IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 10, 2019, accepted July 17, 2019, date of publication July 23, 2019, date of current version August 7, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2930631

Adequate Topology for Efficient Energy Resources Utilization of Active Distribution Networks Equipped With Soft Open Points

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This work was supported in part by the National Key Technologies Research and Development Program of China under Grant 2018YFB0904303, and in part by the Science and Technology Development Fund Through Institute of France-Egypt cooperation (STDF-IFE) under Grant number 31161.

ABSTRACT Active distribution networks concerned with providing efficient control technologies for large-scale integration of distributed generation (DG) units into the distribution systems. This research proposes a methodology for distribution networks reconfiguration by controlling number, sharing, size, and location of DG units. Also, the soft-open points (SOPs) are added instead of the tie line switches. The SOPs are benefited with its high capability in controlling active/reactive power flow to enhance transmission system performance. The main target of this work is to increase the efficiency of energy utilization through minimizing the power system losses and improving system voltage profile while preserving all system constraints within permissible limits with reliable and flexible networks in normal and abnormal conditions with a suitable penetration level of DG. A modified particle swarm optimizer is developed to find the best system configuration, size, and placement of DG units as well as the size and allocation of SOPs. Research methodology is tested on two standards: the IEEE 33-node and 69-node distribution networks under different operating cases. This paper compares the obtained results with those in the literature to prove the capabilities of the proposed work. Finally, the suggested work pursues the optimal number of DG units with their appropriate penetration levels and selects the most convenient location of SOPs for adequate network reconfiguration.

INDEX TERMS Efficiency of energy utilization, active distribution networks, distributed generation, soft-open points, modified particle swarm optimization.

I. INTRODUCTION

The concept of smart electric Distribution Networks (DNs) and better energy utilization are the main future research trends. The penetration of DG units results in many benefits depending on the sizing and siting of units [1]–[3]. Also, providing DNs with smart power electronic devices called Soft-Open Points (SOPs), enhances system performance and controllability and affords flexible system configuration in both normal and emergencies especially in case of faults [4]–[6]. This study aims at handling SOPs capabilities with Active Distribution Networks (ADNs) for a better configuration that enhance system performance and reliability. This study increases total system efficiency and raises system voltages to acceptable levels, moreover it increases the hosting capacity of DG units with the help of SOPs [7]. It also finds the most suitable places, sharing, and size of DG units also SOPs best control and proves its role in moving the traditional system towards more control and being smarter as such new technologies relief all system advance.

A lot of studies exploited the wide area of distribution networks after the penetration of DG units that incorporates the concept of ADNs. Some studies covered control strategies for penetration and high penetration of DGs challenges

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

and problems investigation [8]–[10], and others considered the benefits of the presence of DG units in the distribution system and its role of optimizing all distribution networks functions [11]–[14]. Also, some studies focused on providing Distribution systems with new technologies like SOPs [15]–[17] and automation systems and all of this can be in short term studies or for long term planning [4], [18], [19].

In the literature, researches configured the idea of optimal sizing and siting of DGs into static DNs. The authors of [20] used different optimization techniques to find the best solution for the benefit of minimum losses and better voltage profile. Also, [21] has the same objective and compared its methodology with different techniques, but added the capability of system reconfiguration for better results and other researchers studied only the effect of system reconfiguration without DG units in balanced/unbalanced DNs [22]–[24]. It is important to point here to challenges that face the high contribution of DG to DN that affects its penetration level (*Pl*). Some of these difficulties can be categorized as [25]–[28]:

- Power quality problems (voltage fluctuations, flickers, harmonies, etc.);
- Voltage fluctuations of the equipment's resulted from climate changes
- Economic problems related to high costs;
- Protection problems in the presence of DG especially the loss of coordination between protection devices,
- The Problem of islanding and increase the current flow that may lead to exceeding the thermal loading in case of minimum load or high generation

SOPs concept initiated from the point that flexible AC transmission system (FACTS) which is not convenient for DNs so there were D-FACTS devices to benefit from the capabilities of FACTS devices in DNs. In [29], the SOPs concept was proposed as an active/reactive power management tool to modify network topology to mitigate the impacts of the high penetration levels of DG units. Researches in [15], [29] studied the SOPs control of the power flow in distribution networks and enhancing voltage profile at load buses in both normal and faulty operating conditions. Reference [30] introduces different control modes of the SOPs under normal/abnormal operating conditions. In [4], SOPs have the capabilities in the planning of distributed storage systems in ADNs. The authors in [31] exposed to the optimal operation of SOPs in ADNs under unbalanced 3-phase. They succeed to prove the capability of SOPs to reduce network losses and enhance system voltage profile but they didn't take SOP capacity control or DG penetration level into consideration. In [32], authors take a large penetration level of photovoltaics into account and used 2 SOP devices to eliminate voltage fluctuations with low power losses. All of the abovementioned research work demonstrates the benefit of SOP devices as an efficient way of solving DNs problems and enhancing its performance.

Various optimization techniques were investigated for solving engineering problems such as particle swarm (PSO), Genetic Algorithms (GA), Ant colony optimizer (ACO) [33]–[35] and Seeker optimization Algorithm (SOA) [36], [37]. PSO is the simplest well-known structure, lowest number of controlled parameters, most powerful, and most frequently used optimizer that can be implemented to solve engineering problems and especially with FACTS devices installation problems [31]. PSO is a metaheuristic algorithm that uses the swarm searching with a guidance capability to find optimal results. A lot of modifications to traditional PSO mentioned in the literature to enhance its performance; sometimes to reach optima faster or to get better results compared to other techniques or even other modifications [20]. Many researchers focused on increasing the hosting capacity of DG units and study its effect on system losses and voltage stability [7] each with a single objective.

The main contributions of this paper are briefed as follows:

- Proposing a modified PSO version for better performance of the tool and also better and comparative results with literature for two standard systems and test cases.
- Detecting the minimum size of DG units that results in the best system losses and voltage profile, and investigating the effect of the number of the DG units used in different locations and minimum sizes for best results with the same optimal reconfiguration and DG units' allocation.
- Studying losses and voltage profile concerning for SOP capacity and control and its role in increasing DG penetration level.
- Provide a procedure for finding the optimal DNs reconfiguration accomplished with DG allocation and SOP switching action.

The rest parts of this work are organized as follows: Section 2, introduces mathematical modeling of SOPs into DNs. Section 3 prevails the objectives and constraints of problem formulation equations. The MPSO optimizer is explained in section 4; then test systems, MPSO parameters settings, and different study cases are summarized in section 5. A detailed discussion of obtained results in 6 and finally conclusions are drawn in section 7.

II. THE PRINCIPAL AND MODELLING OF SOFT OPEN POINTS (SOPs)

In this study, SOP is considered a multi-function power electronic device installed into DNs to be used as an active/reactive power flow control tool in place of tie line switch between two feeders. The static model is initiated, as there are no dynamic considerations in this work focus. Back-to-back voltage source converter (VSC) based SOP with P-Q control mode for VSC_i and VDC-Q mode for VSC_j [30] for smooth control of voltage and active/reactive power flow in steady state. SOP can be considered a nearly lossless line between two feeders, but active power flow in that line can be controlled as a value and direction according to Eq. (1) where power entering feeder i P_i^k of kth SOP must be equal to leaving feeder j P_j^k and losses of SOP $P_{Losses}^k \cong 0$

can be neglected [4] where the number of SOPs are limited to N_{SOP} according to planning considerations.

$$P_i^k + P_j^k + P_{Losses}^k = 0; \quad k \in N_{SOP} \tag{1}$$

Also, reactive power entering and leaving can be controlled as a direction, but with different values and different directions to represent the capability of reactive power Q_i^K, Q_j^K absorbed or compensated at buses i, j that must be preserved in permissible converters limits $Q_{i,jmin}^K.Q_{i,jmax}^K$ of the kth SOP as in 2,3:

$$Q_{imin}^K \leq Q_i^K \leq Q_{imax}^K; \quad K \in N_{SOP} \tag{2}$$
$$Q_{jmin}^K \leq Q_j^K \leq Q_{jmax}^K; \quad K \in N_{SOP} \tag{3}$$

VSC connected to feeders i or j restrict kth SOP to specific capacity S_i^k so that active/reactive power entering or leaving must satisfy it and it is available that rating of both converters is different as in 4,5:

$$\sqrt{(P_i^k)^2 + (Q_i^k)^2} \leq S_i^k; \quad K \in N_{SOP} \tag{4}$$
$$\sqrt{(P_j^k)^2 + (Q_j^k)^2} \leq S_j^k; \quad K \in N_{SOP} \tag{5}$$

Figure 1 provides a summary of the presence of SOP into DN with the optimizer that controls the ADN switches (s), DG units, and SOPs operation utilizing the network control system.

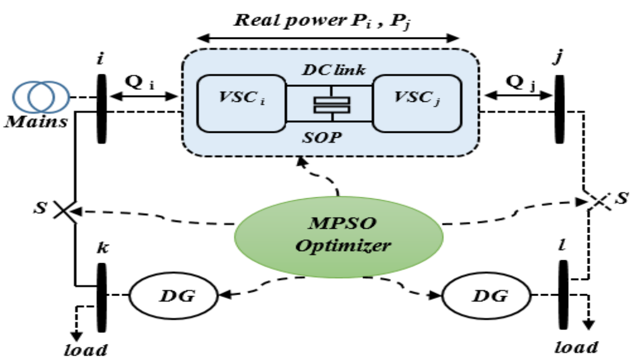

FIGURE 1. SOP modeling and installation into ADN.

III. PROBLEM FORMULATION

A multi-objective framework is introduced for handling the main goals of minimizing the active losses and reducing total voltage deviation with suitable DG penetration level. The control variables involve the following:

- Number of DG units (NDG) and their locations
- Sharing penetration level and siting of DG units into the distributing systems
- SOP site and sizing (Reactive power value absorbed or injected / active power flow value and direction)
- The status of sectionalized switches of lines
- Adaptive parameters of MPSO (σ, W_1:W_3,P. size)

In Eq. (6), the main objective of the problem is formulized by minimizing power losses (P_{Losses}) and the total voltage deviation of feeders' voltages V_i beyond nominal voltage V_n with number of feeders Nf and weighting factors W_1:W_3 for the multi-objective action.

$$Obj = Min(W_1 \times P_{Losses} + W_2 \times V.D + W_3 \times \frac{1}{Pl}),$$
$$V.D = \sum\nolimits_{i \in Nf} |V_n - V_i| \tag{6}$$
$$Pl = \left(\sum\nolimits_{i \in NDG} P_{DGi}\right) / P_{Gt},$$
$$P_{Gt} = \sum\nolimits_{i \in NDG} P_{DGi} + P_{slack} \tag{7}$$
$$P_{Losses} = \sum\nolimits_{i.j \in Nf} Real\left(\mu_{ij} * I_{ij}^2 * Zl_{ij}\right) \forall\, Zl \in Nl \tag{8}$$

Also, to provide the maximum DG units sharing required for best technical results so DG penetration level Pl transpose is added to the objective equation terms multiplied by weighting factor W3. Minimizing losses is given the highest priority with better voltage stability and also with maximization Pl to good levels. Pl in Eq. (7) refers to the percentage of summation DG sharing P_{DGi} to total power P_{Gt} absorbed by the system from DG units added to P_{slack} from the main grid. Distribution network losses P_{Losses} is the sum of all lines Nl real power losses when the line between nodes i and j have impedance Zl_{ij} and current through it are I_{ij} and μ_{ij} is lines sectionalized switch status that can be controlled for switching process as mentioned in expression (8). The combined objective function in Eq. (6) is exposed to a set of operational constraints can be classified as:

1. Total active/reactive power balance stated in Eqs. 9 and 10 where PD_i, QD_i are load concentrated at each node and Q_{losses} is system reactive power losses that can be calculated in terms of expression (11); where Q_i^K and Q_j^K are kth SOP reactive at both ends power and P_{Losses}^k is its real power losses.

$$P_{Gt} = \sum\nolimits_{i \in Nf} PD_i + P_{losses} + P_{Losses}^k \tag{9}$$
$$Q_{Gt} = \sum\nolimits_{i \in Nf} QD_i + Q_{losses} + Q_i^K + Q_j^K,$$
$$Q_{Gt} = \sum\nolimits_{i \in NDG} Q_{DGi} + Q_{slack} \tag{10}$$
$$Q_{Losses} = \sum\nolimits_{i.j \in Nf} Imag\left(\mu_{ij} * I_{ij}^2 * Zl_{ij}\right) \forall\, Zl \in Nl \tag{11}$$

2. Nodal current and load balancing constrain also must be satisfied; Eq. (12) shows that the algebraic sum of all currents entering or leaving node i from or to connected feeders Nc added to current injected into bus i if it is provided DG units I_{DGi} must balance the current I_{loadi} drew by the load at the same bus.

$$\sum\nolimits_{J \in Nc} \mu_{ij} * I_{ij} + I_{DGi} = I_{loadi} \quad \forall i \neq j \tag{12}$$

3. Active/reactive limit of DG units P_{DGi} and Q_{DGi} should be selected according to the available ranges, so the objective function is also constrained with Eqs. 13-15 where the number of DG units NDG is also limited to

the available committed units N_{DG}^{max}:

$$P_{DGi} \leq P_{DGi}^{max} \quad \forall i \in NDG \tag{13}$$
$$Q_{DGi} \leq Q_{DGi}^{max} \quad \forall i \in NDG \tag{14}$$
$$NDG \leq N_{DG}^{max} \tag{15}$$
$$V_i^{min} \leq V_i \leq V_i^{max} .i \in Nf \tag{16}$$
$$S_{ij} \leq S_{ij}^{max} \quad \forall i \neq j \,\&\, i.j \in Nf \tag{17}$$

4. Security constraints are also considered for feeders' voltage levels that must be kept within limits also lines loadings S_{ij} that can't exceed lines thermal loading S_{ij}^{max} as expressed in (16) and (17) respectively. Moreover, when SOP is installed between buses i, j power flow direction P_{ij}^k through the kth SOP can be controlled according to Eqs. 18 and 19 while Kth SOP power flow operator ε_k can be controlled for each SOP between the values 0, +1, −1 to control the power flow direction.

$$\varepsilon_k * P_{ij}^k \leq P_{ij}^{max} \quad \forall k \in N_{SOP} \;\&\; \left|P_{ij}^k\right| = \left|P_i^k\right| = \left|P_j^k\right| \tag{18}$$

$$\varepsilon_k = \begin{cases} 0 & SOP_{ij}^k \text{ disconnected/not exist} \\ 1 & \text{flow from bus i to j} \\ -1 & \text{flow from bus j to i} \end{cases} \tag{19}$$

IV. MODIFIED PARTICLE SWARM OPTIMIZATION (MPSO)

In standard PSO, the term "particles" refers to population members, which are mass-less and volume-less (or with an arbitrarily small mass or volume) and are subjected to velocities or accelerations towards better behavior. Each particle in the swarm represents a solution in a high-dimensional space with four vectors, its current position; the personal best position of each particle after acceleration compared to the old position, the overall best position found in its neighborhood so far and the fourth is particle velocity. Each particle adjusts its position X_{ij} inside the limited search space based on the best position reached by itself $X_{Pbestij}$ and the global best position reached of all particles $X_{Gbestij}$ during the search process for optima that can be detailed with equations as follows:

A. VELOCITY STEP FUNCTION

Traditional PSO, uses step function a_{ij}^t is determined for each ith particle of each jth variable at each iteration t, where $a_{ij}^t \geq 0$ as shown in Eq. (20) is three-term expression. For moving from position to another in the search space; particles are directed by three means termed as inertia function ω (1st term) that can be calculated in each iteration from expression (21) in terms of inertia operator limit values and also maximum suitable iteration number t_{max}; the 2nd term refers to updating current positions process and third represent way to share information of global best solution between old positions. *A modification is essential here* that global best should also guide personal best as an acceleration factor for the convergence process to the best solution this can be mathematically expressed by (22) so another two terms added to old velocity function where C_1, C_2, C_3, C_4 are constant parameters of MPSO and r_1, r_2, r_3, r_4 are random numbers between 0 and 1.

$$a_{ij}^{t+1} = \omega^t a_{ij}^t + c_1 r_1 \left(X_{Pbest.ij}^t - X_{ij}^t\right) + c_2 r_2 \left(X_{Gbest.j}^t - X_{ij}^t\right) \tag{20}$$

$$\omega^t = \omega_{max} - \left((\omega_{max} - \omega_{min})/t_{max}\right) * t \quad \forall \omega \geq 0 \tag{21}$$

$$a_{ij}^{t+1} = a_{ij}^{t+1} + c_3 r_3 \left(X_{Gbest.j}^t + X_{Pbest.ij}^t - 2X_{ij}^t\right) + c_4 r n_4 \left(X_{Gbest.j}^t - X_{Pbest.ij}^t\right) \tag{22}$$

B. UPDATING THE i^{th} PARTICLE LOCATION

Each particle should move towards the optima by correctly updating its position using a step function a_{ij}^t as following in Eq. (23) where the step is added to the current position it may be positive or negative till it reaches zero then it is the optimal solution:

$$X_{ij}^{t+1} = X_{ij}^t + a_{ij}^{t+1} \tag{23}$$

C. SEARCH SPACE LIMIT REDUCTION STRATEGY(LRS)

Another modification here is added to the searching process; where limits of the controlled variables are modified in each iteration to reduce the search cosmos to find the optimal value. So, for the X_j controlled variable limit is adapted in a decreasing manner to make it neighboring to the global best position in each iteration compared to its original limit, LRS can be expressed mathematically using Eqs. (24) and (25) Where, σ is a factor less than 0.1 selected randomly and adjusted according to the problem.

$$X_{j.max}^{t+1} = X_{j.max}^t - \sigma(X_{j.max}^t - X_{Gbest.j}^t) \tag{24}$$
$$X_{j.min}^{t+1} = X_{j.min}^t + \sigma(X_{Gbest.j}^t - X_{j.min}^t) \tag{25}$$

D. VELOCITY LIMIT CONTROL

The final modification is that velocity or step length is limited according to maximum/minimum values of controlled variables X_j^{max}, X_j^{min} which is very effective in speeding reaching the optimal solution. Velocity limits a_j^{limits} can be adapted to each case or system with a suitable selection of value of velocity limit operator β as in expression (26):

$$a_j^{limits} = \pm\beta(X_j^{max} - X_j^{min}) \tag{26}$$

To summarize basic PSO modifications

1. Velocity step function modification as in Eq. 22
2. Search space limit reduction as in Eqs. 24, 25
3. Velocity limit control as in Eq. 26

V. APPLICATIONS

A. TEST SYSTEMS AND CASES UNDER STUDY

Two standard IEEE systems are used to investigate the benefits of the proposed algorithm. The single line diagram of the 1st system in shown Fig.2.a. the considered system is basically 12.66 kV- IEEE 33 balanced radial DN which has

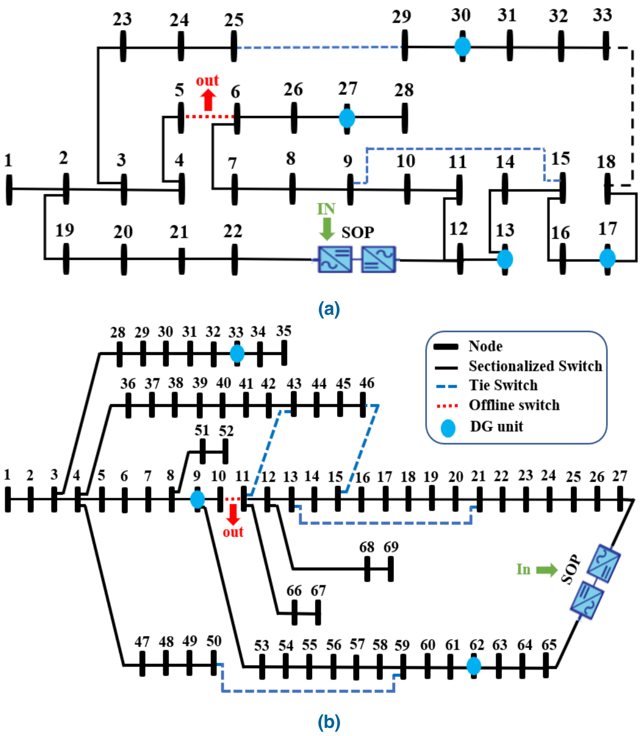

FIGURE 2. The modified IEEE 33, 69 node DNs respectively.

33 nodes, 33 lines and, 5 tie switches; with a total basic load of 3.715MW and 2.3 MVAR [4]. This system is equipped with SOP instead of the tie-line between nodes 12,22 in addition to five DG units as will be discussed in the section of results. The 2nd system is the IEEE 69 node system which is a larger balanced and also radial test system. Fig. 2.b shows the IEEE 69 node system basic topology with the additional DG units and SOP optimal allocation that will be investigated in the part of simulation results. This system is also 12.66 kV but has 69 nodes, 69 lines, and 5 tie line switches; with a total basic load of 3.8 MW and 2.69 MVAR [4]. But this system base power flow loss is very large and also has a very bad voltage profile so it has been selected as a good test case. In both cases bus 1 is slack bus and type of DG is not considered in that study; also, DG is considered synchronized and has no fluctuations (fully controlled and equipped with storage systems). Most of the DG units are normally designed to operate at unity power factor under the recommendation of the standard IEEE 1547 [37].

Four cases are employed to emphasize the contribution of this work as follows:

- Case 1: Normal operating condition without any reconfiguration, DGs insertion or SOPs.
- Case 2: Denotes to the effect of system reconfiguration only without DG using MPSO
- Case 3: introduces DGs insertion without any reconfiguration or SOP using MPSO
- Case 4: Represents the best normal operation case with optimal topology, optimal DG penetration level and also optimal size, control, and placement of SOP using MPSO.

Some of study assumptions for all cases is addressed. Lines power flow is limited to 6 MVA and nodes voltage is also reserved within the range $0.95 \leq V_i \leq 1.05 \ \forall V_n = 1\text{PU}$ [4]. Another assumption; One SOP is considered in this work due to its large cost. Also, one opened switch is considered to conserve system radiality and avoid any further transient and switching problems.

B. MPSO PARAMETER SETTINGS

Parameters settings of MPSO for the two test systems are shown in Table 1 for all cases of study of the two test networks. The proposed model simulations are implemented in MATLAB® software package environment. Table 1 also, illustrates the weighting factors Wi for the ith objective which reveals the relative importance between the m objectives. Wi is potentially adapted to each system and case study by multiplying random value $\varepsilon_i \in [0, 1]$ by a scaling factor sf as shown in Eqs. 27,28. Where; using scaling factor to give the active power losses the highest priority after this comes the other objectives.

$$\sum\nolimits_i^m W_i = 1; \quad \forall 0 \leq W_i \leq 1 \tag{27}$$

$$W_i = \varepsilon_i * sf_i; \quad \text{where, } W_1 > \sum\nolimits_2^m W_i, \qquad sf_i = \frac{1}{i} \times \frac{obj(t+1)}{obj(t)} \tag{28}$$

TABLE 1. Parameters of MPSO and Weighting factors.

Max. Generations(t_{max}):	50		**Velocity limit operator (β):**		0.1	
Inertia limits(ω) [38:40]:	0.4≤ ω ≤0.9		**C_1, C_2, C_3, C_4 [39:41]:**		1.3, 2, 10, 0.0025	
Test System	**Case**	**W1**	**W2**	**W3**	**σ**	**P. Size**
33-Bus	1	0.75	0.25	0	0.08	120
	2	0.8	0.2	0	0.06	120
	3	0.82	0.1	0.08	0.09	180
	4	0.85	0.09	0.06	0.06	180
69-Bus	1	0.79	0.21	0	0.08	180
	2	0.85	0.15	0	0.06	210
	3	0.82	0.12	0.06	0.04	210
	4	0.84	0.12	0.04	0.06	210

Table 1 exposed to LRS factor σ with different cases and different test systems to adapt the search space for all the controlled variables which is a random value between 0 and 1. Besides, the population size (P. Size) differs from a system to another due to the adaptation to the different number of controlled variables it is selected also between 120 and 300. For both test systems, MPSO takes only 10 −15 generations to reach an optimal solution, although there are a large number of variables and other parameters all also constant in all cases while MPSO reaches to optimal very fast as will be discussed later in tool assessment section but maximum number of iterations $\mathbf{t_{max}}$ is set to 50 to avoid local minimum point.

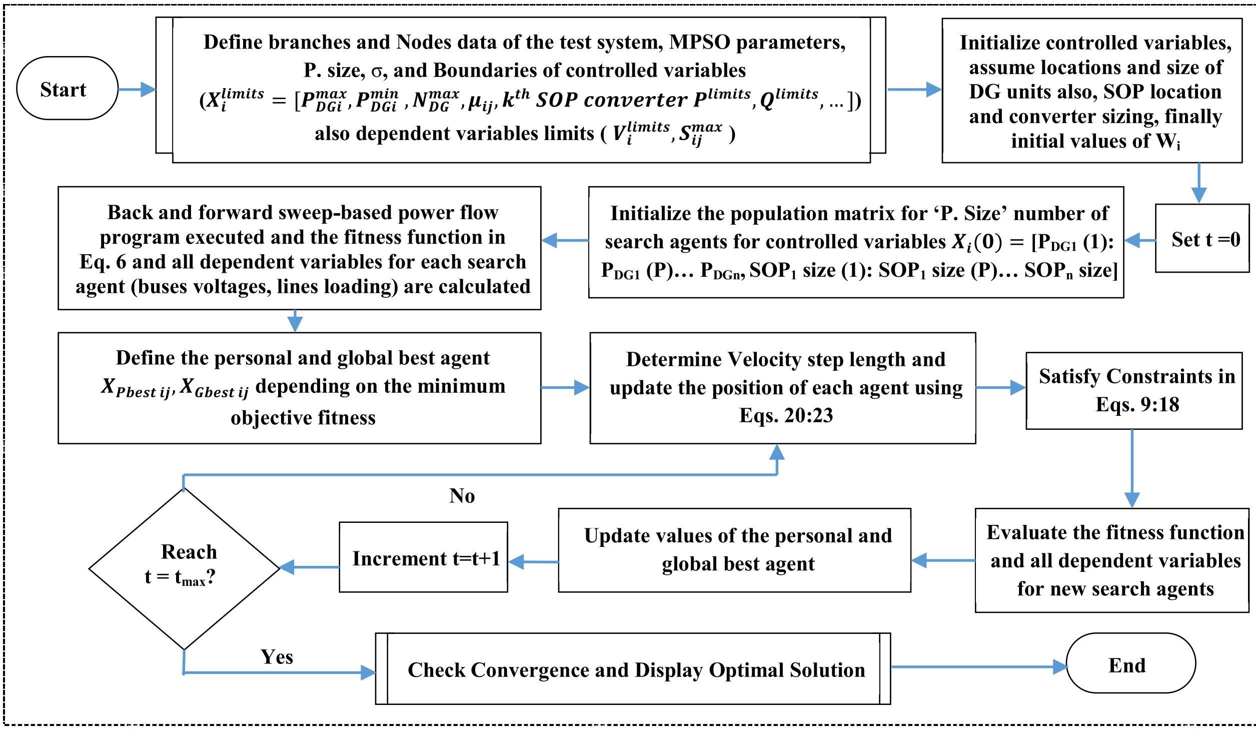

FIGURE 3. Process framework of the proposed algorithm.

C. COMBINATION OF MPSO AND STUDIED PROBLEM

This section concerns with how the optimization handle the power system problem. In other words, defining the power system problem controlled variables and objective function and also system constraints. The complete execution process of the proposed work using MPSO is arranged as in Fig. 3.

VI. SIMULATION RESULTS AND DISCUSSION

A. IEEE 33 NODE TEST SYSTEM SIMULATION RESULTS

Firstly, for the base case (Case 1) system real power losses are 202.6771kW and percentage summation of voltage deviation beyond nominal value calculated from Eq. (29) is 5.568 % also minimum voltage is 0.9131 of node 18. All cases of this system are compared to those in [21] as they used Modified Plant Growth Simulation Algorithm (MPGSA) without considering the SOPs into account while all tie switches in reconfiguration process are used. In Table 2 and for MPGSA, the power losses are the same, but the minimum voltage equals 0.9052 at bus 33 with 3.45 % accumulated voltage deviation.

$$\%Sum.V.D = ((\sum_{i\in Nf} |V_n - V_i|)/Nf) * 100 \quad (29)$$

In case 2, the MPGSA [21] opens some sectionalize switches and closed all tie switches except 37 but MPSO replaced one tie switch with one SOP and open one line as in table 2; that shows two different system reconfiguration using MPSO of the same cases 2 but for reconfiguration a and b where case 2-b give lower losses than MPGSA but gives higher voltage deviation. The voltage deviation can

TABLE 2. MPSO Results for Case 2 compared to Case 1.

	Case 1	MPGSA Case 2 [21]	MPSO Case 2 (a)	MPSO Case 2 (b)
P_{losses} (kW)	202.677	139.5	148.3243	134.861
Min. V_i (PU)	0.9131	0.9343 (N33)	0.9361 (N18)	0.9322 (N18)
$\%Sum.V.D$	5.568%	3.45%	3.76%	3.75%
Switching	---	Open switches: 7,9,14,32,37	L 5-6 open, SOP 12-22 closed	L 2-3 open, SOP 8-21 closed

be enhanced in case 2-a but still MPGSA [21] is better as indicated in Fig. 4.

So, in case 3, DGs penetration levels are incorporated for better performance with the basic configuration where DGs locations, sharing and also size both are controlled. Table 3 shows that MPGSA utilizes only three DGs as an optimal number with a total size limit of 2 MW (1.09 MW sharing) but MPSO proposed five units of total size 1.4 MW (0.751 MW sharing) which results in several improvements on real power losses from 92.87 kW to 71.303 kW and also the same of percentage active losses to total power losses.

Regarding to the minimum voltage which occurs at different nodes which increased to 0.9729 compared to 0.9585 with MPGSA; moreover $\%Sum.V.D$ decreased from 2.47% to 1.64%. Also, Figure 4 shows the extended voltage

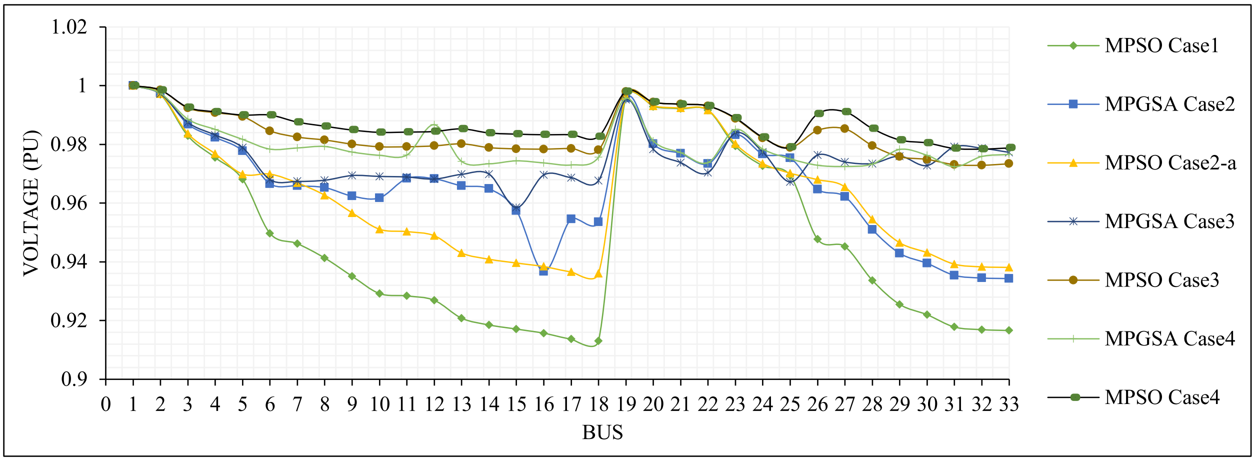

FIGURE 4. Voltage profile comparison between different cases.

TABLE 3. Comparison of MPSO Results for Case 3.

		MPSO					MPGSA [21]		
DG	@ bus	13	17	27	30	33	31	32	33
	Size (kW)	300	200	400	200	300	500	500	1000
	Share (kW)	148	76	278	144	106	247	180	665
Σ Share (MW)		0.751973					1.09		
P_{losses} (kW)		71.3034					92.87		
P_{losses} (%)		82.85%					54.17%		
$\%Sum.V.D$		1.64%					2.47%		
Min. V_i (PU)		0.9729 (N32)					0.9585 (N15)		

profile comparison that shows MPSO for case 3 is better than MPGSA at most of the buses within permissible limits.

Table 4 indicates results for Case 4 where *Pl* reached 32.11 compared with 47.17% by MPGSA that permits with more DG extensions. Moreover, preserving all other variables better such as power losses and voltage deviation ratio that are reduced also to 64.7106 and 1.3%. Voltage profile increased to better levels using MPSO as displayed in Figure 4; that shows that MPSO produces better voltages at most of the buses in case 4 even in case 3 is also better than case 4 using MPGSA and also satisfying voltage constraints.

TABLE 4. Comparison of MPSO Results for Case 4.

		MPSO					MPGSA (without SOP) [21]		
DG	@ bus	13	17	27	30	33	31	32	33
	Size (kW)	300	200	400	200	300	750	625	625
	Share (kW)	159	76	333	144	106	631	557	599
Switching		Line $_{5-6}$>> open & SOP $_{12-22}$>> closed					Open Switches 7, 14, 10,28, 31		
Σ Share (MW)		0.817134					1.7865		
P_{losses} (kW)		64.7106					72.23		
P_{losses} (%)		84.12%					64.36%		
$\%Sum.V.D$		1.30%					2.08%		
Min. V_i (PU)		0.9784 (N32)					0.9724 (N31)		
% *Pl*		32.11%					47.17%		

B. EFFECT OF HOSTING CAPACITY (β) OF DG UNITS ON SYSTEM LOSSES AND VOLTAGES WITH THE SAME CONFIGURATION OF BEST CASE 4 FOR IEEE 33 TEST SYSTEM

size of DG units can be limited according to available units or sizes so it is important to discuss this aspect and it is clear from table 5 that increasing the size of units for different capacity levels (β) also increases units sharing and consequently reduces power losses and voltage deviation.

TABLE 5. Size Limiting of DG units on system losses and voltages.

(β) (kVA)	DG Distribution (kW)						P_{Losses} (kW)	% $Sum. V.D$	Min. V_i (PU)
400	@ bus	17	30	33	13	27	87.5	2.56	0.959
	Size	50	50	100	100	100			
	Share	38.22	49.937	98.78	97.11	97.48			
600	@ bus	17	30	33	13	27	71.9	1.87	0.969
	Size	150	150	100	100	100			
	Share	121.18	148.15	95.78	97.66	95.48			
700	@ bus	17	30	33	13	27	69.6	1.63	0.974
	Size	200	200	100	100	100			
	Share	142.29	197.54	95.78	97.66	95.47			
900	@ bus	17	30	33	13	27	65.7	1.38	0.977
	Size	200	200	100	200	200			
	Share	76.26	199.92	99.74	176.07	194.99			
1400	@ bus	17	30	33	13	27	64.7	1.30	0.978
	Size	200	200	300	300	400			
	Share	76.14	143.51	106.17	158.67	332.64			

Also, it is noted that when the limit is $\beta = 800$ kVA or $\beta = 900$ kVA there is no big difference compared to best case 4 when $\beta = 1400$ kVA so it is not conditioned to follow the best-case limit Also, minimum voltage values (for all cases at node 32) and also %sum. V.D is very close. Figure 5 refers to the influence of DG units sizing on the voltage profile; it also shows that the voltage profile for 900 kW limit is very near to the best case.

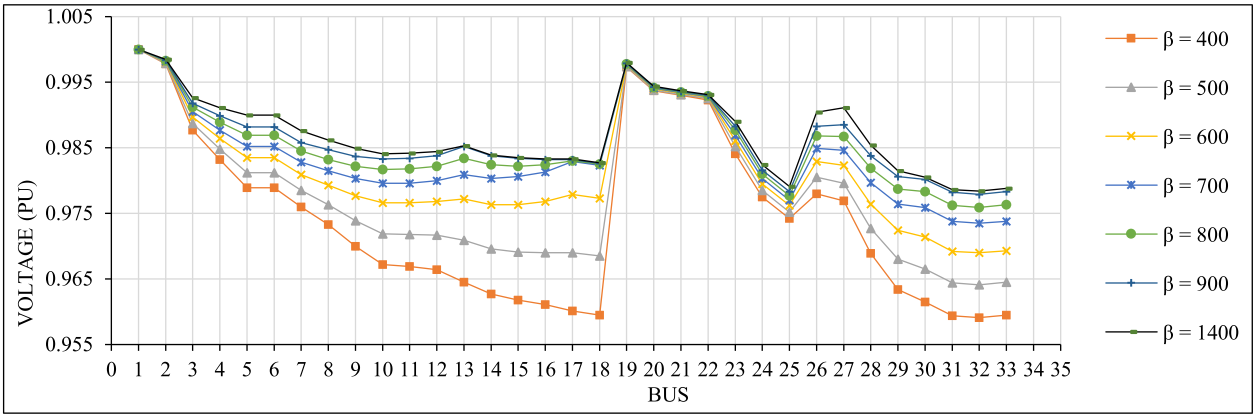

FIGURE 5. Effect of DG size limiting on the voltage profile for $\beta = 400 : 1400$.

TABLE 6. Effects of Size Limiting of DG units on system losses and voltages.

Σ size (kVA) / NDG		DG Distribution (kW)					P_{losses} (kW)	% $Sum.V.D$	Min. V_i (PU)
1400 / 5	@ bus	17	30	33	13	27	64.71	1.303	0.9784 (N32)
	Size	200	200	300	300	400			
	Share	76.14	143.51	106.17	158.67	332.64			
900 / 4	@ bus	17	30	33	13		70.71	1.462	0.9773 (N25)
	Size	100	300	200	300				
	Share	76.02	273.97	104.67	200.72				
1100 / 4	@ bus	17	33	13	27		66.02	1.333	0.9781 (N18)
	Size	200	200	300	400				
	Share	75.77	191.44	159.39	387.50				
1400 / 4	@ bus	30	33	13	27		65.86	1.349	0.9774 (N31)
	Size	200	150	300	350				
	Share	146.33	104.81	235.47	329.50				
800 / 3	@ bus	17	30	33			75.81	1.643	0.9767 (N25)
	Size	300	300	200					
	Share	206.61	289.87	108.90					
750 / 3	@bus	30	33	13			71.84	1.5	0.9773 (N25)
	Size	300	150	300					
	Share	273.09	104.78	279.33					
1200 / 3	@ bus	33	13	27			67.16	1.384	0.9773 (N31)
	Size	400	400	400					
	Share	194.29	237.84	375.88					
1400 / 3	@ bus	30	13	27			66.99	1.373	0.9755 (N32)
	Size	300	300	400					
	Share	251.87	235.48	329.06					

C. EFFECT OF DG UNITS' NUMBER WITH THE BEST LOCATIONS AND SIZING AND SAME RECONFIGURATION OF BEST CASE 4 FOR IEEE 33 TEST SYSTEM

Table 6 shows 7- cases with a different number of DG units with different locations/total size are compared with the best case. It is found that the power losses equal 65.8581 kW which it is very near to the best results obtained in case 4. Also, this can be if we used only 3-DG units with a total size of 1000 kVA where losses reached 66.988 kW. A great effect on system losses and voltage profile are noticed if four DG units are used with a total size of 1100 kVA are located at buses 13, 17, 27. Also, the nodes' voltages are very near to the nominal values with an improved voltage profile. The minimum voltage value is different according to the number of DG units. In this regard, Figure 6 shows the effects of varied DG number (3-5) and their sizing and locations on the power loess and minimum voltage level. For the studied cases, the minimum voltage levels are nearly constant while the % sum. V.D has slight changes and nearly very close. By using 3-units or 4-units it was found good results are compared with the best case.

D. LOSSES AND VOLTAGE PROFILE REGARDING SOP CAPACITY AND CONTROL FOR IEEE 33 TEST SYSTEM

For different reconfiguration cases, SOP controls the active/reactive power flow through the lines. Its capacity must be selected to satisfy these controlled values. From different minimum capacity values in table 7 SOP capacity should be 300 kVA for future extensions or extra loadings. Figure 7.a shows that the capacity of SOP can be controlled for different

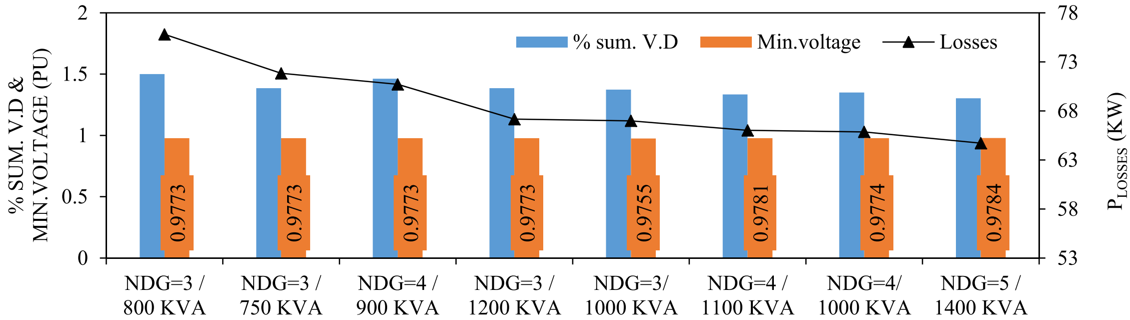

FIGURE 6. Effects of varied DG number, sizing, and locations on the power loess and the minimum voltage level.

TABLE 7. SOP control and minimum capacity for different cases.

Case	SOP control			% sum V.D	Min. V_i (PU)	P_{losses} (kW)
	P (kW)	Q (kVAR)	MIN. Capacity (kVA)			
Case 4	134.09	28.335	137.053	1.303	0.9784	64.71
NDG=4/ 900kVA	128.361	64.773	143.777	1.462	0.9773	70.71
NDG=3/ 800kVA	142.7	19.683	144.09	1.643	0.9767	75.81
β = 500	132.2	99.723	165.602	2.212	0.9641	77.75
β = 400	197.9	53.781	205.084	2.561	0.9591	87.54

cases and therefore their effects on the power losses and voltage profile are noticed. In table 8, increasing load (P&Q with the same percentage) from maximum to 20% in steps over maximum leads to a nearly linear increase of system losses and voltage deviations.

TABLE 8. SOP control to follow different load increase cases.

Load Increase	SOP control			% $Sum.V.D$	Min. V_i (PU)	P_{losses} (kW)
	MIN. Capacity (kVA)	P (kW)	Q (kVAR)			
Max.	137.05	134.1	28.335	1.303	0.9784	64.7
5%	151.57	148.4	30.999	1.375	0.9772	71.5
10%	166.66	163.1	34.557	1.436	0.9762	78.7
15%	182.4	178.5	37.719	1.501	0.9751	86.2
20%	199.37	195.1	41.157	1.572	0.9739	94.1

Therefore, SOP control and capacity must follow that increased also to face an increase in the power flow of lines and give a modified optimal solution which is shown in Figure 7.b. So, the same as concluded from table 7; 300 kVA capacity is suitable for SOP for this system. An important hint here is that with that load increase DG sharing is kept the same of the best case.

To summarize the previous results; Multi-objective optimization is a trail to collect weighted priorities of some

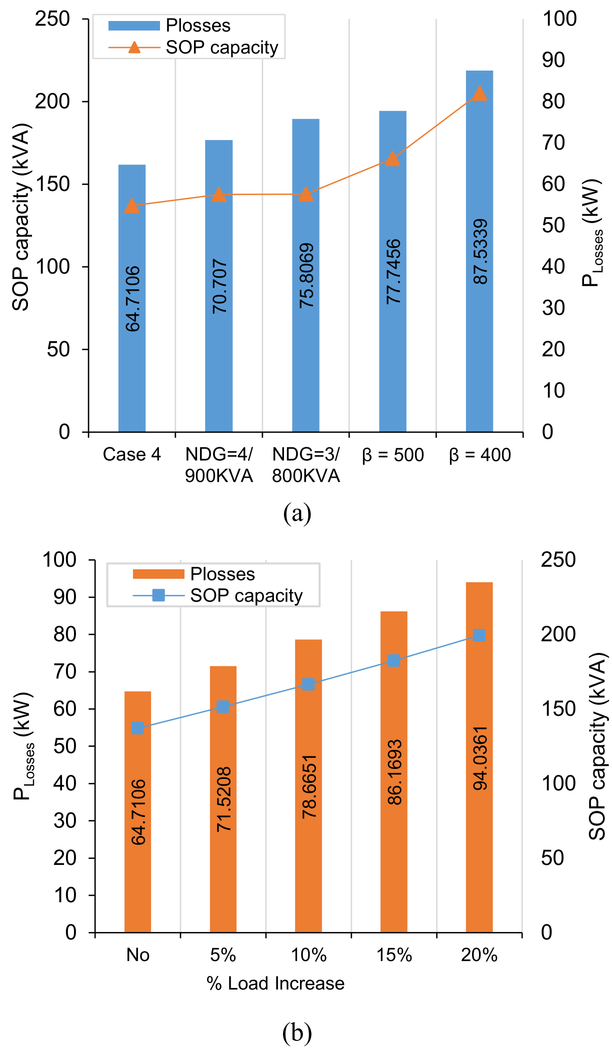

FIGURE 7. Effect of different study cases on system losses under SOP control (Tables 7, 8).

objectives to be achieved at the same time. So, in this work, a comprehensive optimization is performed to investigate the shaded work area in Figure 8 that illustrates the effect of increasing penetration level on the system losses and voltage and also using SOPs to increase the penetration level of DG units.

TABLE 9. Comparison of IEEE 69 bus system results compared to those in literature.

Case 3, and number of DG units are limited to 3 compared to base case 1							
Method	DG Share (kW)	@ bus	P_{losses} (kW) Value	P_{losses} (kW) Decay (%)	V_i (PU) Min.	V_i (PU) Mean	% *Pl*
Case 1	-	-	224.89	-	0.909	0.973	0
S. A DE [20]	603	17	117.16	48	0.940	0.987	49.1
	634	52					
	662	60					
DAPSO [20]	500	9	83.68	63	0.972	0.989	76.2
	521	33					
	1929	62					
MPSO	450	27	73.99	65	0.979	0.992	33.33
	550	33					
	500	61					
Case 3, but number of DG units is limited to 1							
APSO [21]	1647.7	64	96.59	57	….	….	42.6
	1809.1	63	86.98	61	….	….	46.7
	1846.8	62	84.72	62	….	….	47.7
	1872.7	61	83.22	63	0.953	….	48.4
MPSO	1500	64	96.58	57	0.967	0.986	31.5
	1600	63	86.97	61	0.968	0.987	34.3
	1650	62	84.71	62	0.968	0.987	35.5
	1700	61	83.21	63	0.968	0.988	36.7

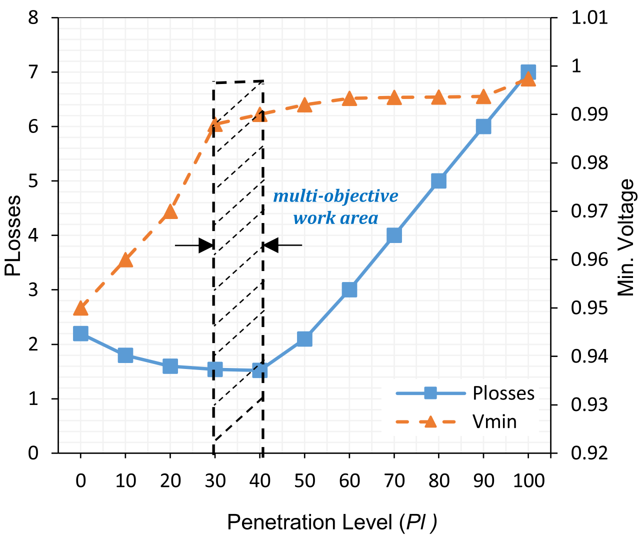

FIGURE 8. DG penetration level effect on system losses and minimum voltage.

E. IEEE 69 NODE TEST SYSTEM SIMULATION RESULTS

The base case 1 of this the second test system, IEEE 69 node power, results 224.98 kW losses and the minimum voltage is 0.9092 PU Then, results using MPSO with the system basic topology and without SOP (Case 3) are compared with other optimization techniques in [20] that used various PSO and DE algorithms with three DG units or only single DG unit as prevailed in table 9.

Case 3 for IEEE 69 system in table 9 showed that MPSO gives losses 73.9972 kW with a percentage decline of loses 65.11 % of basic losses also minimum voltage raised to 0.9789 PU which is better than all techniques used in [20] and with lower *Pl* 33.33 %. Also in [21] simulation results of APSO are compared and this also proved the capabilities of proposed MPSO in enhancing system performance. With only one DG unite at node 61 reduces losses to 83.21 kW with a percentage decrease of 63.02% and a minimum voltage of 0.9683 PU also, with the lower penetration levels of 36.7%, which is very close to APSO [21] but with larger penetration level 48.36 %. Lower *Pl* results in more DG units reserve.

But after inserting SOP and selecting the best system topology is applied with Distributed DG units to get better performance of the system (Case 4: best case). where the topology reconstruction implemented utilizing SOP installed between the nodes 27 and 65 and switches between nodes 10 −11 and 55 −56 are disconnected.

Variation of the number of DG units is applied with the same configuration and SOP position at different control settings in Table 10. Table 10 also, shows that the 3-DGs produced the best case of losses 70.78 kW and % V.D 0.784. Using 2-DG units leads to good results as the power losses equal 72.34 with % V.D of 1.005 which is very close to the best case. Moreover, the penetration levels are reached to 39.9% in case of integrating 3 DG units. Also, in the case of single DG unit results was acceptable.

Furthermore, the minimum voltage is enhanced from 0.9092 PU of the base case to 0.9799 in the best case of three DG units as in the circled region in Fig. 9 that shows also that voltage profile is enhanced to a good extent. Table 11 studies the loading effect for the IEEE 69 system with the same configuration and DG penetration level of the best case 4.

TABLE 10. Summary of different number DG units of IEEE 69 bus system for case 4 compared to case 1.

Case	DG Distribution			Power Losses		SOP control			Bus Voltage			% *PI*
	Size (kW)	Share (kW)	@ bus	Value (kW)	Decline (%)	P (kW)	Q (kVAR)	Min. Size (kVA)	Min. (PU)	at bus	% V. D	
Case 1	-	-	-	224.89	-	-		-	0.9092	56	2.662	0
Case4 /1-DG	1300	625.76	61	79.51	64.65	159.64	103.96	190.51	0.9691	27	1.214	28.29
Case4 /2-DG	400	99.50	27	72.34	67.83	95.715	67.35	117.036	0.9741	56	1.005	35.37
	1200	548.21	61									
Case4 /3-DG	400	130.44	27	70.78	68.52	96.312	69.054	118.51	0.9799	56	0.784	39.39
	400	16.325	33									
	1000	601.96	61									

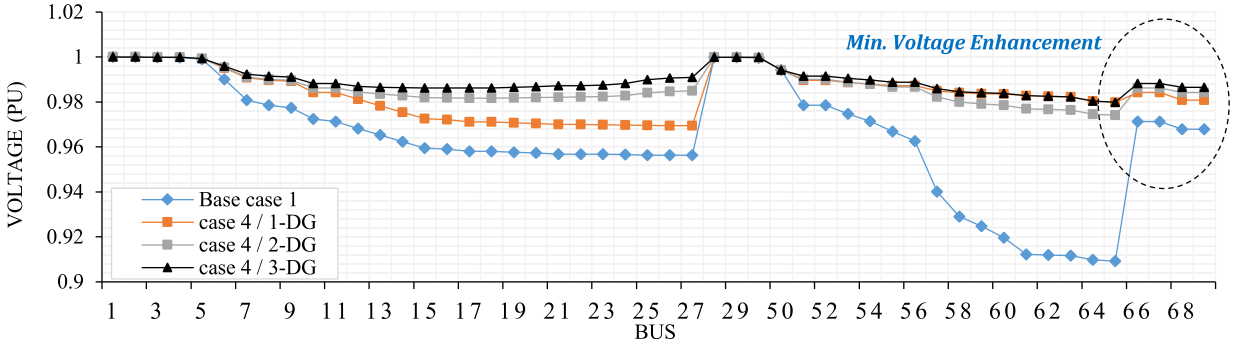

FIGURE 9. Voltage profile enhancement for cases in table 10.

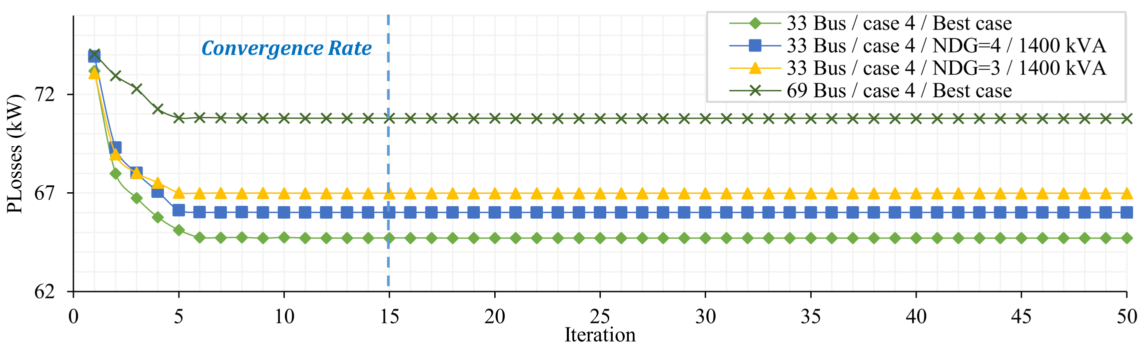

FIGURE 10. MPSO convergence curves for different cases.

TABLE 11. SOP control for different loading conditions of 69 node system.

Table XI
SOP control for different loading conditions of 69 node system

% Load Increase	SOP control			% sum. V.D	Min. V_i (PU)	P_{losses} (kW)
	MIN. Capacity (kVA)	P (kW)	Q (kVAR)			
No	118.51	96.31	69.05	0.7839	0.9799	70.79
5%	130.97	106.12	76.75	0.8264	0.9789	78.21
10%	144.17	116.19	85.35	0.8619	0.9779	86.01
15%	157.23	130.49	87.72	0.8935	0.9774	94.21
20%	177.03	128.14	122.15	0.9826	0.9734	102.98

In table, 11 load is increased to 20 % over nominal value by 5% step to show the performance of the algorithm and SOP in mitigating this change and maintain all system variables within permissible limits.

This results also linear increase in system losses and V.D so to reduce this increase; another DG unit may be used in other locations or modification in SOP position. The SOP capacity suitable for this system is 300 kVA.

F. TOOL ASSESSMENTS

Proficiency of MPSO tool regarding to the generations number to reach optimal solution is captured here, which reaches optima fast as displayed Figure 10 that collected the convergence curves of the tool and also figure shows that it is required only 10 to 15 iterations to reach an optimal solution with this large of controlled variables.

A comparison between MPSO and other optimization techniques in literature is necessary for clarifying the importance

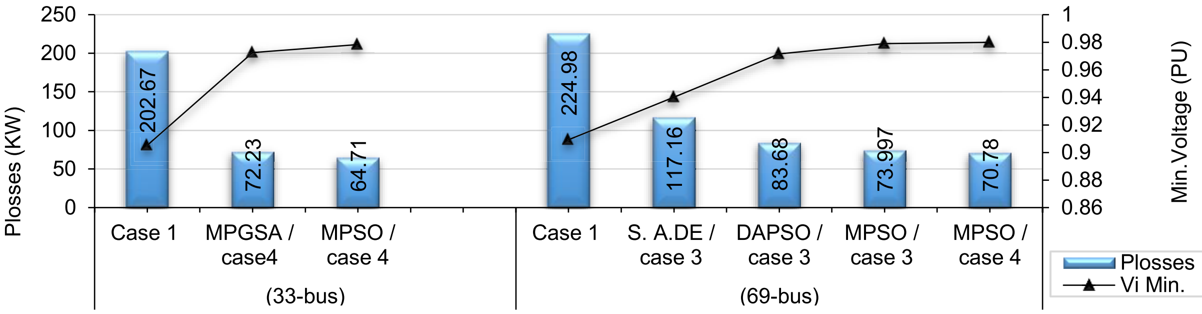

FIGURE 11. Different optimization algorithms for various cases of systems IEEE 33,69 systems.

of tool selection to enhance results which can be summarized with a graphical interface in Figure 11. For IEEE 33 bus system, it results in the best results between all algorithms as it reaches to 64.7106 kW compared to best case in other studies of 72.23 kW and minimum voltage is enhanced to 0.9784 PU; also, for the system IEEE 69 bus MPSO reached to the lowest losses 73.9972 kW where the best case in the literature is 83.22 kW and minimum voltage increased to 0.9789 PU.

VII. CONCLUSION

This paper presented a holistic framework to mitigate distributed generation with the innovative power electronic devices SOPs for enabling the most convenient system reconfiguration aiming at better energy utilization of ADNs. An optimal network layout has been mathematically modeled as a multi-objective outline with relaxing factors to transform it into a single objective function. The validation of the proposed model is achieved through two different standard IEEE systems. Simulation results proved that the proposed model leads to the lowest power losses with an enhanced voltage profile. For IEEE 33 node system proposed MPSO succeeded to define the multi-objective work area while losses reduced by 84.12 % compared to base case and by 20% compared to literature research. In addition to the mentioned benefits above, SOP control and presence helped in choosing the best reconfiguration and controlled on the power flow through the network to achieve the targeted benefits and helped in increasing the hosting capacity of DG units. Regarding to 69 node test system; Losses reduced by 21% compared to well-known optimization techniques like DE and DAPSO with better voltage profile. Also studying the effect of sizing, number and locations of DGs show the extent of enhancements could be achieved with the available DG units. An efficient MPSO has been assessed to give better results at acceptable convergence rates.

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