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Optimal Control and Operation of Fully Automated Distribution Networks Using Improved Tunicate Swarm Intelligent Algorithm

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ABSTRACT Simultaneous control and operation of Capacitor Banks (CBs) and Distributed Generators (DGs) with Distribution Network Reconfiguration (DNR) is the most important modern trend for distribution systems performance enhancement. The complexity and variety of the control variables of this problem represent a challenge for distribution systems planners and operators as well as interested researchers. Optimal solution can provides quantitative as well as qualitative power service to satisfy consumers' satisfaction and reduces dissipated energy. Furthermore, performance enhancement of distribution systems is very vital where improving their performance directly affects the performance of transmission and generation systems. For solving the considered problem, an improved Tunicate Swarm Algorithm (ITSA), which imitates the swarming behaviors of the marine tunicates and their jet propulsions during its navigation and foraging procedure, is proposed. In ITSA, Lévy flight distributions are emerged in the traditional Tunicate Swarm Algorithm (TSA), which improves the diversification searching abilities of the TSA and consequently avoids the stagnation possibilities. The proposed ITSA is applied and tested for optimal DNR simultaneously with optimal control of the switched CBs and dispatchable DGs taking into account daily load variations. The ITSA is compared with other techniques on the standard 33-bus, 69-bus and the large-scale 119-bus distribution systems considering different automation scenarios of the distribution systems. The simulation results reveal that significant enhancement in distribution system performance is obtained through the application of the proposed automation process using the ITSA. ITSA can efficiently search for the optimal solutions of the problem and outperforms the other existing algorithms in the literatures.

INDEX TERMS Automated distribution systems, distributed generators, power losses, tunicate swarm algorithm, voltage stability, distribution network reconfiguration.

I. INTRODUCTION

The rising economic growth in many countries meets a great acceptance, especially the developing ones, which clearly appears in continuous increase of electric power demand [1]. Distribution networks represent the most wide spread part among generation, transmission and distribution systems, which is the final connection between high voltage transmission systems and medium/low voltage consumers. This continuous increase of electric power demand over the rates of the generation and transmission systems expansion may cause an obstacle for many electrical networks due to the restrictions imposed on the prices of electricity production. As well, various reasons have been attributed to the inability to extend electric service of the conventional distribution systems such as the aging of existing distribution networks and the dependence on single feeding source and single path of loads feeding [2], [3]. These may result in significant power losses in distribution systems, which may cost electric utilities millions of dollars per day. Not only that, but also poor service quality may cause severe damage to many modern electrical devices due to its sensitivity to voltage variations [4]. In such stressed circumstances, the distribution systems planners and operators must face such challenges and

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provide quantitative as well as qualitative power service to satisfy consumers' satisfaction and reduce dissipated energy. Analyzing the performance of distribution systems became very vital where improving their indices directly affects the performance of transmission and generation systems as well as providing luxury and consumers' satisfaction.

Performance enhancing of the distribution systems requires generally the use of additional enhancement devices and automating the existing distribution systems to maximize benefit of the existing and additional devices [5]. The use of additional enhancement devices such as capacitor banks (CBs) and distributed generators (DGs) can relive feeder overloading and enhance the system performance. Unfortunately, even with the advent of DGs and utilization of CBs in modern distribution systems, power system operators still face challenges to provide optimal operation and control of the distribution systems to meet load demand variations with reliable and qualified service. Therefore, new trends seek to automate the existing distribution systems to maximize benefits of these devices. The targeted automation process includes controlling the operation of the connected DGs and CBs as well as reconfiguration of the distribution systems to reduce system losses, improve voltage profile, relive feeders and substation loading, improve power quality and enhances system reliability [6], [7]. Distribution network reconfiguration (DNR) is the process of optimal restructuring (tying and sectionalizing) the distribution networks by altering the normally open and normally closed switches within the distribution network. Reconfiguration of distribution systems or addition of external enhancement devices in indiscriminately or inappropriate manner adversely affect the performance of distribution systems [7], [8].

CBs, DGs and DNR are not new topics in performance enhancement of distribution systems, where a lot of researchers got attracted to enhance the performance of the distribution systems by introducing different techniques. Some of these literatures handle the distribution system performance enhancement by separate utilization of CBs, DGs and DNR or combined. Also, different solution techniques were introduced such as the analytical techniques, meta-heuristic and artificial intelligent techniques. As well, single objectives and multi-objectives formulation were considered. In addition, different loading scenarios were introduced.

Optimal placement and control of CBs, DGs and DNR considering the power losses minimization, loadability improvement, voltage profile improvement, and reliability enhancement of the distribution systems either in separate manner or combined are the main target of distribution system planners, operators and researchers [9]. Various solution algorithms have been proposed in the literatures to optimally solve this problem, which can be classified into analytical, meta-heuristic and artificial intelligence techniques [10]. While the analytical techniques are simple and fast but they suffer from a lack of accuracy due to the usage of relaxation to find the optimal solution and can't be applied for multi-objectives. Meta-heuristic techniques can overcome the shortcomings of conventional analytical or heuristic methods, which guarantees that a globally optimal solution can be found [2].

Analytical techniques of DNR are usually based on distinct switching approaches such as interchange switch strategy [11]; close-all switch strategy [12]; sensitivities computation method [13]; derivative a set of linear current flows [14]. Different analytical techniques of CBs placement on distribution systems are also introduced in literatures, which are mainly based on voltage sensitivity index [15] or power losses sensitivity index [16]. As well, the allocation of DGs in distribution systems has been introduced using the analytical techniques such as; modal analysis and continuous power flow [17]; symbiotic organism search (SOS) based approach [18], loss sensitivity factor (LSF) [19], which are widely used in literatures.

To optimize the utilization of CBs, DGs and DNR, new meta-heuristic techniques have been introduced in many literatures in the last two decades. Capacitors' allocations and control have been studied using a range of meta-heuristic methods such as; plant growth algorithm [20]; evolutionary algorithm [21]; teaching learning optimization algorithm [22]; particle swarm optimization algorithm [23]; gravitational search algorithm [24]; ant-colony optimization algorithm [25]; grasshopper optimization algorithm [26]. Similarly, DGs got attention from researchers for optimal allocation. A number of meta-heuristic techniques has been introduced in literatures such as; one rank cuckoo search algorithm [27], which is formulated with multi-objectives of power loss minimization, voltage deviation minimization and voltage stability improvement; grey wolf optimizer [28]; stochastic fractal search algorithm [29]; particle swarm optimization [7]; multi-objective chaotic differential evolution [30]. As well, numerous meta-heuristic techniques have been introduced for DNR to enhance the distribution system performance such as; fireworks algorithm [31]; cuckoo search algorithm [32]; genetic algorithm with varying population [33], [34]; harmony search algorithm [6]; selective firefly algorithm [4].

Combining CBs, DGs and DNR with each other greatly improves the performance of distribution systems, but in return the number of control variables is increased, which increases the complexity of this problem. This in turn, motivated researchers to use new techniques for optimal operation and control of the distribution system devices. Optimal DNR and CBs placement is simultaneously introduced in literatures using different algorithms such as; population-based ant colony search algorithm [35]; hybrid harmony search algorithm [36]; discrete genetic algorithm [37]; improved binary particle swarm optimization method [38]; hybrid shuffled frog leaping algorithm in the fuzzy framework [39]. Similarly, optimal DNR and DGs placement is simultaneously introduced in literatures based on different algorithms such as; genetic algorithm [40]; artificial bee colony algorithm [41]; improved elitist–jaya algorithm [10]; improved sine–cosine algorithm [42]. Also, optimal CBs and DGs placement in distribution systems has been introduced in different literatures using meta-heuristic techniques such as; particle swarm optimization [7]; genetic algorithm [43], enhanced grey wolf algorithm [3].

It is rarely to find simultaneous allocation and control of CBs, DGs and DNR in literatures for its complexity and variety of control variables. Also, different literatures introduce the optimal operation of the distribution systems at peak demand only neglecting practical load variation, which sometimes conflict with practical operating conditions of distribution systems. These variety of the control variables and complexity of introducing a fully automated distribution system by optimal control of the DNR, CBs and DGs simultaneously makes an urgent need to introduce an efficient technique to solve this problem.

Recently, Tunicate Swarm Algorithm (TSA) is a bio-inspired meta-heuristic optimizer algorithm that is firstly proposed by S. Kaur *et al.* in 2020 [44]. Its inspiration and performance are effectively proven over seventy-four benchmark problems compared with several other optimization approaches. Also, it has been applied with great performance for different constrained and unconstrained engineering design problems like pressure vessel, welded beam, speed reducer, 25-bar truss, tension/ compression spring, rolled element bearing, and loaded structure displacement. This efficacy and unpretentious structure opens the research direction to employ and improve this algorithm for the considered problem. A fully automated process of the distribution system is introduced in this paper using a new proposed improved tunicate swarm algorithm (ITSA). The main contributions of the proposed technique are;

- A new proposed ITSA is introduced with an updating process of the conventional TSA which is based on information related to the best tunicate position and social interaction between the tunicates themselves, which create a very high intensification in the search space. On the other side, the diversification of the search agents requires upholding. Therefore, Lévy flight distributions (LFDs) are emerged in the traditional TSA. This emerging improves the diversification searching abilities of the TSA and consequently avoids the stagnation possibilities.
- Simultaneous allocation and control of CBs, DGs and DNR are introduced using the ITSA. This problem is considered one of the most complex planning and operation problems of distribution systems for its complexity and variety of the control variables.
- Dynamic DNR and optimal control of the switched CBs and dspatchable DGs with daily load variation are introduced using the proposed ITSA.
- Application of the proposed ITSA and comparison with conventional TSA and other previous techniques are introduced on a standard 33-bus and 69-bus distribution systems with different automation scenarios. Added to that, the scalability and flexibility of the proposed ITSA are verified on the large scale IEEE 119-bus distribution network. The obtained results prove that the proposed ITSA is reliable, scalable promising and high solution quality compared with the other methods reported in the literatures.

The rest of this paper is organized as follows: Section II describes the mathematical formulation of the considered problem. Section III describes the proposed modified improved tunicate swarm algorithm and the implementation of the proposed ITSA for simultaneous DNR with optimal control of switched CBs and dispatchable DGs. Section IV provides the results obtained by applying the proposed algorithm to fully automate the distribution system using simultaneous DNR and optimal control of CBs and DGs for different standard test systems and different case. Overall conclusion is provided in Section V.

II. PROBLEM FORMULATION

Automation of distribution systems is one of the most favorable and effective structures for improving the power service reliability and the network performance [45]. Automation systems can do immediate switching actions with suitable and optimized network reconfigurations, as proposed in this paper. These prompts automated switchings have been discussed for reducing the outage-experienced loading points with fault occurrences to support the power service reliability. In this discussed paper, the automation level has been formulated through a cost/benefit analysis to place the automatic switches in the network [46]. In addition, a fully automated network has been considered as it is always ever for power utilities where automatic switches have been considered at each branch segment. On the other side, DGs and switched CBs have not been integrated despite their great penetration in modern power systems. In this paper, DGs are considered with immediate control through a reliable communication links with the control center. Not only that but switched CBs are also included to control its operating steps with installed automatic step-switches. The automatic switches and the communications are parts of two major requirements for advanced distribution automation [47], where the electrical system and the communication architectures must be developed together to handle an automated distribution network.

Usually the main target of the distribution systems operators and planners is to fulfill the customer requirements and achieve efficient operation to these systems. Therefore, the objective function (OF) is mainly to minimizes the overall power losses through the distribution network while satisfying the related equality and inequality constraints. This is mathematically expressed as follows:

$$\mathrm{OF} = \mathrm{Min}\left\{\sum_{\mathrm{br}=1}^{\mathrm{N_{br}}} \mathrm{Ploss_{br}}\right\} \tag{1}$$

where, $\mathrm{N_{br}}$ is the total number of system branches.

This formulation searches for the optimal DNR of the open lines for re-configuration purpose and the optimal allocation and control of the CBs and DGs with different loading conditions. The locations of the CBs and DGs should be fixed whatever the loading is varied. On contrary, the CBs and DGs outputs can be optimally dispatched for maximizing their allocation benefits. Thus, the vector of the control variables (CV) is as follows:-

$$CV = \{[\underbrace{O_{T_1}, O_{T2}, \ldots\ldots, O_{T_{No}}}_{\text{Open Tie branches}}];\ [\underbrace{Qsw_1, Qsw_2, \ldots\ldots, Qsw_{N_C}}_{\text{Operating step of switched capacitors}}];\ [\underbrace{Pg_1, Pg_2, \ldots\ldots, Pg_{N_{dg}}}_{\text{Output power of DGs}}]\} \quad (2)$$

where, O_T is the tie branches to be open; No indicates the number of branches that must be opened to keep radial structure of the distribution systems; Qsw is the reactive output reactive power from switched CBs; N_C is the number of the existed switched CBs; Pg is the DG dispatchable output power; N_{dg} is the number of the existed DGs.

Solving the objective function must maintain the equality and inequality operation constraints to keep system reliability and service quality, which are formulated as follow:

$$1 \le O_{Tj} \le No, \quad j = 1, 2, \ldots\ldots No \quad (3)$$

$$Qsw^{min} \le Qsw_j \le Qsw^{max}, \quad j = 1, 2, \ldots\ldots N_C \quad (4)$$

$$Pg^{min} \le Pg_j \le Pg^{max}, \quad j = 1, 2, \ldots\ldots N_{dg} \quad (5)$$

$$V_n^{min} \le V_n \le V_n^{max}, \quad n = 1, 2, \ldots\ldots N_b \quad (6)$$

$$|I_{br}| \le I_{br}^{max}, \quad br = 1, 2, \ldots\ldots N_{br} \quad (7)$$

$$\sum_{j=1}^{N_C} Qsw_j \le PR_Q \sum_{n=1}^{N_b} (Qd_n) \quad (8)$$

$$\sum_{j=1}^{N_{dg}} Pg_j \le PR_G \sum_{n=1}^{N_b} (Pd_n) \quad (9)$$

$$\left(QG_{Sub} + \sum_{j=1}^{N_C} Qsw_j\right)_{Lc} > \sum_{n=1}^{N_b} (Qd_n)_{Lc}, \quad Lc = 1, 2, \ldots\ldots N_{Lc} \quad (10)$$

$$\left(PG_{Sub} + \sum_{j=1}^{N_{dg}} Pg_j\right)_{Lc} > \sum_{n=1}^{N_b} (Pd_n)_{Lc}, \quad Lc = 1, 2, \ldots\ldots N_{Lc} \quad (11)$$

where, Qsw^{min} and Qsw^{max} are, respectively, the minimum and the maximum output reactive power from switched CBs; Pg^{min} andPg^{max} are the minimum and maximum output active power from DGs, respectively; V indicates the voltage magnitude; I_{br} and I_{br}^{max} refer to the current flow of the branches and their maximum limit; Qd and Pd refer to the reactive and active load demand; PR_Q and PR_G are the acceptable penetration level of the CBs and DGs, respectively; N_b is the number of the system buses; QG_{sub} and PG_{sub} are the reactive and active power that supplied from the substation, respectively; N_{LC} is the number of selected load conditions; the subscripts "min" and "max" refers to the minimum and maximum of each corresponding variable.

Equations (3-5) bound the control variables of the open tie branches and control variables of CBs and DGs. Equations (6 and 7) represents the inequality limits of the voltage quality at each loading condition and the safe ampere loading of each branch. Equations (8 and 9) ensure that the output power from the CBs and DGs at any loading condition should not exceed the acceptable penetration level which is specified as 60% of the system loading [48]. Equations (10 and 11) assure powering all the loads in the network as the supplied power from the substations and the CBs and DGs must be more than the loads bulk.

In addition, the active and reactive balance equations should be maintained at each load condition as follow:

$$PG_{Sub} + \sum_{i=1}^{N_{dg}} Pg_i - \sum_{br=1}^{N_{br}} Ploss_{br} = \sum_{j=1}^{N_b} Pd_j \quad (12)$$

$$QG_{Sub} + \sum_{i=1}^{N_C} Qsw_i - \sum_{br=1}^{N_{br}} Qloss_{br} = \sum_{j=1}^{N_b} Qd_j \quad (13)$$

Furthermore, the radial topology of the network should be kept for operation by forming a branch-bus incidence matrix as follows [49], [50]:

$$A_{ij} = \begin{cases} 0, & \text{if line i isn't connected to bus j} \\ -1, & \text{if the line i enter to bus j} \\ 1, & \text{if the line i exits from bus j} \end{cases} \quad (14)$$

The voltage deviation index (VD) and the overall voltage stability index (OVSI) expressed by (15) and (16) are used to analyze the distribution system performance.

$$VD = \sum_{n=1}^{N_b} (1 - V_n) \quad (15)$$

$$OVSI = \sum_{n=1}^{Nb} VSI_n \quad (16)$$

where, VSI_n is the voltage stability index at bus (n). This index is varied from zero at voltage collapse point to unity at no load, which can be easily calculated as in (17).

$$VSI_n = V_{n\text{-}1}^4 - 4(P_{n,eff}X_{n\text{-}1}\text{-}Q_{n,eff}R_{n\text{-}1})^2 - 4(P_{n,eff}X_{n\text{-}1}\text{-}Q_{n,eff}R_{n\text{-}1})V_{n\text{-}1}^2, \quad n = 2, \ldots N_n \quad (17)$$

III. IMPROVED TUNICATE SWARM ALGORITHM

In this section the new improved tunicate swarm algorithm is introduced for optimal allocation and control of the CBs and DGs with optimal DNR considering practical load variations.

A. TUNICATE SWARM ALGORITHM (TSA)

The standard tunicate swarm algorithm is very simple bio-inspired meta-heuristic optimization algorithm that was firstly proposed by S. Kaur *et al.* in 2020 [44]. Its inspiration and performance were effectively proven over seventy-four benchmark problems compared with several other optimization approaches. Its efficacy and unpretentious structure draw the attention to employ and improve this algorithm for the considered problem. Mainly, TSA imitates the swarming behaviors of the marine tunicates and their jet propulsions during its navigation and foraging procedure. In TSA, a population of tunicates (PT) is swarming in order to search for the best source of food (SF) which represents the fitness function. In this swarming, the tunicates updating their positions related to the first best tunicates that are stored and upgraded in each iteration. The TSA begins where the tunicates population is initialized randomly considering the permissible bounds of the control variables. The dimension of the control variables composes each tunicate (T) that can be initially created as:

$$\mathrm{T_n(m) = T_n^{min} + r.(T_n^{max} - T_n^{min}) \quad \forall m \in PT_{size}\ \&\ n \in Dim} \tag{18}$$

where, T(m) is the position of each tunicate (m); n refers to each control variable; r is a random number within range [0,1]; $\mathrm{PT_{size}}$ is the number of the tunicates in the population; Dim is the dimension of the control variables.

The update process of the tunicates position is executed through the following formula:

$$\mathrm{T_n(m) = \frac{T_n{}^{*}(m) + T_n(m-1)}{2 + c_1} \quad \forall m \in PT_{size}\ \&\ n \in Dim} \tag{19}$$

where, T* refers to the updated position of the $\mathrm{m^{th}}$ tunicate based on (20); T(m-1) refers to the neighbor tunicate; $\mathrm{c_1}$ is a random number within range [0,1].

$$\mathrm{T_n^{*}(m) = \begin{cases} SF + A.\,|SF - rand.T_n(m)| & \text{if rand} \geq 0.5 \\ SF - A.\,|SF - rand.T_n(m)| & \text{if rand} < 0.5 \end{cases}} \tag{20}$$

where, SF is the source of food which is represented by the best tunicate position in the whole population; A is a randomized vector to avoid any conflicts between tunicates and each other's which is modelled as:

$$\mathrm{A = \frac{c_2 + c_3 - 2c_1}{VT_{min} + c_1(VT_{max}\text{-}VT_{min})}} \tag{21}$$

where, $\mathrm{c_1}$, $\mathrm{c_2}$ and $\mathrm{c_3}$ are random numbers within range [0,1]; $\mathrm{VT_{min}}$ and $\mathrm{VT_{max}}$ represent the premier and subordinate speeds to produce social interaction.

B. IMPROVED TUNICATE SWARM ALGORITHM (ITSA)

In conventional TSA, the new positions of the tunicates are updated via (19) based on information related to the best tunicate position and social interaction between the tunicates themselves. This creates very high intensification in the search space. On the other side, the diversification of the search agents requires upholding. Therefore, an improved version is introduced by emerging Lévy flight distributions (LFDs) in the TSA. This emerging improves the diversification searching abilities of the TSA and consequently avoids the stagnation possibilities. LFDs are emerged with keeping the simple TSA structure and same computational burden where each tunicate in each iteration may take the same updating process or take the LFDs [51]. To do so, the updating mechanism in (20) is replaced by (22):

$$\mathrm{T_n^{*}(m) = \begin{cases} T_n(m) + \sigma \oplus Levy(\beta) & \text{if I/MaxIt} < \text{rand} \\ SF + A.\,|SF + rand.T_n(m)| & \\ \quad \text{if I/MaxIt} > \text{rand \& rand} \geq 0.5 & \\ SF - A.\,|SF - rand.T_n(m)| & \\ \quad \text{if I/MaxIt} > \text{rand \& rand} < 0.5 & \end{cases}} \tag{22}$$

where, I refers to the current iteration; MaxIt is the maximum number of iterations; σ is the step size; $\oplus$ refers to the entry wise multiplication and β is the LFD coefficient. The second term in the first part in (22) represents the randomized Lévy flights to randomly generate new positions of the tunicates based on random walk. This term can be calculated as follows:

$$\sigma \oplus \mathrm{Levy}(\beta) \approx 0.01 \frac{u}{|v|^{1/\beta}} (T(m) - SF) \tag{23}$$

where, u and ν are normally distributed random number.

Fig. 1 shows a flowchart of the proposed ITSA. The steps can be summarized as follow:

Step 1: Initialize the tunicate population using (18).
Step 2: Specify $\mathrm{VT_{min}}$ and $\mathrm{VT_{max}}$ parameters ($\mathrm{VT_{min} = 1}$; $\mathrm{VT_{max} = 4}$ [47]), and MaxIt.
Step 3: Calculate the fitness function related to each tunicate position.
Step 4: Exclude the tunicate position with the best fitness as a source of food (SF).
Step 5: Update the positions of the tunicates using (22).
Step 6: Remedy any violated control variable by selecting the nearest limit
Step 7: Compute the fitness function related to each new position search and update the tunicate position if it has fitness.
Step 8: Increase the iteration step by one and if it is not equal to MaxIt, repeat the Steps 5–8.
Step 9: Output the optimal solution that is obtained so far.

IV. RESULTS AND DISCUSSION

In this section the new ITSA is introduced for optimal allocation and control of CBs and DGs with optimal DNR considering practical load variations. The proposed ITSA and classical TSA are applied, tested and compared on three standard test systems. The first test system is the 33-bus radial distribution system with 33-bus, 12.66-kV rated and total demand of 3.715 MW and 2.3 MVAr [26]. The second test system is the 69-bus power system with a total load of 3.802 MW and 2.694 MVAr [26]. The third system is the large-scale standard IEEE 11kV, 119-bus radial distribution system with 118 branches. The total load of the system is 22.71 MW and 17.04 MVAr [43].

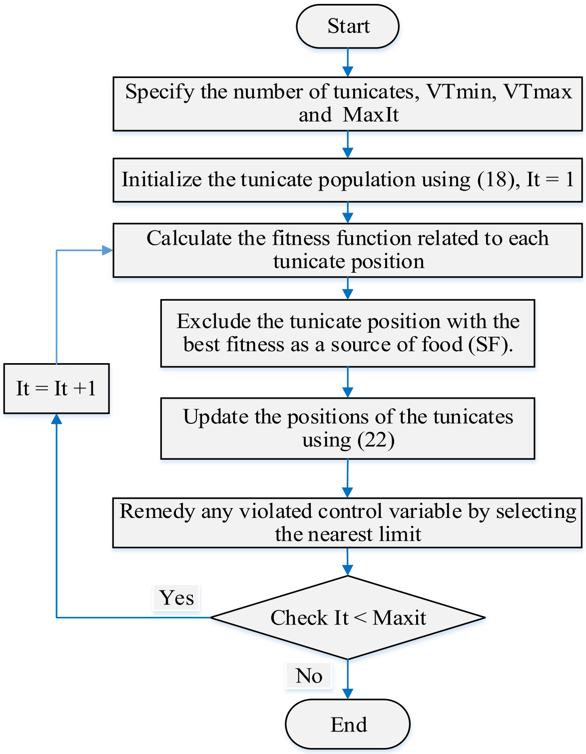

FIGURE 1. A flowchart of the Improved Tunicate Swarm Algorithm.

Four cases are considered in this paper for optimal allocation and control of the CBs, DGs and DNR, which simulate the different scenarios of automation process:

- ***Case 1:*** Optimal allocation of the CBs and DGs at peak load demand and initial system configuration.
- ***Case 2:*** Optimal DNR with optimal control of the CBs and DGs at continuous load variations.
- ***Case 3:*** Optimal DNR with optimal control of the CBs and DGs at discreet load representation.
- ***Case 4:*** Comparative study of the proposed ITSA and other techniques.

The used CBs and DGs should have a fixed location and fixed rated power, therefore the objective of ***Case 1*** is to optimally determine the locations and sizes of the CBs and DGs. The rated power and location of the CBs and DGs are determined at peak load demand using the proposed ITSA with losses minimization objective function. Also, in this case, the system performance with the optimized CBs and DGs is evaluated.

With continuous load variations, the CBs, DGs and system topology should be optimized to achieve operation of the distribution system. ***Case 2*** introduces an optimal determination of DNR with optimal control of the previously allocated switched CBs and connected dispatchable DGs. The daily load variation is considered in this case, to simulate the dynamic operation of automated distribution system.

Case 3 introduces optimal DNR with optimal control of the switched CBs and connected DGs at discrete load levels. Four loading levels are considered which can be applied to reduce the switching number of the automated devices.

Case 4 introduces a comparison between the results obtained by the proposed ITSA and classical TSA as well as other various efficient optimizers. The objective of this case is to evaluate the effectiveness, scalability and flexibility of the proposed ITSA in terms of computation time, convergence characteristics, statistical analysis, optimal solution achievement and stuck behavior.

The parameters of ITSA are: Maxit=100, m =20, number of runs=10 for each case. 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. OPTIMAL ALLOCATION OF THE CBs AND DGs AT PEAK LOAD DEMAND AND INITIAL SYSTEM CONFIGURATION (CASE 1)

The overall system performance and control procedure is affected by sites and sizes selection of the DGs and switched CBs. The main merit of the considered Case 1 is to handle this important issue. In this case, the rated power and location of the CBs and DGs are optimally determined based on the proposed ITSA considering the peak load demand with losses minimization objective function. Also, in this case, the system performance with the optimized CBs and DGs is evaluated. This case represents the base case of automated distribution systems where the benefits of the automation process in their operating points and DNR application will be discussed in the other cases. With continuous load variations, the CBs, DGs and system topology should be optimized to achieve optimal operation of the distribution system.

As stated earlier, the used CBs and DGs in distribution systems should have a fixed location and fixed rated power, which normally determined at peak load demand. Controlled capability of the switched CBs and dispatchable DGs allows the distribution system operators to control their operation with load variations. The proposed ITSA is applied on the 33-bus and 69-bus test systems and the obtained optimal locations and sizes of CBs and DGs are given in Figs. 2 and 3, respectively. The CBs and DGs sizes are discretized to the nearest suitable size.

1) 33-BUS TEST SYSTEM

Applying the proposed ITSA on the 33-bus test system for optimal allocation of the CBs and DGs, the optimal allocation of the CBs on the 33-bus test systems are 300, 900 and 1200 kVAr at busses 14, 19 and 30, respectively, while the optimal allocation of the DGs are 600, 500 and 1200 kW at busses 25, 27 and 33, respectively, as shown in Fig. 2. The total power losses is reduced from 202.66 kW, for initial system, to 41.9452kW after optimal placement of the CBs and DGs with a percentage reduction of 79.3 %. The minimum recorded voltage is increased from 0.9105 p.u at base case to 0.963 p.u after optimal allocation of the CBs and DGs.

In this case, the rated power and location of the CBs and DGs are optimally determined based on the proposed ITSA

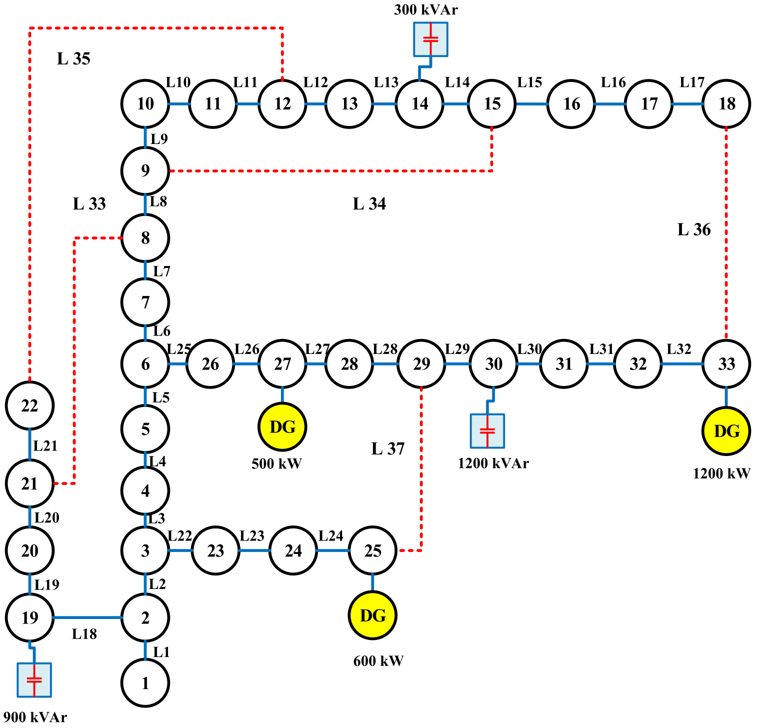

FIGURE 2. Optimal locations and sizes of CBs and DGs on the IEEE 33-bus test system.

considering the peak load demand with losses minimization objective function. While the maximum limits of the rated power of the CBs and DGs are considered 3 MVAR and 3MW, respectively. The proposed ITSA gets the optimal CBs locations and sizes simultaneously with optimal DGs allocations as mentioned earlier. However adding more DGs and CBs may be known to boost the system performance, its higher penetration may cause negative effects [52]. The obtained results based on the proposed ITSA illustrate this issue as the selected CBs and DGs sizes are optimally selected at far less than the maximum permissible limits.

2) 69-BUS TEST SYSTEM

Fig. 3 shows the optimal ratting and locations of the CBs and DGs on the 69-bus test system using the proposed ITSA. The obtained optimal allocation of the CBs, in this case are 3000, 900 and 1500 kVAr and are connected at buses 36, 45 and 60, respectively. The optimal DGs are 500, 1200 and 600 kW at busses 13, 60 and 63, respectively. After optimal allocation of CBs and DGs, the total power loss is reduced from 224.9 kW to 28.087 kW with a percentage reduction 87.51 %. The minimum voltage is increased from 0.9092 to 0.9848 p.u.

B. OPTIMAL DNR WITH OPTIMAL CONTROL OF THE CBs AND DGs AT CONTINUES LOAD VARIATIONS. (CASE 2)

In this case, the optimal DNR is introduced simultaneously with optimal control of the switched CBs and controlling the dispatchable DGs using the conventional TSA and the proposed ITSA with continuous load variations. The optimal operation of distribution systems with continuous load variations represents the worst case for the distribution control center because all control variables of tie lines status, output of CBs and DGs have to be optimized while maintaining all system constraints. Fig. 4 shows the solution procedure for simultaneous DNR with the CBs and DGs allocations. As shown, the proposed ITSA generates the control variables which can be divided into two parts. The first part represents the open tie branches while the second part gives the outputs of DGs and CBs as in (2). After that, the first part of the open tie branches is educed and the matrix of branch-bus incidence is composed to evaluate the determinant of A as given in (14). The radial topology is checked, where the network is radial if the determinant of A is equal to 1 or −1. Else, the network is not radial or islanded. Then the load flow is carried out for the radial condition and the fitness function (1) is evaluated. If the system is not radial, the fitness function is set at infinity.

Fig. 5 shows the assumed daily load profile considered in this case. At each hour, the proposed technique is applied to optimally reconfigure the distribution system and specify the optimal outputs of the CBs and DGs.

1) 33-BUS TEST SYSTEM

The proposed ITSA and conventional TSA are applied for optimal DNR of the 33-bus test system with optimal switching of the CBs and optimal dispatching of the DGs. Each technique is applied for 10 runs, at each hour, and recording

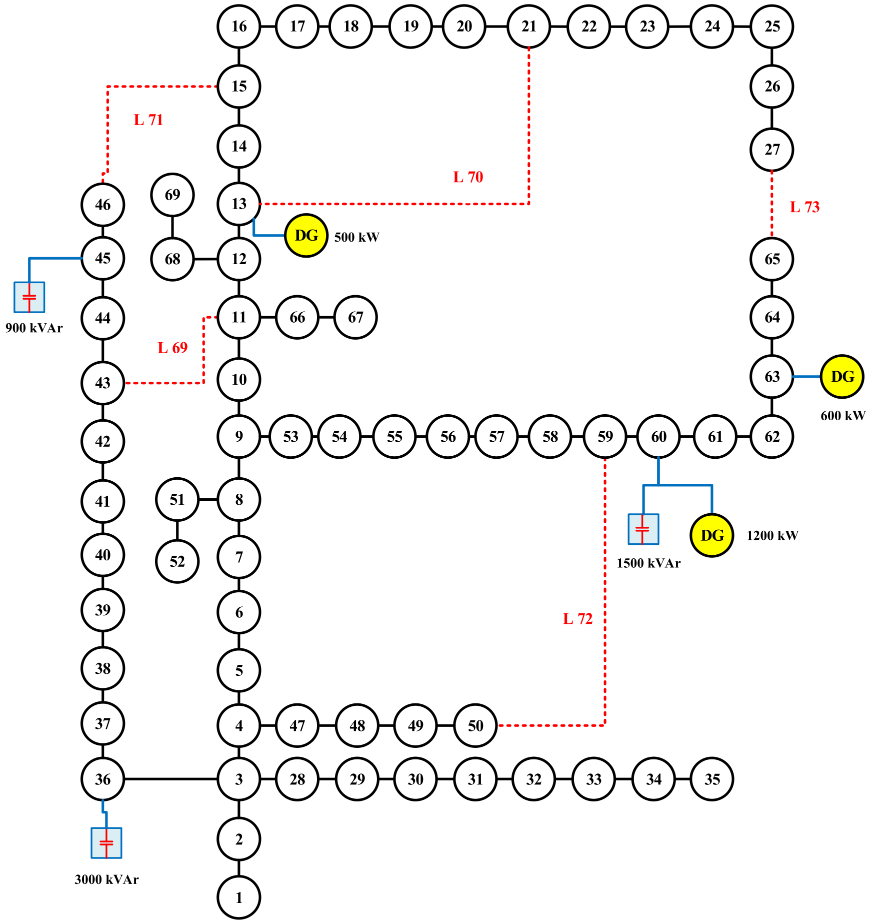

FIGURE 3. Optimal locations and sizes of CBs and DGs on the IEEE 69-bus test system.

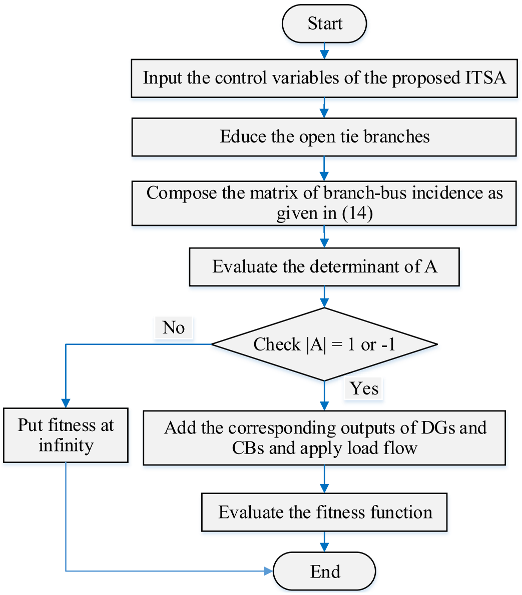

FIGURE 4. Solution procedure of DNR with CBs and DGs allocations.

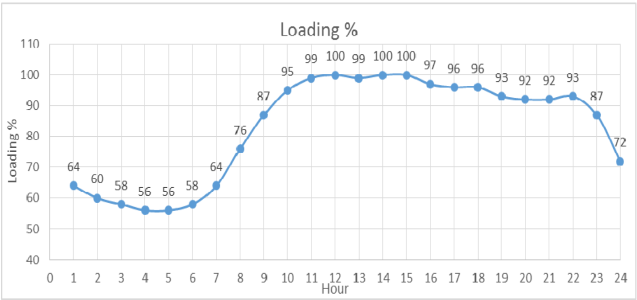

FIGURE 5. Percentage daily loading [53].

the best, average and worst solution. Fig. 6 shows the best, average and worst objective function at every hour for optimal reconfiguration control of the 33-bus test system using the TSA and ITSA. It is clear from this figure that the modification applied to the conventional TSA enhances the controllability and exploration of the ITSA for achieving optimal solution. This clearly appeared in Fig. 7, which shows the standard deviation of the TSA and ITSA every hour for optimal reconfiguration and control of the 33-bus test system. Table 1 shows the robustness indices of the proposed ITSA as compared with conventional TSA via the average objective, standard deviation and standard error. As shown, the proposed ITSA finds successfully lower average fitness for each loading hour. Also, their acquired standard deviation

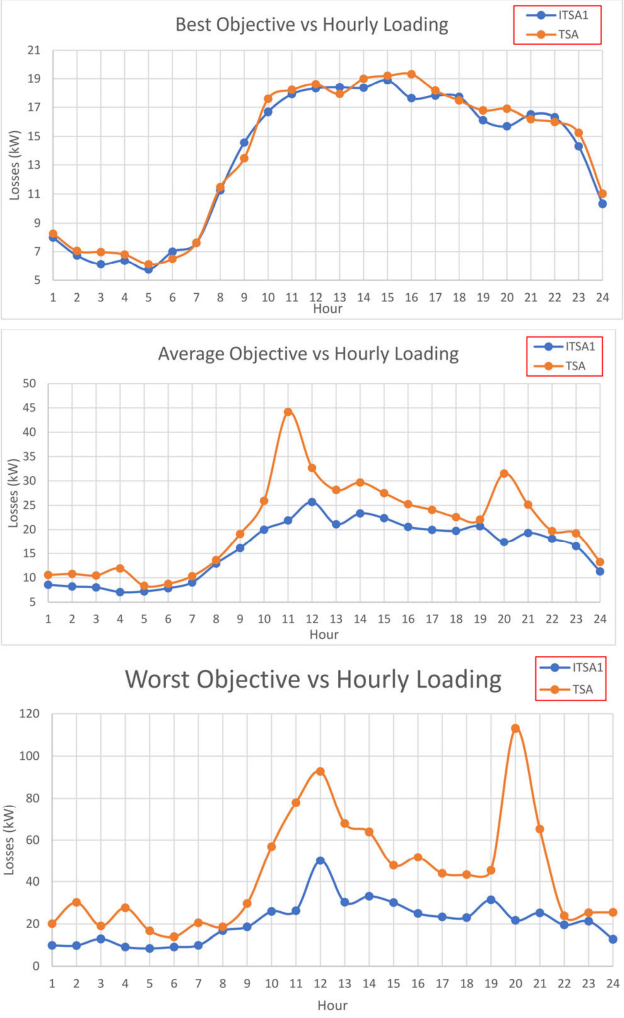

FIGURE 6. Objective function at each hour for optimal reconfiguration and control of the 33-bus test system using the TSA and ITSA.

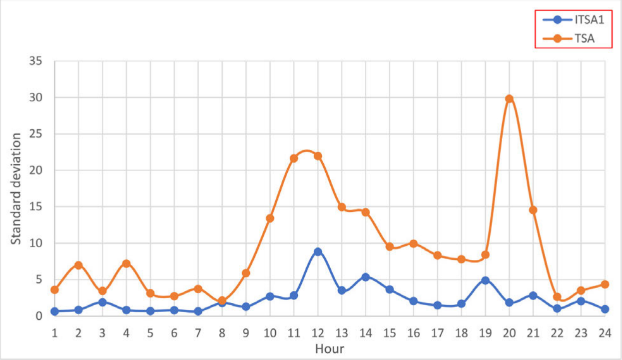

FIGURE 7. Standard deviation of the TSA and ITSA at each hour for optimal reconfiguration and control of the 33-bus test system.

TABLE 1. Statistical analysis of the TSA and ITSA for optimal DNR with optimal control of the CBs and DGs on the 33-bus test system.

	Mean		Standard deviation		Standard Error	
Hour	TSA	ITSA	TSA	ITSA	TSA	ITSA
1	10.5596	8.5624	3.6046	0.6478	1.1399	0.2049
2	10.783	8.1869	6.9505	0.8611	2.1979	0.2723
3	10.4739	8.0027	3.4521	1.9018	1.0916	0.6014
4	11.9043	7.0489	7.1968	0.8369	2.2758	0.2647
5	8.3543	7.1777	3.1311	0.6897	0.9901	0.2181
6	8.7467	7.8436	2.7282	0.8053	0.8627	0.2547
7	10.3259	9.0356	3.7228	0.67	1.1773	0.2119
8	13.6288	12.9237	2.1336	1.7943	0.6747	0.5674
9	19.0937	16.1127	5.9016	1.301	1.8662	0.4114
10	25.9367	19.9942	13.4293	2.6911	4.2467	0.851
11	44.1573	21.8852	21.6293	2.8292	6.8398	0.8947
12	32.6846	25.6808	21.9583	8.8207	6.9438	2.7894
13	28.1507	21.1179	14.9605	3.5357	4.7309	1.1181
14	29.6693	23.3213	14.2321	5.345	4.5006	1.6902
15	27.5305	22.3674	9.5429	3.6509	3.0177	1.1545
16	25.2321	20.5707	9.9165	2.065	3.1359	0.653
17	24.0637	19.9627	8.3351	1.4893	2.6358	0.471
18	22.5799	19.7417	7.7968	1.6938	2.4656	0.5356
19	22.0662	20.6951	8.4214	4.8778	2.6631	1.5425
20	31.5224	17.3934	29.8101	1.8797	9.4268	0.5944
21	25.1553	19.2971	14.5432	2.8012	4.599	0.8858
22	19.7037	18.077	2.6407	1.0606	0.8351	0.3354
23	19.2304	16.5311	3.4994	2.0371	1.1066	0.6442
24	13.2476	11.2875	4.3534	0.9458	1.3767	0.2991
Average			**9.3288**	**2.3013**	**2.9500**	**0.7277**

and error are greatly smaller than the related value of the conventional TSA for each loading hour. The average index of the standard deviation using the proposed ITSA is 2.03 compared to 9.33 for the TSA. Similarly, the average index of the standard error using the proposed ITSA is 0.727 compared to 2.95 for the TSA.

Optimal switching of the connected CBs during daily hours is shown in Fig. 8 using the proposed ITSA, where the capacitor is stepped by 300 kVAr/step. Fig. 9 shows the hourly optimal dispatching of the connected DGs. Table 2 shows the hourly optimal tie switching for optimal reconfiguration of the 33-bus test system. Also, in this table the total power loss at each hour is given, as well as different voltage indices. The results obtained in Table 2 are with optimal control of the CBs and DGs given in Figs. 8 and 9, respectively. The daily power losses, in this case, is found to be 324.277 kW/day using the ITSA and 331.811 kW/day using the TSA, while the system losses with the same loading conditions and without CBs, DGs and DNR is 985.915 kW/day. This means that, the power losses can be reduced to be 32.89% of the initial system losses applying the proposed ITSA and 33.65% using the conventional TSA. Also, it is noted that the power losses for all loading hours are greatly reduced. The maximum reduction percentage of 88.247 % is achieved at hour 5 while the minimum reduction percentage of 54.8803 % is achieved at hour 17.

The voltages at system buses change between the minimum and the maximum recorded voltages of 0.9830 p.u at hour 8 and 1.0077 p.u at hour 24, respectively, which indicates the extent improvement of system voltage performance as shown in Fig. 10. What confirms this is that, the average value of the voltage stability index (VSI) at each bus is about 0.8504, which comes close to optimum VSI values. Fig. 11 shows the voltage profile at peak load (hr = 12) of the 33-bus test system after optimal setting and control of DNR, CBs, DGs using the ITSA. This figure declares the increasing

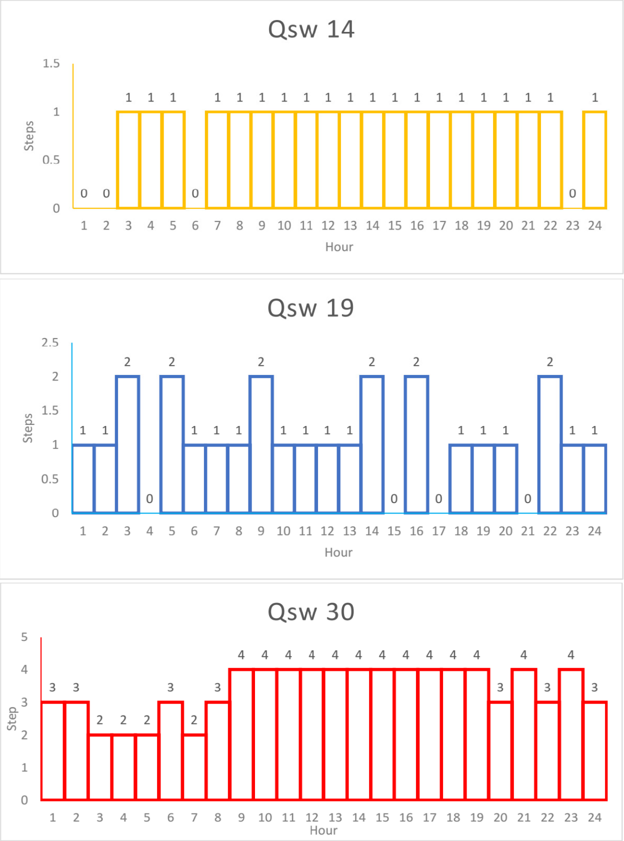

FIGURE 8. Optimal switching at each hour of the connected CBs to the 33-bus test system using the ITSA.

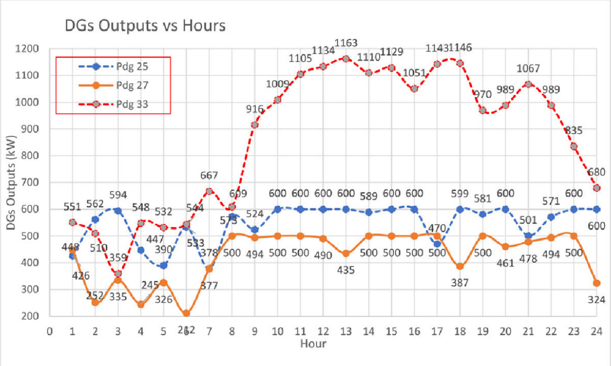

FIGURE 9. Optimal dispatching at each hour of the connected DGs to the 33-bus test system using the ITSA.

of minimum voltages at peak loading condition where the minimum voltage of 0.96 at bus 18 is increased to 1 p.u.

The convergence characteristic, shown in Fig. 12, indicates the effectiveness of the introduced ITSA for achieving optimal solutions as compare with conventional TSA. Fig. 13 shows a comparison between the conventional TSA and ITSA for each successive four hours for 33-bus system. As shown, however TSA is usually converged to an optimal solution faster than ITSA but the proposed ITSA always

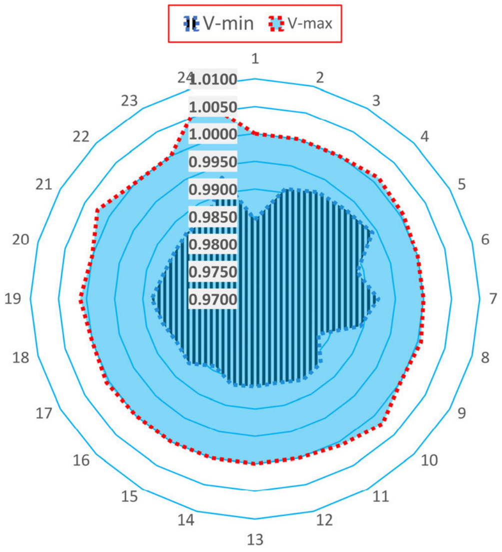

FIGURE 10. Minimum and maximum voltage at each hour of the 33-bus test system after optimal setting and control of DNR, CBs, DGs using the ITSA.

achieve a better solution. The TSA convergence rates in these figures demonstrate its stuck behavior for approximately 50 iterations. On the other side, these figures illustrate the ITSA capability of development and improving the solution quality through the iterations while premature convergence of the TSA is declared.

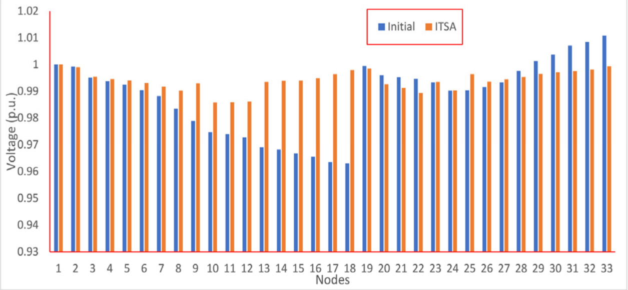

FIGURE 11. Voltage profile at peak load of the 33-bus test system after optimal setting and control of DNR, CBs, DGs using the ITSA.

2) 69-BUS TEST SYSTEM

Similarly, the proposed ITSA and conventional TSA are applied for optimal DNR of the 69-bus test system simultaneously with optimal control of the CBs and DGs for losses minimization. Also, each technique is applied hourly for 10 runs, and the best, the average and the worst solution at each hour are recorded. Fig. 14 shows the calculated standard deviation of the TSA and ITSA at each loading hour for optimal reconfiguration and control of the 69-bus test system. The results clearly confirm the consistency and stability of the proposed ITSA for achieving the objective function. Fig. 15 shows the convergence characteristic of the ITSA and TSA for the optimal setting and control of DNR, CBs and DGs on

TABLE 2. Optimal operation and control of the 33-bus test system with continuous load variations using the proposed ITSA.

Hour	Optimal tie lines					Power losses (kW)	V.D	O.V.S.I	Min voltage (@bus)	Max voltage (@bus)
1	5	11	13	24	34	7.97179	0.28630	27.04967	0.9844 (14)	1.00000 (1)
2	10	13	27	33	34	6.73106	0.17224	28.39921	0.9907 (10)	1.00000 (1)
3	10	12	28	31	33	6.11070	0.16282	28.43255	0.9924 (10)	1.00000 (1)
4	7	8	11	24	27	6.36372	0.09174	27.69788	0.9929 (8)	1.00109 (25)
5	10	12	24	27	33	5.73773	0.07558	27.73583	0.9942 (11)	1.00051 (33)
6	7	8	9	12	28	6.99107	0.17501	28.43553	0.9888 (13)	1.00000 (1)
7	11	13	24	28	33	7.60382	0.16397	28.42088	0.9920 (13)	1.00000 (1)
8	11	13	24	33	34	11.25178	0.13550	28.50804	0.9894 (11)	1.00058 (14)
9	5	8	12	24	33	14.55031	0.29947	27.01229	0.9830 (8)	1.00000 (1)
10	9	12	24	33	34	16.67911	0.15185	28.49587	0.9866 (10)	1.00209 (33)
11	10	12	24	33	34	17.91710	0.17699	28.37623	0.9870 (10)	1.00071 (33)
12	8	9	12	24	33	18.32480	0.19678	27.34594	0.9858 (10)	1.00000 (1)
13	8	9	12	27	33	18.39530	0.23929	27.21016	0.9859 (10)	1.00000 (1)
14	8	9	12	24	33	18.36625	0.20991	27.30468	0.9862 (10)	1.00000 (1)
15	10	12	28	33	34	18.87815	0.23184	29.15423	0.9842 (10)	1.00000 (1)
16	8	9	12	28	33	17.63056	0.23370	28.20355	0.9866 (10)	1.00000 (1)
17	8	9	12	24	33	17.80735	0.17843	27.40786	0.9860 (10)	1.00051 (33)
18	8	10	12	27	33	17.72641	0.24471	27.19686	0.9871 (10)	1.00000 (1)
19	10	12	24	33	34	16.11328	0.15234	28.46556	0.9884 (10)	1.00114 (33)
20	9	12	28	33	34	15.69933	0.24960	29.09769	0.9869 (10)	1.00000 (1)
21	8	9	12	24	33	16.50283	0.14545	27.54445	0.9866 (10)	1.00239 (33)
22	9	12	28	33	34	16.30527	0.26131	29.05614	0.9871 (10)	1.00000 (1)
23	10	13	24	33	34	14.29310	0.22869	28.20741	0.9869 (13)	1.00000 (1)
24	10	24	27	33	35	10.32344	0.14834	28.76207	0.9928 (24)	1.00768 (25)

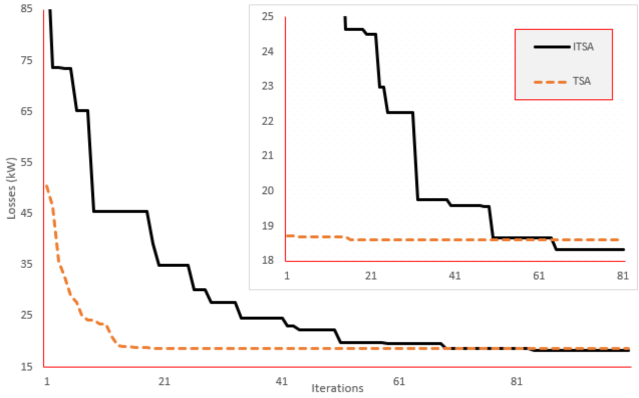

FIGURE 12. Convergence characteristics of conventional TSA and ITSA for optimal setting and control of DNR, CBs, DGs on the 33-bus test system at peak load demand.

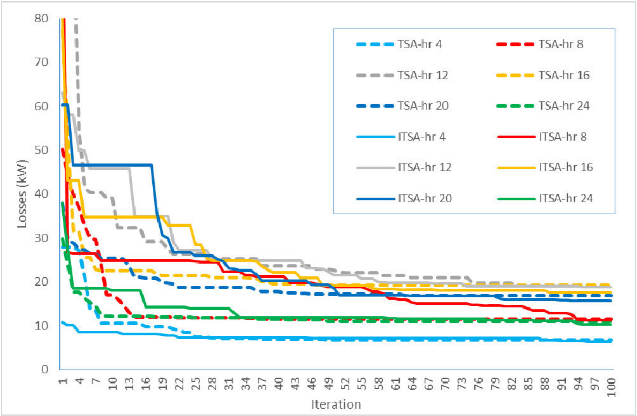

FIGURE 13. Convergence Comparisons between TSA and ITSA for each successive four hours of the 33-bus system.

the 69-bus test system at peak load demand. Table 3 shows the robustness indices of the proposed ITSA as compared with TSA via the average objective, standard deviation and standard error. The proposed ITSA always find successfully lower average fitness, standard deviation, and error for each loading hour. The average index of the standard deviation using the proposed ITSA is 1.21 while the corresponding index is 6.205 for the TSA. Similarly, the average index of the standard error using the proposed ITSA is 0.383 while the corresponding index is 1.96 for the TSA. These results show that the proposed ITSA is more robust than the TSA.

Optimal switching of the connected CBs during daily hours is shown in Fig. 16 using the proposed ITSA. Fig. 17 shows the hourly optimal dispatching of the connected DGs. Table 4 shows the hourly optimal tie switching for optimal reconfiguration of the 69-bus test system at each hour. Also, in this table the system power loses at each hour are given, as well as voltage deviations compared to 1 p.u, overall voltage stability index, minimum and maximum hourly recorded voltage. Voltage profile at peak load of the 69-bus test system after optimal setting and control of DNR, CBs and DGs using the ITSA is introduced in Fig. 18. From the obtained results, it is found that, the power losses for all loading levels are greatly reduced applying the proposed technique. The maximum reduction percentage of 92.5088 % is achieved at hour 5 while the minimum reduction percentage of 50.2683 % is achieved at hour 11. The proposed technique can reduces daily power losses from 843.056 kW/day with CBs and DGs

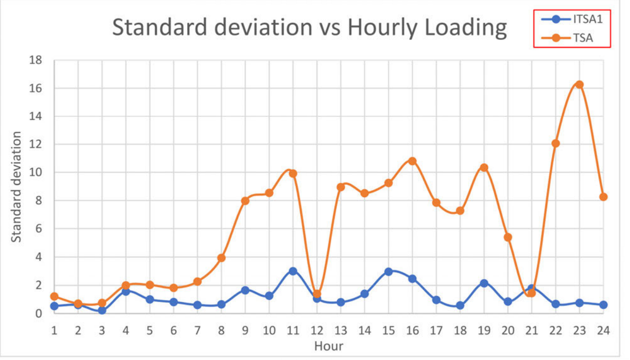

FIGURE 14. Standard deviation of the TSA and ITSA at each hour for optimal reconfiguration and control of the 69-bus test system.

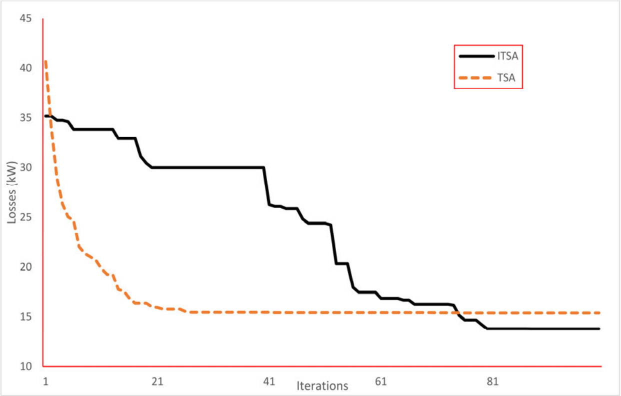

FIGURE 15. Convergence characteristics of conventional TSA and ITSA for optimal setting and control of DNR, CBs, DGs on the 69-bus test system at peak load demand.

allocations shown in Fig. 3 (without automated control of their outputs and without DNR control) to 239.113 kW/day using TSA and 236.722 kW/day using ITSA. The obtained results by the proposed technique improve the system voltage performance for all the loading hours where the minimum voltage of 0.9889 p.u at bus 27 is acquired at hour 11 while their maximum of 1.003 p.u at bus 60 is acquired at hour 17. The voltage at all system buses change between these recorded minimum and maximum values. As shown, in Fig. 18, the minimum voltage of 0.985 at bus 27 is increased to 1 p.u while the maximum voltage of 1.01 at bus 45 is decreased to approximately 1 p.u. this figure declares the great capability of the proposed automation process in improving not only the lower voltages but also the higher values towards the most preferable level to the consumers of 1 p.u. What confirms this is that, the average value of the voltage stability index (VSI) at each bus is about 0.9193, which comes close to optimum VSI values.

C. OPTIMAL DNR WITH OPTIMAL CONTROL OF THE CBs AND DGs AT DISCRETE LOAD REPRESENTATION (CASE 3)

TABLE 3. Statistical analysis of the TSA and ITSA for optimal DNR with optimal control of the CBs and DGs on the 69-bus test system.

Hour	Mean TSA	ITSA	Standard deviation TSA	ITSA	Standard Error TSA	ITSA
1	6.7875	5.7318	1.2067	0.537	0.3816	0.1698
2	5.7001	5.2465	0.7078	0.6107	0.2238	0.1931
3	5.8095	4.7884	0.7593	0.2287	0.2401	0.0723
4	5.4722	5.2292	1.9915	1.563	0.6298	0.4943
5	5.9933	4.9461	2.0272	0.9978	0.6411	0.3155
6	5.8817	5.18	1.8237	0.8184	0.5767	0.2588
7	7.3248	5.9886	2.2681	0.6103	0.7172	0.193
8	12.1367	8.4243	3.9454	0.6525	1.2476	0.2063
9	15.7629	11.7646	7.971	1.6517	2.5207	0.5223
10	16.9569	14.211	8.5378	1.2651	2.6999	0.4001
11	20.5189	15.9547	9.9116	3.0006	3.1343	0.9489
12	17.0854	14.9681	1.3953	1.0689	0.4412	0.338
13	18.3377	14.7376	8.9442	0.8088	2.8284	0.2558
14	18.9541	15.152	8.5101	1.401	2.6911	0.443
15	19.4261	16.7485	9.2504	2.9605	2.9252	0.9362
16	19.433	15.2771	10.8012	2.4681	3.4156	0.7805
17	17.5421	14.1908	7.8413	0.967	2.4796	0.3058
18	18.5654	13.9474	7.2755	0.5867	2.3007	0.1855
19	18.6197	13.1665	10.3408	2.1483	3.27	0.6794
20	16.0714	12.7474	5.3955	0.856	1.7062	0.2707
21	13.5958	13.3982	1.4461	1.7864	0.4573	0.5649
22	17.3315	12.7886	12.0593	0.6762	3.8135	0.2138
23	19.6774	11.464	16.2676	0.7579	5.1443	0.2397
24	11.5683	7.4536	8.2522	0.6184	2.6096	0.1956
Average			**6.2054**	**1.21**	**1.9623**	**0.3826**

Although there is no standard number of switching of the CBs or tie switches, increasing the number of daily switching of the CBs or the tie switches reduces their lifetime and increases the maintenance costs. Therefore, in this case, dividing the daily load profile to minimum number of load levels is adopted [54]. Fig. 19 shows the applied four load levels to the load curve that is considered in previous case. The application of discrete load levels reduces the switching number of the automated devices while in return the daily power losses may be deviated to increased values. Therefore, the need for optimal operation and control of DNR with CBs and DGs based on discrete load representation is increased. This case introduces the application of the proposed ITSA for minimum losses achievement with discrete load levels.

In this case, the proposed technique for fully automated distribution system is evaluated using statistical analysis compared with the standard TSA. Also, the quality verification of introduced automation process is evaluated in terms of different numerical indices compared to the non-automated system. Equations (24-28) formulate the suggested indices to be deemed for this case study.

$$\%\mathrm{PLI} = \frac{\mathrm{PL}}{\mathrm{PD}} * 100 \tag{24}$$

$$\%\mathrm{V_{min}I} = \frac{\min\left(\mathrm{V_i}\right)}{\mathrm{V_{flat}}} * 100, \quad \mathrm{i} = 1, 2, \ldots .\mathrm{N_b} \tag{25}$$

$$\%\mathrm{V_{max}I} = \frac{\max\left(\mathrm{V_i}\right)}{\mathrm{V_{flat}}} * \ 100, \quad \mathrm{i} = 1, 2, \ldots .\mathrm{N_b} \tag{26}$$

$$\%\mathrm{V_{DD}I} = \{\sum_{\mathrm{i=1}}^{\mathrm{Nb}} |(1 - V_{\mathrm{i}})|\} * 100 \tag{27}$$

$$\%\mathrm{VSI} = \sum_{\mathrm{i=1}}^{\mathrm{Nb}} \frac{\min\left(\mathrm{VSI_i}\right)}{\mathrm{V_{flat}}} * 100, \quad i = 1,\ 2, \ldots .\mathrm{N_b} \tag{28}$$

TABLE 4. Optimal operation and control of the 69-bus test system with continuous load variations using the proposed ITSA.

Hour	Optimal tie lines					Power losses (kW)	V.D	O.V.S.I	Min voltage (@ bus)	Max voltage (@ bus)
1	10	14	17	53	73	5.22919	0.13462	63.51364	0.9958 (27)	1.0000 (1)
2	9	13	17	25	53	4.77374	0.10723	62.62740	0.9966 (69)	1.0003 (60)
3	10	13	17	58	73	4.50808	0.13656	64.49002	0.9932 (65)	1.0000 (36)
4	10	11	14	26	55	4.27566	0.14676	62.49272	0.9935 (27)	1.0000 (36)
5	10	14	20	55	64	4.16708	0.13033	64.51706	0.9943 (64)	1.0001 (36)
6	10	14	20	58	64	4.45235	0.13098	65.50149	0.9939 (64)	1.0000 (36)
7	10	13	19	26	53	5.27215	0.12748	62.55548	0.9957 (27)	1.0000 (36)
8	10	14	17	56	72	7.69636	0.15178	63.44621	0.9955 (65)	1.0001 (36)
9	10	14	17	26	53	10.42787	0.13289	62.54295	0.9919 (27)	1.0000 (1)
10	10	17	26	43	54	13.03030	0.28731	62.00429	0.9892 (27)	1.0001 (36)
11	10	13	17	26	55	13.84845	0.19774	62.31896	0.9889 (27)	1.0001 (36)
12	10	14	19	58	64	13.77441	0.22428	64.17230	0.9918 (64)	1.0000 (1)
13	10	14	19	54	64	13.62393	0.24109	63.12692	0.9917 (65)	1.0000 (36)
14	10	14	20	53	64	13.77634	0.23885	64.11369	0.9910 (64)	1.0000 (1)
15	10	14	19	55	64	13.80834	0.21876	63.20431	0.9923 (64)	1.0001 (36)
16	10	13	19	54	73	13.08857	0.17877	63.34650	0.9898 (65)	1.0001 (36)
17	10	14	20	52	72	12.96097	0.13798	64.59600	0.9945 (50)	1.0030 (60)
18	10	14	18	26	55	13.23656	0.26483	62.08011	0.9904 (27)	1.0000 (36)
19	10	13	20	72	73	12.11851	0.12310	65.54321	0.9945 (65)	1.0007 (60)
20	9	14	17	26	58	11.80095	0.15338	63.46054	0.9911 (27)	1.0001 (36)
21	10	13	17	25	54	11.83941	0.17805	62.38214	0.9911 (26)	1.0000 (36)
22	10	14	19	57	64	11.70122	0.16941	63.37926	0.9941 (65)	1.0000 (1)
23	10	14	18	58	73	10.50579	0.11188	64.58239	0.9943 (65)	1.0001 (36)
24	10	13	17	26	52	6.80582	0.19694	62.31557	0.9929 (27)	1.0000 (36)

$$\%\mathrm{BLI} = \frac{\max\left(\mathrm{S_j}\right)}{\mathrm{S_{j\text{-}thermal}}} * 100, \quad j = 1,\ 2, \ldots \mathrm{N_{br}} \tag{29}$$

where; %PLI is the percentage power losses index; PL and PD are the total system power losses and demand, respectively; $\%\mathrm{V_{min}I}$ and $\%\mathrm{V_{max}I}$ are the minimum and maximum voltage index in percentage, respectively; $\mathrm{V_{flat}}$ is the reference voltage that is 1 p.u.; $\%\mathrm{V_{DD}I}$ is the percentage voltage drop index; $\mathrm{V_i}$ is the voltage of each bus i; %VSI and $\mathrm{VSI_i}$ are the percentage voltage stability index and voltage stability index at each bus i, respectively; %BLI is the percentage branch loading index; $\mathrm{S_j}$ and $\mathrm{S_{j-thermal}}$ are the power flow through branch j and the branch thermal power limit, respectively.

The first index (24) is used to expresses the reduction in the power losses with automation process. The target of this index is to be minimized which indicates more technical benefits. The minimum and maximum voltage indices in (25 and 26) aims to flat the system voltage at all buses around the flat optimum value that is 1 p.u. Subsequently, the target of the $\%\mathrm{V_{min}I}$ is to be maximum while the target of $\%\mathrm{V_{max}I}$ is to be minimum. $\%\mathrm{V_{DD}I}$ (27) represents the summation of voltage deviation of all system buses while the percentage voltage stability index (28) represents the stability of the system buses and avoidance of voltage collapse. The branch loading index (29) shows the loading percentage of the system branches and how much the automation process can relieve the system loading.

In this section, firstly optimal tie lines switching is identified simultaneously with switched CBs control and DGs dispatching. Secondly, a comparison between standard TSA and the proposed ITSA in term of statistical analysis is introduced. Finally, the automated distribution system with fully control of switched CBs and dispatching the DGs as well as tie lines optimization is compared, in this case, with non-automated distribution systems (Case 1).

TABLE 5. Statistical analysis of the TSA and ITSA at different load levels of the 33-bus test system.

Loading Level	Min		Average		Max		Std	
	TSA	ITSA	TSA	ITSA	TSA	ITSA	TSA	ITSA
Level-1	7.0723	6.6229	9.9764	7.7454	28.7835	10.8980	6.6463	1.3025
Level-2	10.7879	10.7331	13.0396	12.2192	15.9733	14.7109	1.5461	1.1867
Level-3	18.5342	18.3358	25.8633	21.4150	50.0707	27.2523	9.1926	2.4764
Level-4	14.7001	14.5103	21.2055	17.1641	39.7786	26.5899	8.0781	3.4777

TABLE 6. Optimal tie switching of the 33-bus test system with discrete load representation using the proposed ITSA.

	Level-1	Level-2	Level-3	Level-4
Optimal tie lines	5, 10, 13, 24, 34	9, 12, 24, 33, 34	9, 12, 27, 33, 34	8, 9, 12, 28, 33

1) 33-BUS TEST SYSTEM

The proposed ITSA and conventional TSA are applied for optimal control of the DNR, CBs and DGs on the 33-bus test system for total losses minimization considering the discrete load representation. Each technique is applied for a 10 run, at each load level. The best, the average, the worst solution and the standard deviation are given in Table 5. Table 6 shows the optimal tie switching at each load level applying the ITSA. Figs. 20 and 21 show the optimal control of the CBs and DGs, respectively. Fig. 22 shows a comparison between the convergence characteristic of the conventional TSA and the

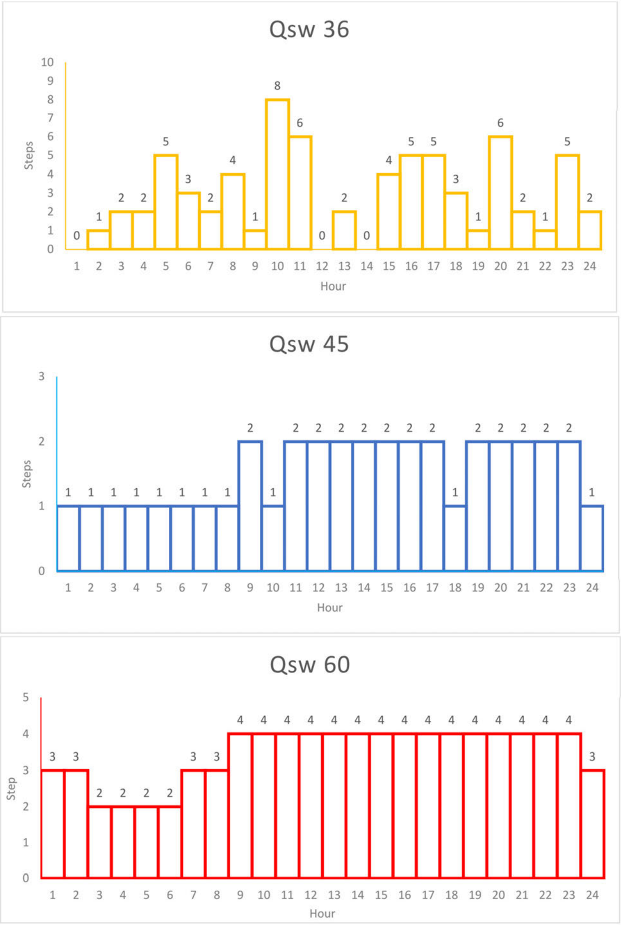

FIGURE 16. Optimal switching at each hour of the connected CBs to the 69-bus test system using the ITSA.

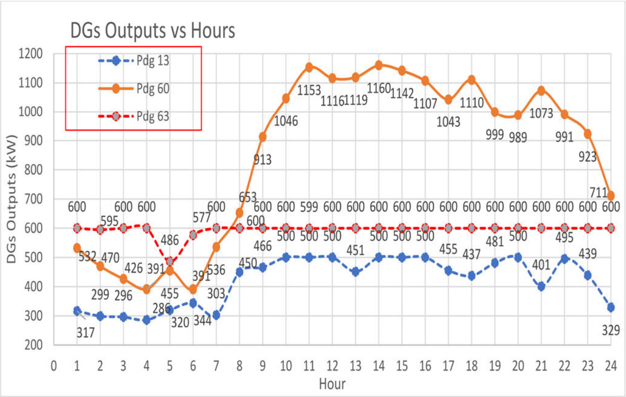

FIGURE 17. Optimal dispatching at each hour of the connected DGs to the 69-bus test system using the ITSA.

introduced ITSA at each load level. From the obtained results, it is found that proposed technique can effectively achieve the optimal solution at all load levels as compared to the TSA. Also, convergence characteristic shown in Fig. 22 illustrates the capability of the ITSA for improving the solution quality through the iterations while premature convergence of the TSA is declared.

As mentioned above, a comparison between automated distribution systems using the proposed ITSA and the non-automated system (Case 1) is introduced. Table 7 gives comparative results in terms of the total system losses, minimum and maximum voltage and different quality indices illustrated previously (24-29).

From the obtained results, it is found that the proposed technique successfully reduces the system daily power losses from 973.019 kW/day to 324.021 kW/day, which seems identical to the power losses obtained with hourly operation of the DNR, CBs and DGs (Case 2). This indicates the validity of relying on dividing the system daily load to certain load levels in reducing the switching number of automated devices. However, at the same time, this requires an effective and robust technique to achieve the main objectives functions and maintain all system constraints within the allowable burden.

Also, it is clear that the proposed control of the tie lines, CBs and DGs can achieve the target of all indices. The loss percentage index is minimized to 0.1783, 0.2889, 0.4936, and 0.3906 % at load levels (1:4), respectively with automated system versus 1.2483, 0.9885, 1.0935, and 0.9825% without automation, at the same load levels. As well, the %VminI is maximized to be just below 100% at all load levels. Similarly, the %VmaxI is slightly above 100% at load level-2 and typically aligned with 100% at the remaining load levels. What confirms the above is the %VDDI, which greatly reduced with the introduced optimal control and operation of tie lines, CBs and DGs. The minimum value of the %VDDI is 12.3868% at load level-2 while the opposite value without automation is 27.9523%. This in turn leads to improvement in the %VSI. Finally, the loading of the system branches is lower than the half loading capacity as the related %BLI does not exceed 35% at any load level with and without automation.

2) 69-BUS TEST SYSTEM

Similarly, the proposed ITSA is applied and tested on the 69-bus system for optimal control and operation of DNR, CBs and DGs at different load levels. Table 8 shows the statistical analysis of the TSA and ITSA which clearly shows a significant decrease in the standard deviation of the ITSA than the conventional TSA. Table 9 gives the optimal tie line for optimal DNR at each load level. Figs. 23 and 24 give the optimal setting of the control variables of the CBs and DGs, respectively. Fig. 25 shows the convergence characteristic of the ITSA and TSA for optimal setting and control of DNR, CBs and DGs on the 69-bus test system at each load level.

Table 10 gives a comparison results in term of the total system losses, minimum and maximum voltage and different quality indices illustrated previously. It is clear, from this table, that the proposed control of the tie lines, CBs and DGs can achieve the target of all indices. The loss percentage index is minimized to 0.1221, 0.1994, 0.3508, and 0.2795% at load levels (1:4), respectively with automated system versus 1.3645, 0.8944, 0.7273, and 0.7349 % without automation,

TABLE 7. Comparison between the proposed automation processes and non-automated 33-bus test system.

	Level-1		Level-2		Level-3		Level-4	
	Non-automated	Automated	Non-automated	Automated	Non-automated	Automated	Non-automated	Automated
Power losses (kW)	46.3744	6.6229	36.7217	10.7331	40.6239	18.3358	36.4988	14.5103
Min voltage @ bus	0.9981(22)	0.9887(14)	0.9848 (18)	0.9894 (10)	0.9649 (18)	0.9861 (10)	0.9737 (18)	0.9879 (10)
Max voltage @ bus	1.0433 (33)	1 (1)	1.0302 (33)	1.0002 (33)	1.0124 (33)	1 (1)	1.0203 (33)	1 (1)
Ploss_Index % (Minimized)	1.2483	0.1783	0.9885	0.2889	1.0935	0.4936	0.9825	0.3906
Vmin_ Index % (Maximized)	99.8069	98.8689	98.4827	98.9397	96.4859	98.6078	97.3706	98.7877
Vmax_ Index % (Minimized)	104.3329	100	103.0170	100.0219	101.2395	100.0000	102.0262	100.000
VD_ Index % (Minimized)	31.6744	19.9329	27.9523	12.3868	43.1695	20.7539	35.0565	24.74
VSI_ Index % (Maximized)	99.2297	95.86	94.0677	95.85	86.6673	94.58	89.89	95.27
LBI_ Index % (Minimized)	31.2161	20.5888	26.4002	26.6197	31.5835	36.0194	26.1133	30.893

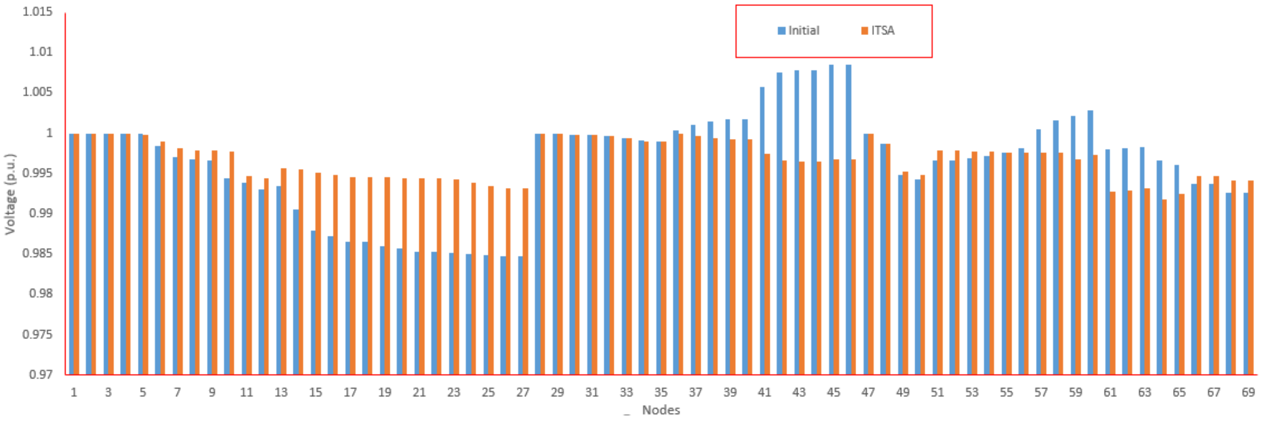

FIGURE 18. Voltage profile at peak load of the 69-bus test system after optimal setting and control of DNR, CBs, DGs using the ITSA.

at the same load levels. As well, the $\%V_{\min}I$ is maximized to be just below 100% at all load levels. Similarly, the $\%V_{\max}I$ is slightly above 100%. The minimum and maximum percentage voltage index obtained with the introduced automated system overcome the non-automated. What confirms the above is the %VDDI, which greatly reduced with the introduced optimal control and operation of tie lines, CBs and DGs. The minimum value of the %VDDI is 8.8732% at load level-1 while the opposite value without automation is 48.8657%. This in turn leads to improvement in the %VSI. Finally a great loading relieve is achieved with the proposed automation where the maximum %BLI value is 36.5942% at load level-3, while the opposite value is 86.3547% without CBs, DGs and ties lines control and automation. It can be said, from the obtained results, the system daily performance in this case is enhanced much more than the similar case with continuous load variation in addition to minimization of the switching number.

TABLE 8. Statistical analysis of the TSA and ITSA at different load levels of the 69-bus test system.

Loading Level	Min		Average		Max		Std	
	TSA	ITSA	TSA	ITSA	TSA	ITSA	TSA	ITSA
Level-1	4.6449	4.6415	8.1005	5.0010	27.6053	6.0697	7.0339	0.4368
Level-2	7.8485	7.5790	11.1612	8.5353	29.7809	10.1664	6.6409	0.9401
Level-3	13.6151	13.3352	16.4345	15.1552	31.1051	20.1404	5.2359	1.9574
Level-4	10.6587	10.6244	12.2657	11.8670	14.9495	13.5303	1.4577	0.9128

TABLE 9. Optimal tie switching of the 69-bus test system with discrete load representation using the proposed ITSA.

	Level-1	Level-2	Level-3	Level-4
Optimal tie lines	10, 14, 20, 26, 53	10, 14, 17, 56, 73	10, 14, 18, 52, 72	10, 14, 20, 54, 64

D. COMPARATIVE STUDY OF THE PROPOSED ITSA AND OTHER TECHNIQUES (CASE 4)

In this section, a comparison between the proposed ITSA and the conventional TSA and other previous techniques is introduced. This comparison is introduced for optimal CBs and DGs locations and sizes only, without DNR, because there are no previous available literatures in this area. To make a faire comparison, the CBs and DGs output is assumed to be integer, neglecting standard commercial values. The main objective of this comparison is to check the effectiveness and robustness of the proposed technique as well as to check scalability and flexibility of the proposed ITSA on large-scale distribution system.

Table 11 shows the comparison results between the proposed ITSA and other techniques such as TSA, WCA [55]

TABLE 10. Comparison between the proposed automation processes and non-automated 69-bus test system.

	Level-1		Level-2		Level-3		Level-4	
	Non-automated	Automated	Non-automated	Automated	Non-automated	Automated	Non-automated	Automated
Power losses (kW)	51.8689	4.6415	33.9989	7.5790	27.6485	13.3352	27.9363	10.6244
Min voltage @ bus	0.9967 (50)	0.9969 (20)	0.9951 (27)	0.9920 (65)	0.9856 (27)	0.9944 (50)	0.9898 (27)	0.9945 (64)
Max voltage @ bus	1.0334 (60)	1.0012 (60)	1.0211 (60)	1.0000 (1)	1.0085 (45)	1.0024 (60)	1.0118 (60)	1.0000 (36)
Ploss_Index % (Minimized)	1.3645	0.1221	0.8944	0.1994	0.7273	0.3508	0.7349	0.2795
Vmin_ Index % (Maximized)	99.6730	99.6873	99.5077	99.1986	98.5633	99.4391	98.9804	99.4539
Vmax_ Index % (Minimized)	103.3446	100.1165	102.1122	100.00	100.8546	100.245	101.1823	100.0042
VD_ Index % (Minimized)	48.8657	8.8732	31.4476	18.8983	33.7509	13.994	30.165	14.3352
VSI_ Index % (Maximized)	98.6985	98.76	98.0452	96.83	94.3761	97.78	95.9836	97.83
LBI_ Index % (Minimized)	89.2147	27.7823	86.9813	29.4443	86.3547	36.5942	86.6283	33.1604

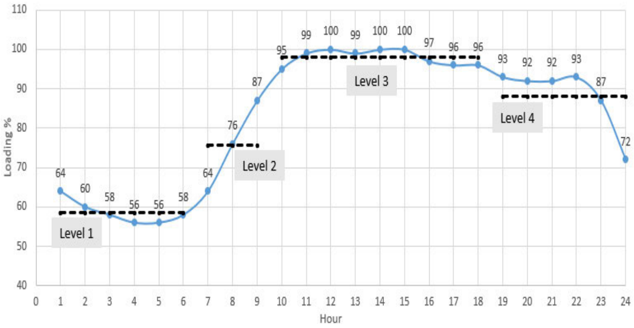

FIGURE 19. Daily loading with assumed load levels.

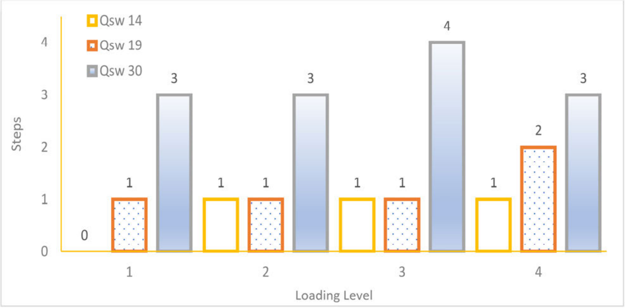

FIGURE 20. Optimal switching at each load level of the connected CBs to the 33-bus test system using the ITSA.

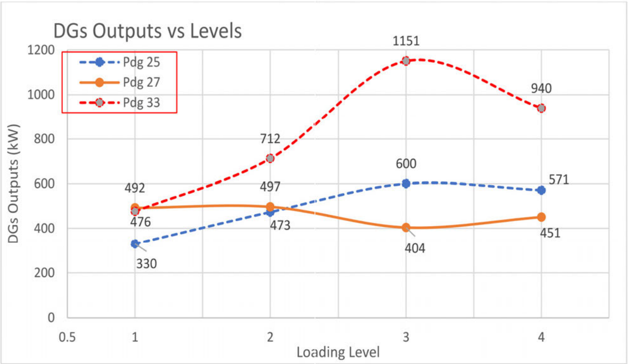

FIGURE 21. Optimal dispatching at each load level of the connected DGs to the 33-bus test system using the ITSA.

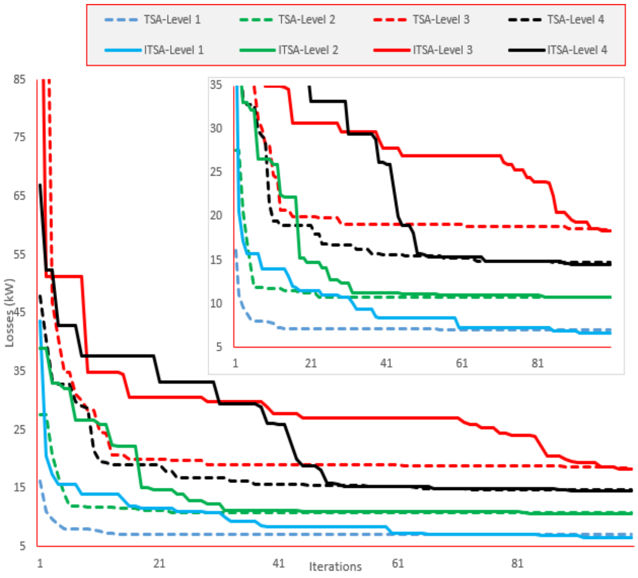

FIGURE 22. Convergence characteristics of conventional TSA and ITSA for optimal setting and control of DNR, CBs, DGs on the 33-bus test system at each load level.

and BFOA [56] for optimal allocation of CBs and DGs on the 33-bus test system. Table 12 introduces a comparative analysis between the proposed ITSA and other techniques such as PSO, slime mould algorithm (SMA) [57], conventional TSA, crow search algorithm [58], GA [43], and evolutionary algorithm (EA) [59] for optimal allocation of CBs and DGs on the 69-bus test system. This comparison verifies the efficiency of the proposed ITSA for optimal solution achievement where the lowest value of power losses is obtained applying the proposed technique. The power losses after optimal allocation of the CBs and DGs using the proposed ITSA is greatly reduced to reach a percentage reduction of 92.89% and 96.976% for the 33-bus and 69-bus systems, respectively. Also, the convergence comparison between the proposed ITSA and other techniques, shown in Fig. 26, clarify the effectiveness of the improved diversification abilities of the ITSA for searching optimal solution and avoiding the stagnation possibilities.

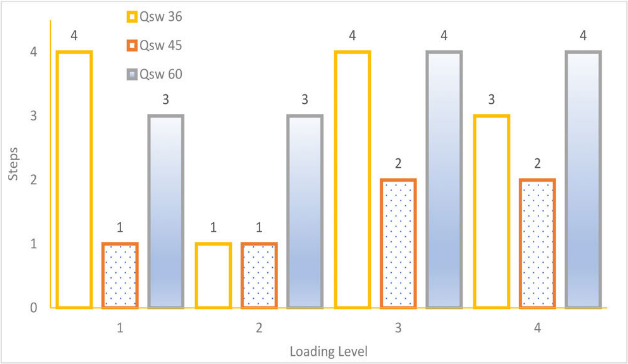

FIGURE 23. Optimal switching at each load level of the connected CBs to the 69-bus test system using the ITSA.

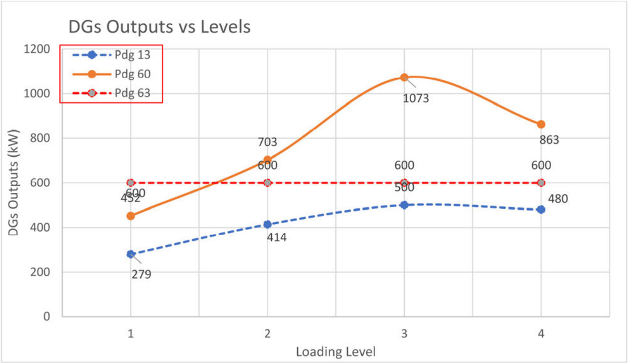

FIGURE 24. Optimal dispatching at each load level of the connected DGs to the 69-bus test system using the ITSA.

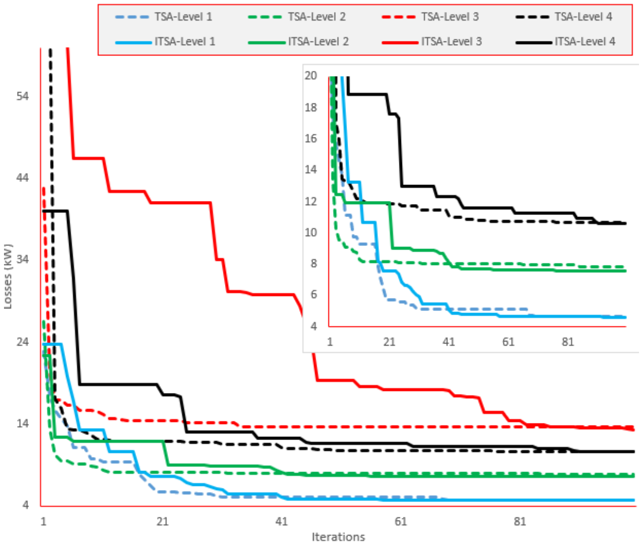

FIGURE 25. Convergence characteristics of conventional TSA and ITSA for optimal setting and control of DNR, CBs, DGs on the 69-bus test system at each load level.

One of the major challenges facing the new optimization techniques is the capability of application on large-scale systems. Therefore, a comparison between the proposed ITSA and TSA is introduced for optimal allocation of the CBs and DGs in a large-scale 119-bus test system. Table 13 gives a comparison between the TSA and the proposed ITSA. For large-scale systems, the advantages of the proposed ITSA over conventional TSA is greatly appeared where the losses is reduced by a percentage of 81.52% using the ITSA. Also, convergence characteristic shown in Fig. 27 greatly shows the advantages of the introduced modification to the TSA. Although, TSA is converged to an optimal solution faster than ITSA but the proposed ITSA gets a better solution. This confirms the capability of the ITSA of development and improving the solution quality through the iterations while premature convergence of the TSA is declared.

TABLE 11. Comparison results of optimal allocation of CBs and DGs on the 33-bus test system.

		WCA	BFOA	TSA	Proposed ITSA
Optimal CBs size (location)		465 (23) 565 (30) 535 (14)	163 (18) 338 (33) 541 (30)	1060 (30) 246 (11) 566 (24)	834 (30) 603 (7) 269 (15)
Optimal DGs size (location)		973 (25) 1040 (29) 536 (11)	542 (17) 160 (18) 895 (33)	766 (24) 917 (30) 976 (12)	788 (13) 742 (25) 1085 (30)
Losses (kW)	202.66	24.68	41.41	15.0	14.4

TABLE 12. Comparison results of optimal allocation of CBs and DGs on the 69-bus test system.

	Initial	PSO	SMA	TSA	CSO	GA	EA	Proposed ITSA
Optimal CBs size (location)		1222 (61) 344 (66) 235 (69)	708 (2) 623 (130 1091 (61)	379 (11) 15 (38) 1230 (61)	1367 (61) 311 (67) 323 (68)	355.08(17) 1243.66(61)	353(17) 1239(61)	288 (9) 292 (23) 1149 (61)
Optimal DGs size (location)		799 (66) 1689 (61)	497 (16) 112 (30) 1625 (61)	582 (17) 205 (49) 1586 (61)	535 (17) 1728 (61) 299 (67)	522.85(18) 1734.1(61)	1731(61) 520(17)	291 (10) 491 (15) 1500 (61)
Losses (kW)	224.9	10.6515	9.0053	8.5693	7.5488	7.2	7.2	6.8012

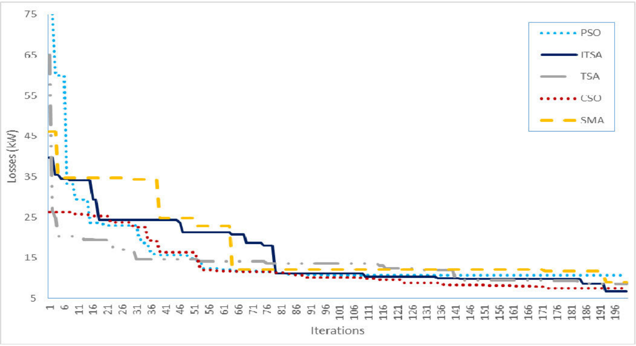

FIGURE 26. Convergence comparison between the ITSA and other techniques for optimal CBs and DGs allocation on the 69-bus system.

Added to that, the computation time and complexity of the problem is discussed for the TSA and ITSA technique as shown in Table 14. In this table, the computational complexity is evaluated based on the big O notation [60]. From this table, a comparable computational time is acquired for both algorithms for the 33-bus test system and the 69-bus test system with slight lower time for the proposed ITSA. However, the proposed ITSA is much faster for the large-scale 119-bus test system with 139.14 sec compared to 149.631 sec for the conventional TSA. For fair comparison, both algorithms have the same computational complexity where it is O(2000n), O(2000n), O(250000n) for 33-bus test system, 69-bus test system and 119-bus test system, respectively.

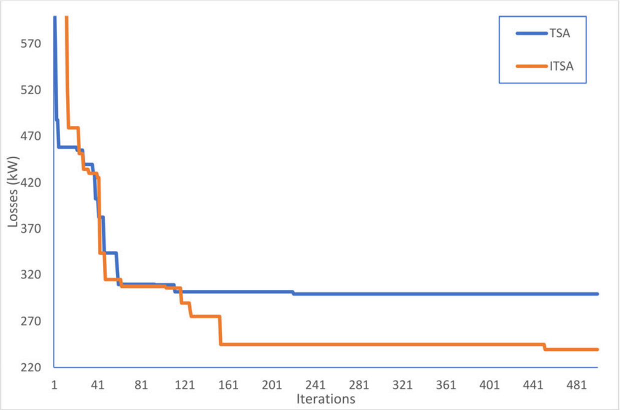

FIGURE 27. Convergence comparison between the ITSA and other techniques for optimal CBs and DGs allocation on the 119-bus system.

TABLE 13. Comparison results of optimal allocation of CBs and DGs on the 119-bus test system.

	Initial	TSA		ITSA	
Optimal CBs size (location)		2700 (10) 857 (39) 1352 (40)	989 (74) 1270 (98) 2365 (111)	1898 (40) 1464 (76) 1095 (86)	718 (93) 789 (103) 1855 (111)
Optimal DGs size (location)		3000 (39) 1442 (72) 1568 (77)	1778 (82) 474 (98) 2350 (119)	2570 (40) 1253 (62) 2772 (71)	2339 (81) 895 (93) 2779 (119)
Losses (kW)	1298.1	272.7628		239.804	

TABLE 14. Comparison results of computation time and complexity.

	33-bus test system		69-bus test system		119-bus test system	
	TSA	ITSA	TSA	ITSA	TSA	ITSA
Average computational time (sec)	17.225	16.645	22.433	22.212	149.631	139.1405
No of individuals	20		20		50	
Max no of Iterations	100		100		500	
computation complexity	O(2000n*)		O(2000n)		O(250000n)	

*n refers to the number of control variables in each system

V. CONCLUSION

This paper presents an effective and robust solution technique for simultaneous distribution network reconfiguration with capacitor banks and distributed generators allocation and control, which is very important to distribution system operators for enhancing the performance, quality and reliability of distribution systems. The complexity and variety of the control variables of this problem represent a challenge for distribution systems planners and operators as well as researchers and make it difficult for most of the previous techniques to achieve the optimal solution. A Modified version of newly proposed meta-heuristic Tunicate Swarm Algorithm (ITSA), which imitates the swarming behaviors of the marine tunicates and their jet propulsions during its navigation and foraging procedure, is proposed. The ITSA is applied and tested on the standard 33-bus, 69-bus and large-scale 119-bus distribution systems considering different scenarios of daily loading variation and operation strategies. Also, comparisons between the proposed ITSA and other techniques such as PSO, GA, EA, WCA, BFOA, TSA and CSA are introduced. For all cases and scenarios, the results affirm the qualification of the proposed ITSA in term of power losses minimization, voltage enhancement, convergence characteristics and standard deviation. The value of power losses in some cases of the test systems is reduced by a percentage of 96.97%, which can save millions of dollars per year. Also, the proposed ITSA overcome other techniques in term of lower computation time, better statistical analysis, optimal solution achievement and avoiding stuck problem. Based on the proposed technique, distribution automation center can optimally controls and operates the distribution system automated devices and consequently provides quantitative and qualitative power service to satisfy consumers' satisfaction and reduces dissipated energy. Fully automated distribution systems with simultaneous control and operation of CBs, DGs and DNR under contingencies will be the focus of author's future research.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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