIGURE 6. Convergence curve of the proposed ISFOA, SFOA and PSO for IEEE 33-node Feeder.

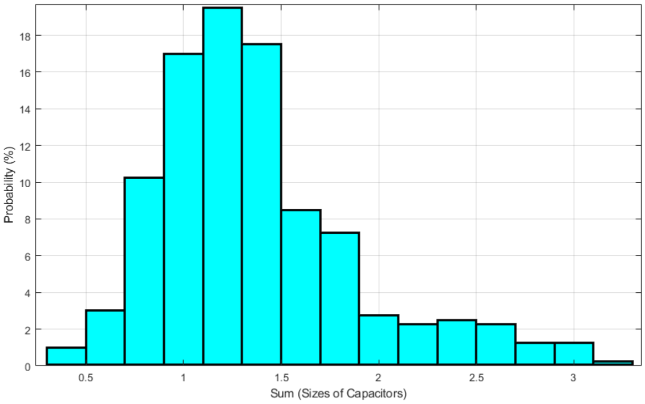


FIGURE 7. Probabilities of the acquired solutions via the proposed ISFOA for IEEE 33-node system.

TABLE 4. Optimal configuration with capacitor re-allocations via the proposed ISFOA considering wind power uncertainties.

Locations (Lq (node))	10	29	33		
Sizes (Qc (kVAr))	400	600	200		
Open Switches (SW)	33	34	35	36	37
Sum of Qc (MVAr)			1.2		

B. PRACTICAL 84-NODE SYSTEM OF TP

This system is the practical 11 feeder 84-node system of TPC. It consists of 84-node, 95 line and 13 tie-line switch. Fig. 8 depicts the system diagram. The rated kV is 11.4 while the total demand of 28350 kW and 20700 kVAr [64]. In this system, 13 open switches are existed at lines from 84:96. Four capacitors are optimally considered, as referred in [66], at nodes 6, 19, 71 and 79 with sizes of 200, 400, 600 and 600 kVAr, respectively. Therefore, the total existed sizes are 1800 kVAr. The distribution nodes (1:46), at the feeders A:F, follow the load pattern of Group-A while the rest (47: 84), at the feeders G:L, follow the load pattern of Group-B. In this test case, the proposed ISFOA, SFOA and PSO are applied for the proposed formulation. Their optimal control variables are illustrated in Table 5.

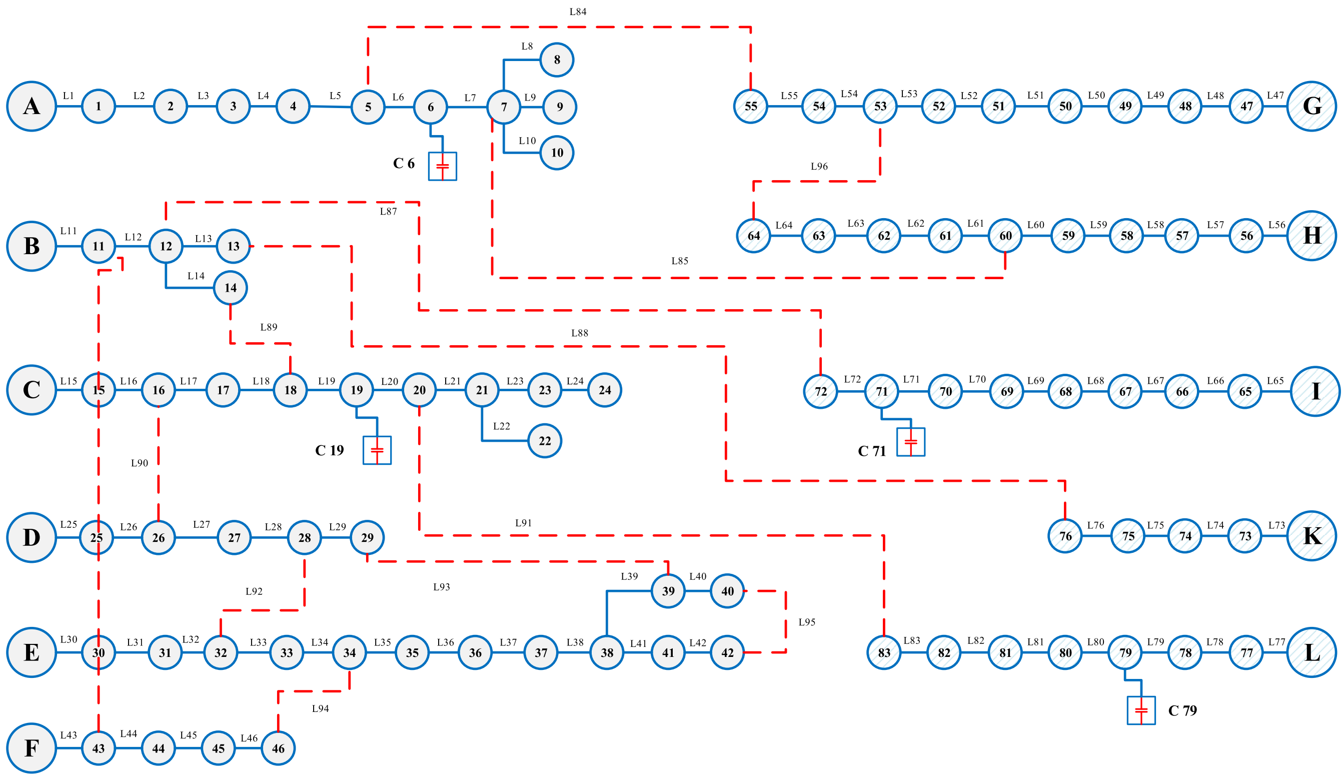


FIGURE 8. IEEE 84-node distribution system.

TABLE 5. Optimal capacitor re-allocation and reconfigurations of the 84-node system.

Items	Locations (Lq (node))				Sizes (Qc (kVAr))			
	Initial	PSO [69]	SFOA	ISFOA	Initial	PSO [69]	SFOA	ISFOA
Capacitor	6	7	53	9	200	400	200	400
	19	19	55	65	400	800	1400	1000
	71	55	56	72	600	1000	400	800
	79	62	70	82	600	600	800	600
		72		84		800		600
		80				1200		
Open Switches (SW)	84	7	7	7				
	85	33	13	34				
	86	38	32	38				
	87	42	37	55				
	88	62	41	63				
	89	72	55	72				
	90	83	61	82				
	91	84	72	86				
	92	86	82	88				
	93	88	86	89				
	94	89	89	90				
	95	90	90	92				
	96	92	92	95				

From this table, the proposed ISFOA obtains a further increase in installing new capacitors where all the existed capacitors at nodes 6, 19, 71 and 79 are untangled and re-allocated. The obtained locations are at nodes 9, 65, 72, 82 and 84 and the corresponding sizes are 400, 1000, 800, 600 and 600, respectively. These re-allocations are associated with an optimal configuration by opening the switches at lines 7, 34, 38, 55, 63, 72, 82, 86, 88, 89, 90, 92 and 95.

Table 6 tabulates the obtained system performance assessment in terms of the economic and technical issues. As shown, the proposed ISFOA obtains the least total costs of the operational losses and the capacitor costs by minimizing it from initially 173641 US$ to 139770 US$. The power losses are greatly reduced from initially 211.9331, 392.9574, 358.072 and 253.6787 kW to 158.348, 304.175, 267.6137 and 191.3289 kW at all loading levels (L1:L4), respectively.

TABLE 6. Performance evaluation of the 84-node system.

Items		Initial	PSO [69]	SFOA	ISFOA
Losses (kW)	L1	211.933	154.089	172.961	158.348
	L2	392.957	293.275	322.150	304.175
	L3	358.072	252.576	278.227	267.614
	L4	253.678	181.779	204.533	191.329
Min. Voltage (p.u.)	L1	0.9588	0.9758	0.9694	0.9771
	L2	0.9438	0.9686	0.9633	0.967
	L3	0.9324	0.969	0.9626	0.963
	L4	0.9512	0.9774	0.9697	0.9722
Losses Costs (US$)		173641	127060	140710	132220
Sum of Qc (MVAr)		1.8	4.8	2.8	3.4
Capacitor Costs (US$)		-	13200	5000	7550
Total Costs (US$)		173641	140260	145710	139770

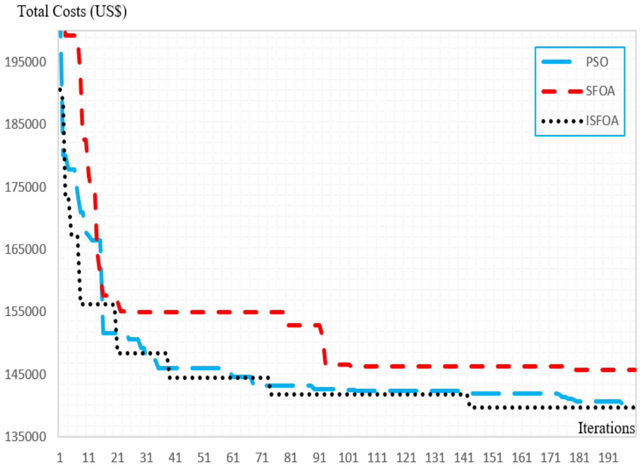


FIGURE 9. Convergence curve of the proposed ISFOA, SFOA and PSO for IEEE 84-node System.

Also, the minimum voltages are greatly improved from initially 0.9588, 0.9438, 0.9324 and 0.9512 p.u. to 0.9771, 0.967, 0.963 and 0.9722 p.u. at all loading levels (L1:L4), respectively. The convergences of ISFOA, SFOA and PSO are depicted in Fig. 9 which indicates the great capability of the proposed ISFOA in finding the global minimum of 139770 US$ compared to the PSO and SFOA which achieve total costs of 140260 and 145710 US$, respectively.

To consider the uncertainties of the wind power, random nodes are selected to install wind DGs at 13, 24, and 30 with sizes of 813.4, 1094.6, and 1066 kW, respectively. By applying the ISFOA, Fig. 7 displays the related probabilities of the acquired solutions based on their size summation of the capacitors. As shown, high probability of approximately 30 per cent is driven at sum of capacitor size within range of 3.4-3.8 MVAr and the maximum probability of 10 per cent at 3.6 MVAr where the regarding optimal solution is illustrated in Table 7. From this table, the optimal locations are 7, 53, 72, 80 and 84 with sizes 400, 1200, 400, 800 and 600 kVAr, respectively where the must open tie lines are 7, 34, 38, 62, 72, 76, 81, 84, 86, 89, 90, 92, and 95.

TABLE 7. Optimal configuration with capacitor re-allocations via the proposed ISFOA considering wind power uncertainties.

Locations (Lq (node))	7	53	72	80	82
Sizes (Qc (kVAr))	400	1200	400	800	600
	7	34	38	62	72
Open Switches (SW)	76	81	84	86	89
	90	92	95		
Sum of Qc (MVAr)			3.6		

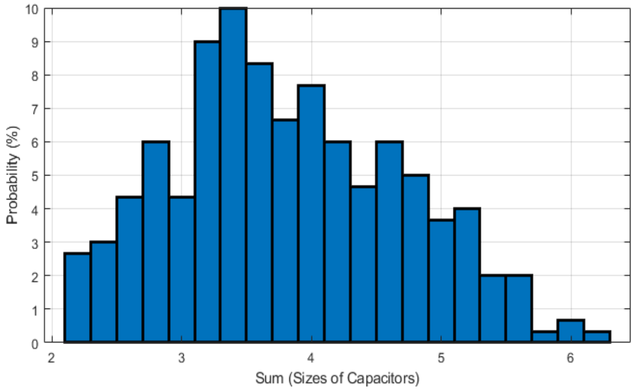


FIGURE 10. Probabilities of the acquired solutions via the proposed ISFOA for 84-node system.

C. SCALABILITY ANALYSIS ON LARGE SCALE DISTRIBUTION SYSTE

The scalability and competitiveness of the ISFOA are proven with utilizing the large scale 118-node DN shown in Fig. 11. It is composed of 118 nodes and 117 distribution segments while its real and reactive power demands are 22,709.70 kW and 17,041.10 kVAr, respectively. The ISFOA is compared with recent optimizers called harmony search (HS) [71], artificial bee colony (ABC) [72], shark smell (SS) [73], cuckoo search (CS) [13] gravitational search (GS) [74], and salp swarm method (SSM) [75]. This aims to reduce the combined energy losses and shunt compensation costs as;

$$O_f = \text{Min}\left[TK_e\text{Losses} + \sigma\left(K_c\sum_{i=1}^{N_C} Qc_i + K_i N_C\right) + K_{op} N_C\right] \tag{21}$$

where, K_e is the energy losses cost (0.06 \$/kWh); K_c is the capacitor's purchase cost (25 \$/kVAr), K_i and K_{op} is their installation and operational costs (1600 \$ and 300 \$), respectively. Losses are the total power losses. T refers to 8760 hours in the year. σ equals 10% as depreciation factor N_C is the VAR number compensation nodes (11 site) [73].

For this DN, the initial power losses are 1298.10 kW, without VAR compensation, and their annual costs are 682,281\$. The SFOA and ISFOA are run for 50 times to minimize the considered target and the best obtained capacitor allocations are staggered in Table 8. The losses are reduced to 812.5 kW with 37.41% reduction compared to the initial case.

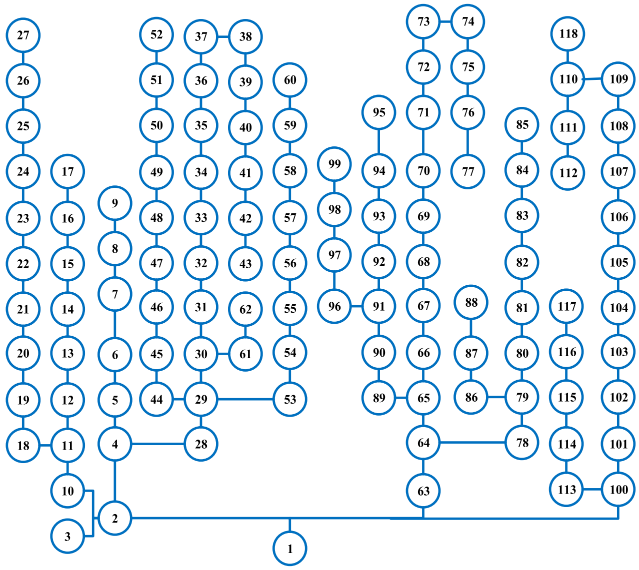


FIGURE 11. 118-node distribution system.

TABLE 8. Application of SFOA and ISFOA for the 118-node DN.

ISFOA		SFOA	
Site	Size (kVAR)	Site	Size (kVAR)
22	1050	21	1350
33	1350	34	1500
40	1350	40	1500
42	750	48	1350
48	1200	60	150
71	1200	75	1500
75	600	80	1500
81	1500	84	300
92	1200	92	1500
109	1350	108	1500
111	1200	119	1350
Power losses = 812.5 kW		Power losses = 815.3 kW	
Loss Reduction % = 37.41 %		Loss Reduction % = 37.19 %	

Table 9 shows a detailed comparison between the proposed ISFOA, SFOA and GS, ABC, CS, HS, SS and SSM in terms of the power losses, kVAR compensation, best, mean and worst values of the obtained total costs. From this table, the proposed ISFOA outperformed the other compared algorithms. It leads to the lowest power losses. Also, the acquired total costs using the proposed ISFOA is the minimum with 433706 $ as shown in Fig. 12. Furthermore, the proposed ISFOA outperforms the other competitive algorithms by attaining the lowest values in terms of the best, mean and worst cases.

This effectiveness of the proposed ISFOA compared to the other reported algorithms presents great value since the acquired total costs using the proposed ISFOA is the minimum with 433706 $ where the nearest obtained costs are 435360 $ based on the proposed SFOA as well. This means that the savings reaches to 1654 $ for just utilization of an improved version of the SFOA. Otherwise, the nearest reported results are recorded by SSM [75] of 437230 $. This means that the value of savings reaches to 3524 $ based on the proposed ISFOA.

TABLE 9. Results of competitive algorithms for 118-node DN.

Applied algorithm	kVAr Compensation	Losses (kW)	Best	Mean	Worst
GS [74]	8050	892.95	474824	480492	492323
ABC [72]	12250	862.03	459626	471689	484046
CS [13]	12050	837.37	446613	448916	450418
HS [71]	13100	833.51	444846	446165	449705
SS [73]	12900	830.15	443028	445123	445973
SSM [75]	12100	819.5	437230	-	-
SFOA	13050	813	435360	442942	457678
ISFOA	12750	812.5	433706	437973	443548

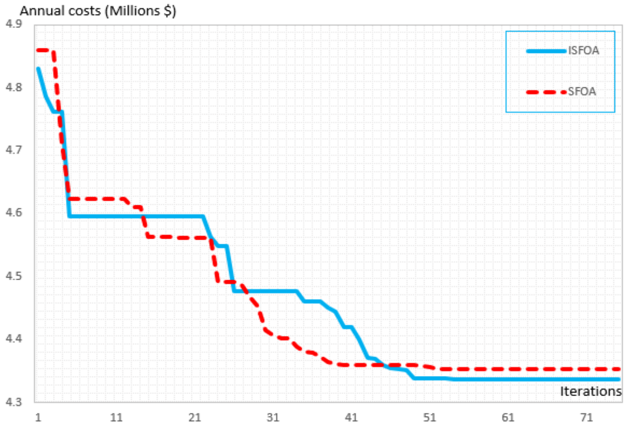


FIGURE 12. Convergence curve of SFOA and ISFOA for the 118-node DN.

V. CONCLUSION

This paper proposes an improved sunflower optimization algorithm (ISFOA) for performance enhancement of smart distribution networks. The proposed ISFOA is applied for optimal capacitor banks re-allocation on different distribution test systems. Different load conditions simulating practical daily and annual load pattern is applied. Minimization of the operational costs related to power losses and investment costs of capacitor banks is the main objective of the proposed ISFOA. The proposed allocation procedure supports the time of use tariff with different charge rates at different times of night or day. It introduces an ISFOA develops the pollination and the mortality rates in an adaptive manner to overcome the restrictions in the conventional SFOA search capability. Significant techno-economic merits are achieved as the proposed ISFOA demonstrates high competence through the applications on IEEE 33-node feeder, and 11 feeder practical 84-node system of TPC. In terms of the solution quality, the ISFOA superiority is demonstrated with best convergence rates compared with the conventional SFOA and PSO, where the power losses can be reduced with a percentage of 22.6 to 32.6% with a total operation cost saving of 20 to 24.5%. Added to that the scalability is tested for 118-node distribution systems where the outperformance of the proposed ISFOA is demonstrated over several recent techniques. The proposed ISFOA achieves the most economical solutions compared with other optimization techniques.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support received from Taif University Researchers Supporting Project Number (TURSP-2020/86), Taif University, Taif, Saudi Arabia.

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