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Optimal Allocation of Distributed Generation and Distribution Static Compensator Using Improved Multi-Objective Function and INFO Optimization Algorithm

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***Abstract*—** This paper presents an improved multi-objective function (MOF) by simultaneously applying the voltage stability index (VSI) and system loadability (SL) for sustainable operation of a distribution network via the optimum location and sizing of distributed generations (DGs) and distribution static compensators (DSTATCOMs). In other words, with the approach of increasing the voltage profile, first, the candidate busbar for installation is determined based on the VSI, and then, by applying higher weights in the mentioned function, more priority is given to these busbars. This function is optimized by weighting candidate busbars using the INFO algorithm. The system loadability is included in the multi-objective function along with the total costs (involving the investment costs of distribution static compensators and distributed generations) and network loss. The sizes of the DGs and DSTATCOMs are enhanced using an INFO optimization algorithm. The operational economic benefits are represented by calculating the annual cost savings. The effectiveness of the proposed methodology is evaluated on 33- and 69-node distribution networks. Based on the findings, the proposed methodology is found to be more effective compared to other methods reported in the literature, and it provides more optimal answers compared to the non-consideration of the VSI.

***Keywords*—** Distributed generation; distribution static compensators; Voltage stability index; System loadability; INFO optimization algorithm.

Nomenclature

C_{DG-inv}	Distributed generation investment cost [$/kW]	W_{ij}	Weighting coefficient of the cost function
$C_{DG-O\&M}$	Distributed generation operation and maintenance cost [$/kWh]	pen	Penalty coefficient
$C_{DSTATCOM-inv}$	Distributed static compensator investment cost [$/kVAR]	λ	Loadability
C_{loss}	Cost of losses [$/kWh]	λ_0	Nominal system loadability
i	index of bus number	λ_{max}	Maximum loadability
I	Branch current (p.u.)	mm	Branch number connecting node ‘mm’ and node ‘mm+1’
OF_{cost}	Objective function of costs [$]	$I(mm)$	Current of branch ‘mm’
OF_1	Total Power Losses	$V(mm)$	Voltage magnitude of node ‘mm’
OF_2	DG O&M and Investment Cost	$V(mm+1)$	Voltage magnitude of node ‘mm+1’
OF_3	DSTATCOM Investment Cost	$r(mm)$	Resistance of branch ‘mm’
$OF_{Loadability}$	Loadability objective function	$X(mm)$	Reactance of branch ‘mm’
P	Local active load of bus (p.u.)	$Q(mm+1)$	Total reactive power fed through node ‘mm+1’

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P_0	Nominal active load [kW]	$P(mm+1)$	Total real power fed through node 'mm+1'
P_{loss}	Active power loss [kW]	N_{mm}	Voltage stability index for node selection
Q	Local reactive load of bus (p.u.)	N_{node}	Node with the highest voltage stability index
Q_0	Nominal reactive load [kVAR]	MOF	Multi-Objective Function
$Q_{DSTATCOM}$	Distributed static compensator injected reactive power (p.u.)	VSI	Voltage Stability Index
Q_{min}	Minimum distributed static Compensator capacity [kVAR]	SL	System Loadability
Q_{max}	Maximum distributed static compensator capacity [kVAR]	DG	Distributed Generation
a	The quadratic coefficient of the quadratic equation	DSTATCOM	Distribution Static Compensator
b	The linear coefficient of the quadratic equation	O&M	Operation and Maintenance
c	The constant or the free term of the quadratic equation	GA	Genetic Algorithm
D_i	Distance of the ith points from the origin	PSO	Particle Swarm Optimization
X	Branch reactance (p.u.)	ABCA	Artificial Bee Colony Algorithm
R	Branch resistance (p.u.)	ACO	Ant Colony Optimization
S_{DG}	Distributed generation capacity [kVA]	ALOA	Ant Lion Optimization Algorithm
S_{max}	Maximum distributed generation capacity [kVA]	CSA	Cuckoo Search Algorithm
S_{min}	Minimum distributed generation capacity [kVA]	FPA	Flower Pollination Algorithm
U	Bus voltage (p.u.)	WHOA	Wild Horse Optimization Algorithm
U_{min}	Minimum acceptable voltage (p.u.)	INFO	WeIghted meaN oF vectOrs
U_{max}	Maximum acceptable voltage (p.u.)		

1. INTRODUCTION

Distributed generation (DG) has recently attracted significant attention for integration into power distribution systems because of its several benefits, such as voltage profile enhancement and power loss reduction with improved security and reliability [1-2]. DGs can support the system voltage, decrease the system losses, relieve the distribution congestion, delay the system upgradation, and enhance the system's security and reliability [3]. Various issues have been discussed by Walling et al. [4] regarding power penetration by DGs in distribution networks. Issues related to determining the optimum size and location of DG units with the aim of reducing power losses, enhancing the voltage profile, and stabilizing the voltage of distribution networks have been active research areas in the past few years. Appropriate sizing and placement of DG units are essential for preventing overvoltage and power losses [5]. Das and Gampa presented the optimal sizing and placement of DGs through a genetic algorithm (GA) that considers average hourly load changes [6]. A multi-objective performance index was formulated by Mohandas et al. to improve the voltage stability by using the optimal sizing and placement of DGs via the artificial bee colony algorithm (ABCA) [7]. Kumar and Murty presented a heuristic approach based on the voltage stability index (VSI) and the power stability index for the optimal placement of DGs while considering the load growth, voltage stability margin, and combined load power factor [8]. With the approach of load time sequence features to optimally place the DG, a multi-objective function was presented and optimized by Liu et al. [8] using the improved non-dominated sorting GA-II algorithm. Viral and Khatod [9] presented an analytical method for the reactive and active elements of branch currents regarding loss minimization through optimal DG sizing and placement. Optimization procedures consist of a series of iterative algorithms that facilitate the achievement of desired system characteristics by minimizing a specifically selected objective function [10]. Multi-objective optimization models have been developed in various studies [11–13]. A methodology was proposed by Akhlaghi and Moravej [14] using the cuckoo search algorithm to optimize the sizing and placement of DGs within the distribution network. A comparison was performed between the cuckoo algorithm [14], genetic algorithm, and particle swarm optimization methods to assess their effectiveness. Optimal sizing and placement were proposed by Hung et al. [15] in distribution networks, considering both dispatchable and undispatchable DGs. Only undispatchable DGs (biomass) were considered in the present study. Kumar and Murthy [16] compared different DG allocation approaches to optimize placement within a radial distribution network. Bohre et al. [17] combined particle swarm optimization (PSO) and GA in load models to optimize DG sizing and placement within distribution networks. In [18], it was shown that proper DG allocation can reduce costs and increase reliability. An analytical method was used to reduce the losses in [19]. In [20], collective animal behavior optimization was used to minimize voltage deviations and line losses in distribution networks. Taking loadability into account, Karami et al. [21] used a genetic algorithm to optimize the sizing and location of DGs and distribution static compensators. Due to the development of distributed systems, the limited active and reactive powers of DG sources, increased demands and loads, and high installation costs, the use of DG sources is limited. Therefore, it is essential to use an alternative FACT device, such as a DSTATCOM, for which the implementation cost is lower than that of the new distribution networks, to enhance the voltage profile, losses, and power factor. The sizing and placement of DGs and DSTATCOMs must be simultaneously studied within the optimization procedure to achieve a power system's optimal operation. In [22], the optimal placement and size of DGs and a DSTATCOM to reduce total power loss were studied using PSO. In [23], the simultaneous optimal placement and reconfiguration of DSTATCOMs and DGs were presented using fuzzy and ant colony optimization (ACO) to decrease losses and improve the voltage profile. In [22-23], multi-objective optimization and loadability studies were conducted, and Pareto analysis was considered.

It is worth noting that the optimal number of DGs and DSTATCOMs is an important issue in the investment cost of installed devices in a system and has not been considered in the literature. In those studies, the researchers considered a limited number of these two devices in their simultaneous locating and sizing; for example, two DGs and two DSTATCOMs or three of each; this issue is considered here as well. The investment costs are inserted into the objective function to determine the optimal number of devices for system cost minimization. If too many devices are installed, system costs will increase; however, if a few devices are installed, the other objectives of this study, such as loadability improvement or loss reduction, cannot be supported. Therefore, the quantity of each type of device that should be installed is critical and is considered in this paper in the objective function. Abdelaziz et al. [24] similarly proposed a model based on a multi-objective function (MOF) using parallel architectures of graphics processing units in DG allocation that is capable of handling huge computational burdens. It has been suggested that [25] Cholesky decomposition and Latin hypercube sampling can handle related random data. However, the problem is that the simulation-oriented models [24–25] incur enormous computational costs. Therefore, an affine arithmetic interval decision-making method is presented [26] that provides strong optimal results. However, as an approximate technique, it only considers the upper and lower bounds of indefinite parameters.

In [27], the multi-objective optimal planning of wind- and capacitor banks and solar-distributed generations was investigated by considering various sources of uncertainty, such as plug-in electric vehicles. Hui et al. used a differential evolution algorithm to optimize the location, size, and power factor of the DG to minimize network losses and maximize DG integrity [28].

In this paper, INFO and Pareto optimization are used to evaluate the placement, number, and size of DSTATCOMs and DGs in distributed systems while simultaneously considering system loadability (SL) and total cost. The total cost includes the installation, operation, and maintenance (O&M) costs of the DGs and DSTATCOMs and the losses. This study considers a modified quadratic objective function for the sustainable operation of a distribution network by enhancing the voltage profile and reducing the reactive and real power losses. In other words, we considered the enhancement of the voltage profile first by determining the candidate busbar for installation based on the VSI and then by giving a higher priority to these busbars by applying higher weights to the mentioned function. They indicate more optimal answers than do non-considerations of the VSI. In addition, we enhance this function by weighting the candidate busbars and employing an INFO algorithm to discover the optimal answer to the function [28-31]. Our work differs from previous studies because we have improved this multi-objective function. In [32] The flower pollination algorithm is explained as a static VAR compensator to mitigate power system oscillations in the distribution system. Also, in [33], the Ant Lion Optimization Algorithm has been used in optimal allocations and DG sizing. An improved whale optimization approach was proposed to reduce power losses in a distribution system according to the operational constraints of the system [34]. The cuckoo search technique for optimizing the location of STATCOM and increasing the loadability in multi-machine power systems was proposed in [35]. To reduce the annual cost, the allocation of DSTATCOMs in the radial distribution network of 33 and 69 using the black widow optimization algorithm was presented in [36]. The optimal allocation of PV-STATCOM to reduce losses and improve voltage characteristics using the hunter-prey optimization algorithm was proposed in [37]. In [38], under healthy and unhealthy environmental conditions, the location and optimal size of DSTATCOMs and DGs were determined using the dwarf mongoose optimization algorithm. In [39], an optimal simultaneous scheduling approach for DG and electric vehicle (EV) according to demand response using a self-adaptive particle swarm optimization algorithm and the clustering technique K-means was presented. In [40], a battle royale optimization algorithm was proposed to optimize the placement of EVs and reduce the active and reactive power losses in a distribution system with DGs. The optimal allocation of EVs in the distribution system including DG and DSTATCOM with the objectives of reducing voltage deviation, reducing power losses, and using the African vulture hybrid optimization algorithm and pattern search was proposed in [41]. The main objectives of the reviewed literature are listed in Table 1. Considering this table, it can be seen that in most of the methods in the literature, the objective function is based on loss reduction and economic analysis. Of course, very few studies have considered VSIs or SLs in MOFs. It is noticed that SL and VSI have not been presented simultaneously in the literature so far, and our main motivation in this paper is to use VSI and SL simultaneously for sustainable operation of distribution networks. With this approach, an improved MOF with the simultaneous use of VSI and SL is presented as the main innovative contribution of the proposed method compared to previous methods for optimizing the location and size of DGs as well as DSTATCOM.

Table 1. Main objectives of the literature review.

Ref.	Optimal allocation of DGs	Optimal allocation of DSTATCOM	Objective Function			
			Loss reduction	Economic analysis	System loadability (SL)	Voltage stability index (VSI)
[5]	✓		✓	✓		
[6, 7]	✓					✓
[8]	✓			✓		
[9, 10, 12-14, 17]	✓		✓			
[11]	✓		✓			✓
[15]	✓		✓	✓		✓
[19]	✓	✓		✓	✓	
[20]	✓	✓		✓		
[21, 22]	✓	✓	✓			✓
[28]	✓	✓	✓			
Proposed	✓	✓	✓	✓	✓	✓

In addition, we considered the enhancement of the voltage profile, first determined the candidate busbar for installation based on the VSI, and then gave a higher priority to these bus bars by applying higher weights to the mentioned function. The SL is included in the MOF along with the total costs, including the investment costs of distribution static compensators, distributed generations, and network loss. The optimal solution was investigated in two types: continuous (DSTATCOMs and DGs size) and distinct (number, size, and location of devices) by considering the VSI and SL. The proposed MOF was run on the IEEE 33- and 69-bus test systems and the results are provided. It can be concluded that the advantages of the proposed technique are:

- Simultaneous sizing and location of DGs and DSTATCOMs.
- VSI-based sensitivity analysis was performed to determine the optimum positions of the DSTATCOMs and DG units.
- Considering the operating, maintenance, and investment costs of devices.
- Identifying the optimal number of devices, which is crucial from a system cost point of view.
- Considering the total loss and loadability of the system.
- Adapting MOFs to objectives and system.

2. CANDIDATE NODES FOR DG AND DSTATCOM PLACEMENTS

This algorithm has three operators: rule update, vector combination, and local search, which update the positions of the vectors in each generation. In this section, we determine the busbars that are prioritized for installing DSTATCOMs and DGs using the sensitivity analysis of the VSI. In fact, we identify candidate busbars and give them higher priority in subsequent calculations by applying more weights. Node selection was performed via sensitivity analysis. In this method, the selected node to set the DGs and DSTATCOMs must be able to maintain the desired targets to reduce the voltage profile of power loss. As shown in Fig. 1, the sensitivity index parameters used in this study can be well clarified by the contribution of the electrical correspondent 'mm'.

In the circuit diagram representation, the branch 'mm' links node '*mm*' to 'mm+1'. 'P(*mm*+1)', 'Q(*mm*+1)', and 'V(*mm*+1)' are the real and reactive power fed through node '*mm*+1' and the magnitude of the voltage at node '*mm*+1', respectively. The equivalent circuit diagram shown in Fig. 1 shows the following relations are held [29].

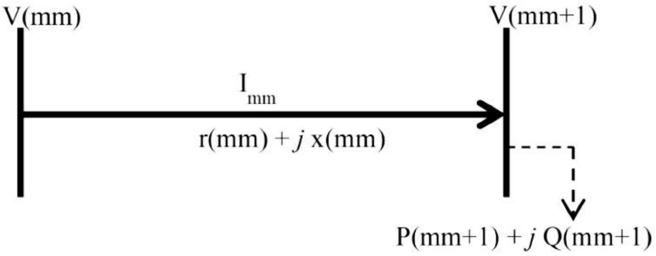


Fig. 1. Equivalent circuit diagram.

$$I(mm)=\frac{V(mm)-V(mm+1)}{r(mm)+jx(mm)} \tag{1}$$

$$P(mm+1)-jQ(mm+1)=V(mm+1)^{*}I(mm) \tag{2}$$

From Eqs. (1) and (2), we obtain:

$$\begin{aligned}&|V(mm+1)|^{4}-\left\{|V(mm)|^{2}-2P(mm+1)\,r(mm)-2Q(mm+1)\,x(mm)\right\}|V(mm+1)|^{2}\\&+\left\{P^{2}(mm+1)+Q^{2}(mm+1)\right\}\left\{r^{2}(mm)+x^{2}(mm)\right\}=0\end{aligned} \tag{3}$$

Eq. (3) can be written as a quadratic equation as follows:

$$|V(mm+1)|^{4}-b.|V(mm+1)|^{2}+c=0 \tag{4}$$

where

a = 1, and

$$b=|V(mm)|^{2}-2P(mm+1)\,r(mm)-2Q(mm+1)\,x(mm)$$

$$c=(P^{2}(mm+1)+Q^{2}(mm+1))(r^{2}(mm)+x^{2}(mm))$$

The real solution $|V(mm+1)|^{2}$ exists if this condition holds:

$$-(b)^{2}-4.a.c\geq 0 \tag{5}$$

After simplifying Eq. (4), the following relation is obtained:

$$|V(mm+1)|^{4}\geq 4\left[P(mm+1)x(mm)-Q(mm+1)r(mm)\right]^{2}+4\left[P(mm+1)r(mm)+Q(mm+1)x(mm)\right]|V(mm+1)|^{2}$$

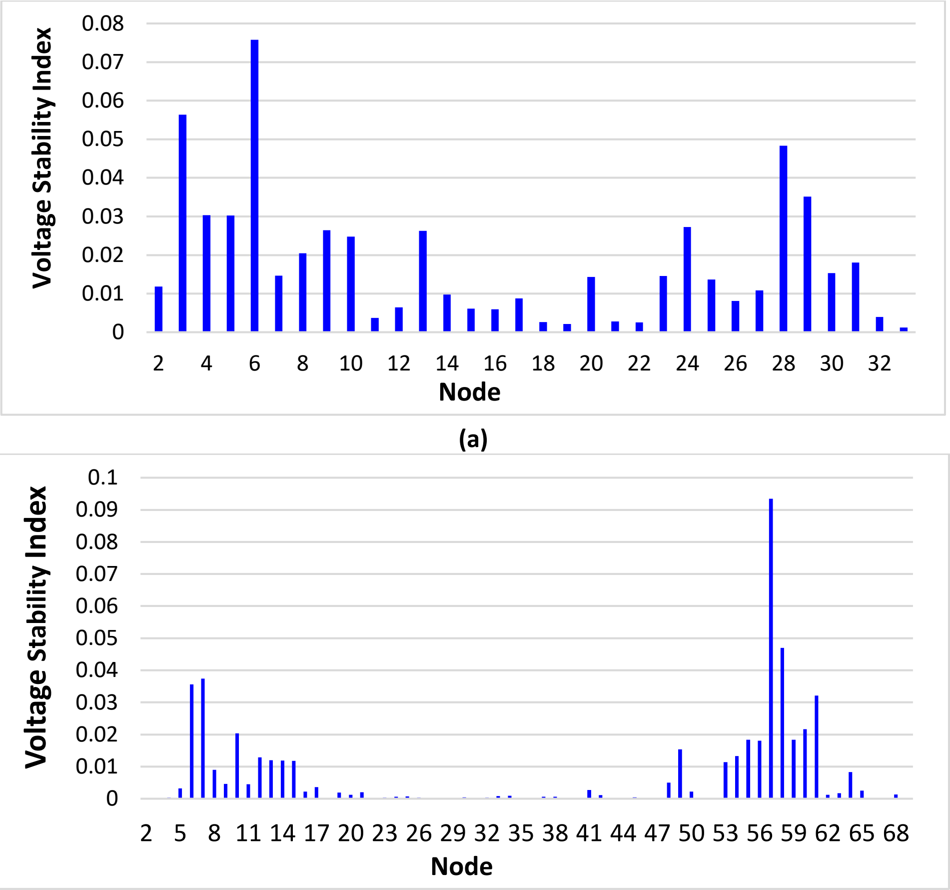
Eq. (6) is expressed as follows:

$$N_{mm} = \frac{4\{\, P(mm+1)x(mm) - Q(mm+1)r(mm)\,\}^2 + 4\{\, P(mm+1)r(mm) + Q(mm+1)x(mm)\,\}|V(mm+1)|^2}{|V(mm+1)|^4} \tag{6}$$

where

$$P(mm+1) = \mathrm{Re}\left\{V^*(mm+1).I(mm)\right\}$$
$$Q(mm+1) = -\mathrm{Im}\left\{V^*(mm+1).I(mm)\right\}$$

As defined in Eq. (6), the term 'N_{mm}' presents the VSI. Fig. 2 shows the value of the voltage stability index for 33-buse and 69-buse systems. The node at which 'N_{mm}' is maximum is more sensitive to voltage collapse.



(a)

(b)

Fig. 2. Sensitivity index values for: a) 33-node; b) 69-node distribution networks.

At such nodes, the scope for enhancing the distribution network's voltage stability extends. Therefore, nodes with a greater VSI are taken for placing the DGs and DSTATCOMs. By obtaining the sensitivity index 'N_{mm}' for all nodes, the stability index values are organized in descending order, and the maximum N_{mm} is obtained according to Eq. (7).

$$N_{node} = \max(N_{mm}) \tag{7}$$

The node with the maximum voltage sensitivity index is more appropriate for the optimal position of the DGs and DSTATCOM. In Fig. 2, the nodes are ranked for the study distribution network via VSI analysis. As shown in Fig. 2, we consider two modes (N_{mm} >0.03), and nodes 3, 4, 5, 6, 28, and 29 were selected for installation. Then, taking N_{mm} >0.04, nodes 3, 6, and 28 were chosen.

3. INFO-BASED MULTI-OBJECTIVE OPTIMIZATION APPROACH

The INFO algorithm is a population-based optimization algorithm that does not take inspiration from nature and uses a weighted average of vectors [42]. The number, location, and size of the DGs and DSTATCOMs are optimized using a multi-objective optimization procedure. The proposed MOF has two parts: total costs and SL, which have conflicting behaviors. Improvement of the SL increases the total cost, whereas minimization of the total cost causes the SL to decline. The formulation of the multi-objective function considers the following objective that is relevant over a period of 30 years.

The initial component of the multi-objective function encompasses all expenses associated with the system. This objective function has three parts as shown in the following equation:

$$OF_{\cos ts} = OF_1 + OF_2 + OF_3 \tag{8}$$

where each part is calculated as follows:

OF_1: Total power losses. This factor in the power system considering unequal and equal restrictions will cause a loss reduction in the distributed systems. The network's real power loss is calculated according to Eq. (9).

$$P_{loss} = \sum_{i=1}^{n} R_i \left|I_i\right|^2 \tag{9}$$

Therefore, the cost of power loss for 30 years [19] can be obtained using the following equation:

$$OF_1 = P_{loss} \times C_{loss} \times 8760 \times 30 \tag{10}$$

where C_{loss} represents loss cost, which is 0.05 $/kWh [43].

OF_2: DG O&M and Investment Cost. Therefore, the DGs' O&M costs and investments are calculated as follows:

$$OF_{21} \,\&\, OF_{22} = S_{DG} \times 0.85 \times C_{DG-inv} + S_{DG} \times 0.85 \times C_{DG-O\&M} \times 8760 \times 30 \tag{11}$$

In this study, the power factors of all DGs are assumed to be 0.85. In Eq. (11), $C_{DG\text{-}inv}$ represents the DG investment cost (210 $/kW), and the constant denotes the DG-O&M cost (0.02 $/kWh) [43].

As explained in the previous section, we determined the busbars for installing the DG based on the VSI analysis. In the present study, we divided DG O&M and Investment Cost into two sections of Eq. (11). OF_{21}: DG O&M and Investment Cost are related to candidate busbars, and OF_{22}: DG O&M and investment cost are associated with other non-candidate busbars. We applied the impact and importance of each of these two parts using W_{21} and W_{22} weights in the calculations.

$$OF_2 = W_{21} \times OF_{21} + W_{22} \times OF_{22} \tag{12}$$

OF_3: DSTATCOM investment cost. To consider the investment cost of DSTATCOM, the following equation should be calculated:

$$OF_{31} \,\&\, OF_{32} = Q_{DSTATCOM} \times C_{DSTATCOM-inv} \tag{13}$$

In Eq. (13), $C_{DSTATCOM-inv}$ denotes the DSTATCOM investment cost (60 $/kVAR) [44]. In this study, we determined candidate busbars for installing DSTATCOM based on a VSI analysis. In the present study, we divided the DSTATCOM Investment Cost into two sections of Eq. (13). OF_{31}: DSTATCOM Investment Cost is related to candidate busbars, and OF_{32}:

DSTATCOM investment cost is associated with other non-candidate busbars. We applied the impact and importance of each of these two parts using W_{31} and W_{32} weights in the calculations, as stated in Eq. (14).

$$OF_3 = W_{31} \times OF_{31} + W_{32} \times OF_{32} \tag{14}$$

Ultimately, based on the above points regarding total costs, the Eq. (15) is obtained as follows:

$$OF_{\cos ts} = OF_1 + (W_{21} \times OF_{21} + W_{22} \times OF_{22}) + (W_{31} \times OF_{31} + W_{32} \times OF_{32}) + pen \tag{15}$$

where the pen is the penalty coefficient for preventing an increase in the number of DSTATCOMs. The penalty for applying the maximum number of available DSTATCOMs is 10. The pen penalty for applying the constraint is the maximum number of available dstatcoms, which is equal to 10 numbers.

In the simulations, the maximum available number of DSTATCOMs was assumed to be 10. First, this is due to the low investment cost of DSTATCOMs. Compared with DGs, DSTATCOMs incur no operating costs. Second, DSTATCOMs are usually placed on buses that are usually at the ends of the feeders of the 33-bus test systems.

This constraint indicates that if the number of stations exceeds 10, a large value is considered for Pen, which is summed using the cost function in the next step.

SL The second part of the MOF comprises all the system costs. To determine the system's highest SL, all the reactive and active loads were incremented in the power flow problem in the step as follows:

$$P_i = \lambda_i \times P_0, \quad Q_i = \lambda_i \times Q_0 \ \lambda_i = \lambda_0 + (i \times 0.01) \qquad i = 1.2.... \tag{16}$$

In this paper, λ_0 is assumed to be equal to 1. λ_i is increased until a voltage collapse occurs and a divergence in the load flow calculation is observed. The latest acceptable λ is the maximum SL (λ_{max}). To improve the SL (maximize it) and minimize it, the following objective function is determined:

$$OF_{Loadability} = \frac{1}{\lambda_{\max}} \tag{17}$$

In each iteration, for each individual in the optimization procedure, the total cost of the system is calculated according to Eq. (14), and then λ_i is increased to define the highest SL of the system according to Eq. (16). The constant parameters of the objective functions are as follows:

$$U_{\min} \le U_i \le U_{\max} \tag{18}$$

$$S_{\min} \le S_{DG} \le S_{\max} \tag{19}$$

$$Q_{\min} \le Q_{DSTATCOM} \le Q_{\max} \tag{20}$$

$$\begin{gathered} S_{\max} = 200KVA, S_{\min} = 20KVA, \\ Q_{\max} = 200KVAR, Q_{\min} = 20KVAR, \\ U_{\max} = 1.05pu, U_{\min} = 0.95pu \end{gathered} \tag{21}$$

The case studies are the IEEE 33-bus test systems, and there are 32 buses in general for the 33-bus test system that are selected with the same and equal priority to site the DSTATCOMs and DGs. In addition, the size of each device should be determined. However, in this paper, we determine some buses based on the stability index as candidate busses for the voltage profile improvement approach and consider these busses in the priority of installation by appropriate weighting in MOFs. As shown in Fig. 2, we consider two modes in this paper: nodes 3, 4, 5, 6, 28, and 29 are selected for installation with N_{mm}> 0.03, and nodes 3, 6, and 28 are selected as candidates with N_{mm}> 0.04.

In the simulation results section, both cases N_{mm}> 0.03 and N_{mm}> 0.04 are considered. Of course, it should be noted that these busbars are only installation candidates and have a higher weight in the objective function. As previously stated, we selected these busbars in the MOF for installation by weighing different parts of the function. Our objective in optimization is to minimize costs and optimize the system's loadability. The improvement of voltage is intended for the purpose of introducing high-priority candidate busbars. To enhance the voltage profile using the SL index, we identified candidate busbars for installation and then optimized the size and location of DGs and DSTATCOMs using INFO by minimizing the total cost and considering the SL index.

4. SIMULATION RESULTS AND DISCUSSION

Various optimization techniques have been used to define the optimum size and location of the DG units in distributed systems. However, the fact that it does not need to set up normalizing factors is one of the most important advantages of the Pareto front approach. In this study, Pareto and INFO optimization techniques were used for the simultaneous sizing and locating of DGs and DSTATCOMs according to VSI, SL, and total cost. Fig. 3 shows the flowchart for MOF enhancement using the INFO optimization algorithm.

To express the efficiency of the proposed algorithm, in this paper, 6 cases considering the VSI and one case without considering the VSI were evaluated and simulated. Fig. 4 and Fig. 5 show the results of the Pareto analysis using INFO for the 33- and 69-bus test systems, respectively.

The simulation results for the 33- and 69-bus test systems are presented in Tables 2 and 3, respectively.

As shown in Table 2 and Fig. 6a, in Case 1, the DGs and DSTATCOM are placed in the 33-bus system regardless of the VSI. In this case, although the total cost is low (0.3569 pu), its loadability is high (0.6061 pu), which leads to an increase of Di to 0.9285. In cases 2–4, DGs and DSTATCOMs were allocated by considering the VSI and sensitivity coefficient greater than 0.03. In case 2, by applying weight to the objective function of DGs, the values of total cost, loadability, and Di are 0.2627, 0.5556, and 0.8285, respectively. In case 3, by applying weight to the objective function related to DSTATCOMs, the values of total cost, loadability, and Di are 0.3418, 0.5882, and 0.8993, respectively. In case 4, by applying the coefficient in both objective functions related to DGs and DSTATCOMs, the total cost was equal to 0.2101, which is lower than in the previous cases.

In cases 5-7, considering the VSI and the sensitivity coefficient of >0.04, DGs and DSTATCOMs were allocated. In case 5, by applying a weight to the objective function of DGs, the values of total cost, loadability, and Di are equal to 0.2148, 0.5848, and 0.8545, respectively. In case 6, the values of total cost, loadability, and Di are equal to 0.3606, 0.6173, and 0.9445, respectively. Finally, in case 7, weighting was performed on both the objective functions of the DGs and DSTATCOMs, which resulted in an optimal Di value of 0.8086.

As shown in Table 3 and Fig. 6b, in case 1, in the 69-bus system, regardless of the VSI, the DGs and DSTATCOMs have been located, and in this case, the total cost, loadability, and Di values are equal to 0.7523, 0.5128, and 1.0449, respectively. In cases 2–4, DGs and DSTATCOMs were allocated by considering the VSI and sensitivity coefficient greater than 0.03.

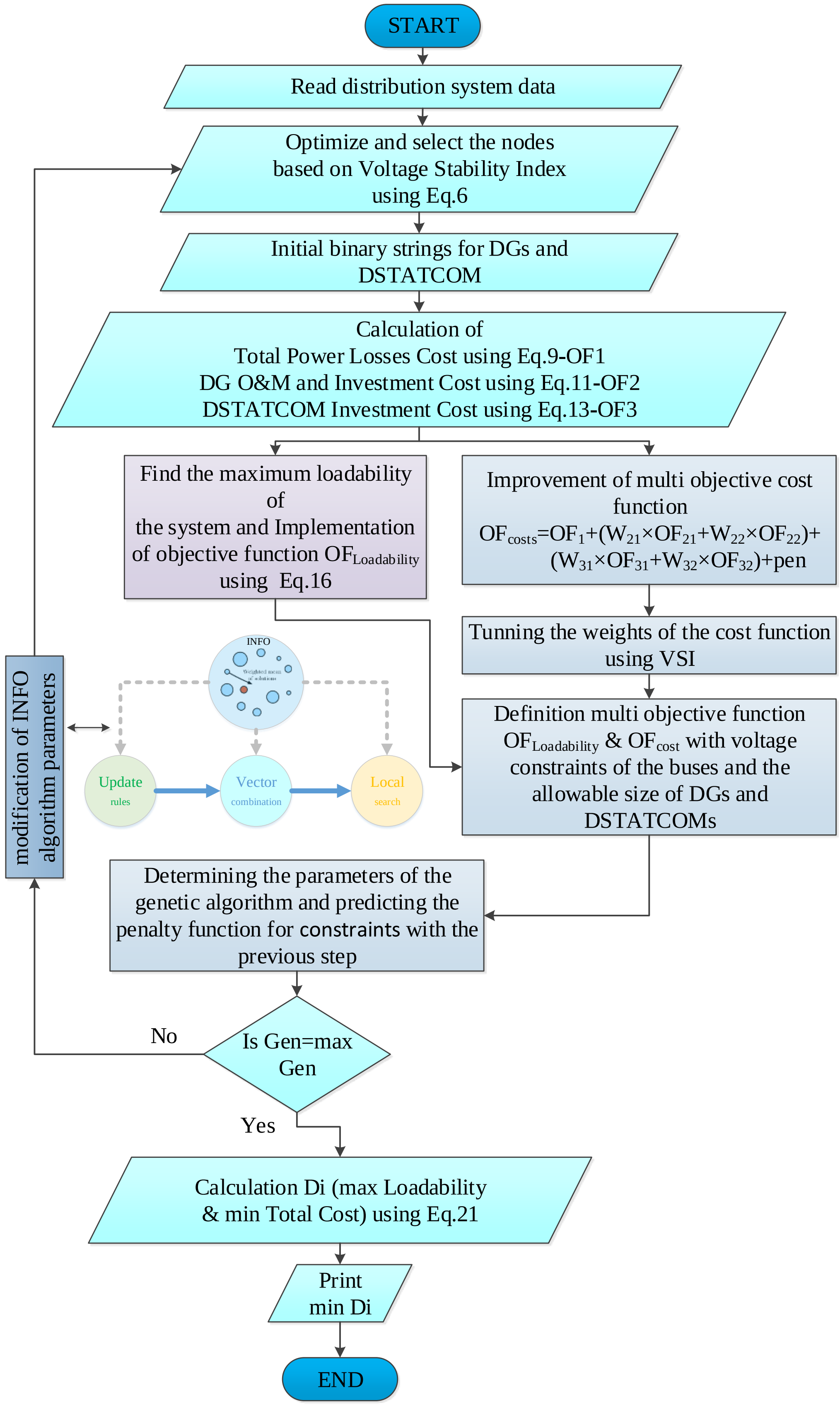
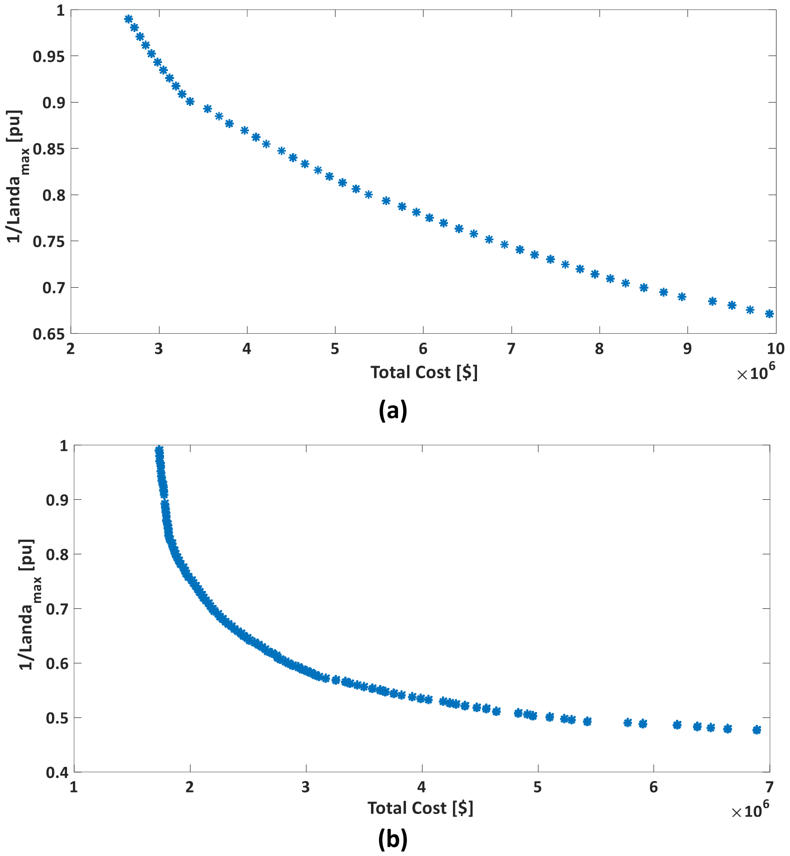


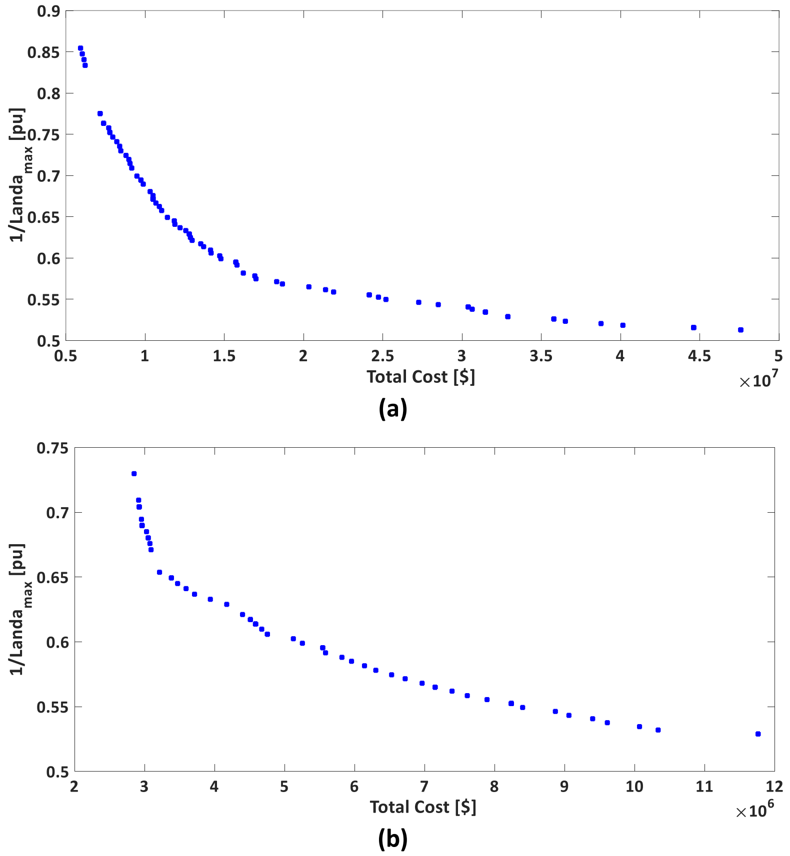
Fig. 3. Flowchart of objective MOF optimization.



(a)

(b)

Fig. 4. Pareto front results for the 33-bus test systems: a) state 1 (without VSI); b) state 7 (with VSI).



(a)

(b)

Fig. 5. Pareto front results for the 69-bus test systems: a) state 1 (without VSI); b) state 7 (with VSI).

Table 2. Optimal sizes and locations of DGs and DSTATCOMs for the 33-bus test system.

	Effect of weights on optimization	DG busses	DG capacities [kVA]	DSTATCOM busses	DSTATCOM capacities [kVAR]	Case
without VSI	–	9, 12, 13, 15, 16, 17, 18, 23, 27, 29, 30, 31, 32	66.321, 200, 146.37, 122.75, 129.18, 200, 91.587, 54.242, 118.7, 200, 174.69, 148.43, 120.48	3, 5, 6, 7, 8, 11, 26, 27, 31, 32	200, 108.89, 20, 134.72, 108.1, 197.16, 20, 91.057, 173.13, 106.78	1
With VSI (Nmm>0.03)	effect on DG optimization	2, 4, 6, 7, 9, 10, 11, 12, 13, 14, 21, 23, 24, 25, 26, 27, 29, 30, 31, 32	149.06, 46.803, 200, 142.47, 167.15, 63.876, 200, 200, 125.28, 200, 20, 32.293, 20, 200, 200, 137.93, 200, 85.717, 200, 158.95	4, 7, 10, 19, 20, 23, 27, 31	30.033, 20, 200, 78.04, 200, 129.88, 53.87, 73.897	2
	effect on the DSTATCOM optimization	8, 10, 12, 13, 15, 16, 21, 25, 27, 28, 29, 30, 31, 32	144.96, 104.96, 63.448, 200, 165.83, 189.32, 147, 162.4, 70.323, 190.2, 189.95, 40.472, 164.42, 174.52	3, 4, 5, 10, 13, 25, 28, 32	69.078, 165.6, 66.424, 182.37, 123.06, 20, 41.316, 162.21	3
	effect on DG and DSTATCOM optimization	1, 7, 9, 11, 12, 13, 14, 15, 17, 19, 20, 21, 22, 23, 25, 27, 28, 29, 30, 31, 32	20, 20, 200, 183.67, 20, 64.834, 174.78, 73.909, 177.55, 163.53, 170.99, 81.553, 40.771, 139.81, 121.83, 194.8, 192.4, 69.391, 20.739, 200, 175.4	5, 10, 12, 16, 23, 25, 27, 29, 32	87.002, 27.675, 29.458, 20, 149.49, 181.9, 200 69.39, 169.54	4
With VSI (Nmm>0.04)	effect on DG optimization	1, 4, 5, 7, 8, 9, 11, 12, 14, 15, 17, 21, 27, 29, 30, 31, 32	200, 20, 37.006, 200, 20, 20, 91.651, 46.57, 140.49, 200, 200, 57.648, 20, 200, 153.86, 200, 200	3, 5, 14, 16, 20, 26, 29, 30, 31	80.23, 200, 104.63, 190.8, 200, 20, 182.86, 20, 94.137	5
	effect on the DSTATCOM optimization	3, 5, 10, 11, 13, 14, 15, 16, 17, 21, 22, 28, 29, 30, 32	106.82, 189.92, 164.19, 185.92, 20, 178.46, 86.934, 185.31, 200, 54.777, 183.36, 96.819, 21.025, 149.45, 193.72	10, 11, 18, 26, 28, 29, 31, 32	125.27, 161.3, 84.509, 78.277, 88.843, 116.26, 78.666, 20	6
	effect on DG and DSTATCOM optimization	9, 11, 12, 13, 14, 15, 16, 17, 27, 28, 29, 30, 31, 32	200, 20, 182.25, 75.747, 126.74, 54.919, 191.28, 200, 21.841, 197.63, 39.894, 200, 200, 200	6, 7, 13, 26, 27, 28, 29, 30, 31, 32	21.862, 20, 51.746, 200, 200, 200, 163.4, 161.14, 21.306, 195.52	7

In case 2, by applying weight to the objective function of DGs, the values of total cost, loadability, and Di are 0.3617, 0.5291, and 0.8311, respectively. In case 3, by applying weight to the functions related to DSTATCOMs, the total cost, loadability, and Di were 1.2256, 0.5208, and 1.4299, respectively.

In case 4, by applying the coefficient in both objective functions related to DGs and DSTATCOMs, Di is equal to 0.7941, which is reduced compared to the previous cases. In cases 5-7, considering the VSI and sensitivity coefficient of more than 0.04, DGs and DSTATCOMs were allocated. In case 5, by applying weight to the objective function of DGs, the total cost, loadability, and Di are 0.3125, 0.5208, and 0.8001, respectively.

In case 6, the total cost, loadability, and Di are 0.6781, 0.5076, and 0.9875, respectively. Finally, in case 7, weighting was performed on both the objective functions of the DGs and DSTATCOMs, which resulted in the best value of Di equal to 0.7463 and the lowest total cost equal to 0.268.

According to these figures, any point can be selected as the optimal point based on the importance of the two objective functions.

If the maximum SL is more consequential, the points located near the cost axis should be selected because they minimize the maximum SL. On the other hand, if the total cost is more important, the points located near the maximum SL axis must be selected because they lead to the minimum total cost values.

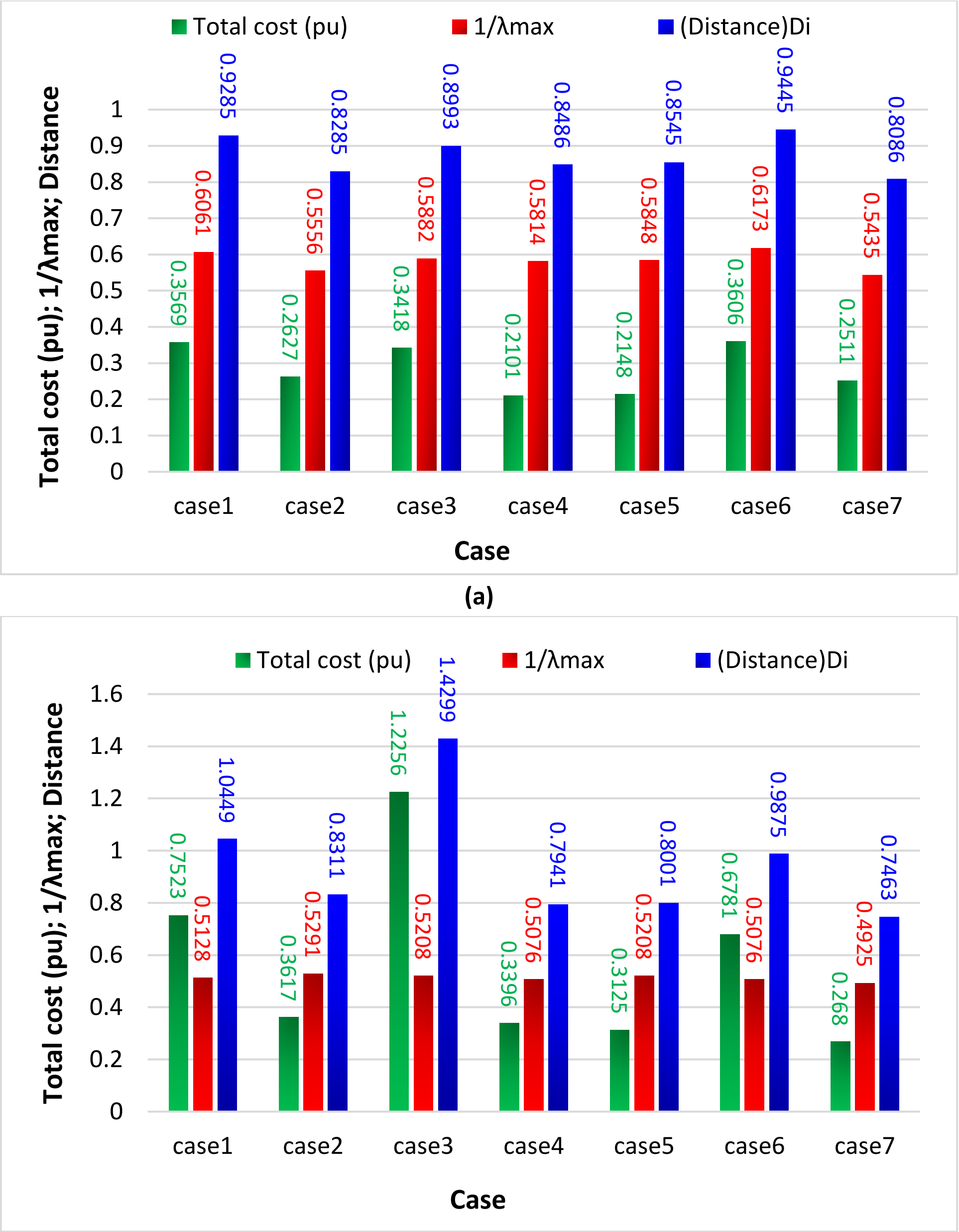
Table 3. Optimal sizes and locations of the DGs and DSTATCOMs in the 69-bus test system.

	Effect of the weights on optimization	DG busses	DG capacities [kVA]	DSTATCOM busses	DSTATCOM capacities [kVAR]	Case
Without VSI	–	6, 7, 8, 10, 11, 12, 14, 15, 16, 18, 19, 21, 23, 24, 29, 33, 35, 40, 44, 47, 51, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68	71.755, 186.98, 200, 146.23, 20, 159.09, 198.34, 200, 200, 200, 20, 182.61, 101.46, 187.39, 70.647, 87.596, 101.77, 152.39, 173.43, 90.464, 200, 200, 182.16, 126.29, 91.428, 197.42, 200, 198.56, 200, 200, 196.98, 199.84, 199.6, 20, 138.95, 49.638, 199.73	16, 32, 43, 55, 57, 60, 61, 63, 67	180.8, 106.49, 200, 125.84, 200, 150.7, 20, 20, 200	1
with VSI (Nmm>0.03)	Effect on DG optimization	3, 8, 9, 10, 11, 12, 14, 19, 20, 21, 22, 23, 24, 25, 28, 38, 41, 50, 51, 52, 53, 54, 56, 57, 58, 59, 60, 61, 62, 63, 64, 66, 67	110.43, 177.73, 110.42, 78.772, 200, 200, 28.817, 20, 200, 168.85, 197.22, 163.66, 198.52, 200, 62.858, 20, 20, 200, 30.827, 176.15, 36.343, 20, 161.64, 199.76, 187.58, 200, 200, 200, 175.12, 132.01, 195.78, 20, 140.17	6, 11, 43, 57, 58, 60, 61, 63, 64, 67	20, 48.272, 200, 200, 23.13, 122.38, 20, 175.93, 200, 166.91	2
	effect on DSTATCOM optimization	6, 7, 8, 9, 10, 11, 12, 13, 14, 17, 18, 19, 20, 21, 24, 26, 31, 37, 39, 42, 49, 50, 51, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 67	196.19, 178.21, 20.025, 96.033, 145.81, 199.58, 98.961, 200, 72.487, 121.17, 92.419, 74.476, 80.366, 192.69, 27.298, 20.386, 20.019, 51.881, 20.044, 20.653, 195.98, 148.98, 179.89, 179.67, 145.2, 177.73, 41.464, 195.68, 192.66, 167.74, 181.85, 170.04, 199.43, 193.8, 198.5, 193.64, 184.62	10, 19, 23, 33, 60, 61, 62, 63, 64, 65	185.46, 40.705, 101.04, 114.53, 199.97, 121.99, 129.4, 125.83, 20.294, 148.13	3
	effect on DG and DSTATCOM optimization	17, 20, 25, 34, 37, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65	200, 148.23, 22.828, 20, 20, 20, 200, 200, 20, 200, 200, 200, 200, 200, 200, 200, 200, 200, 200, 200	8, 22, 32, 56, 57, 59, 60, 62, 63, 67	200, 200, 20, 200, 20, 200, 110.17, 200, 125.95, 105.93	4
with VSI (Nmm>0.04)	Effect on DG optimization	5, 7, 8, 9, 10, 11, 13, 15, 16, 17, 18, 19, 20, 21, 23, 26, 32, 37, 38, 48, 50, 52, 53, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67	176.58, 200, 191.49, 186.51, 176.35, 200, 192.14, 200, 95.202, 200, 28.511, 98.58, 147.24, 200, 26.272, 20, 192.5, 109.4, 59.134, 20, 200, 48.332, 174.06, 167.07, 197.7, 193.67, 199.99, 200, 199.69, 200, 60.982, 197.03, 200, 124.99, 191.47, 200	5, 13, 18, 29, 42, 50, 59, 61, 62, 64	132.82, 28.511, 191.76, 146.98, 32.189, 44.323, 118.66, 81.879, 200, 20	5
	effect on DSTATCOM optimization	7, 8, 9, 10, 11, 15, 16, 17, 19, 21, 22, 23, 24, 25, 30, 36, 37, 39, 41, 47, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 66, 68	20, 104.3, 200, 112.69, 103.06, 112.26, 200, 27.245, 175.9, 92.644, 200, 20, 173.13, 140.52, 20, 200, 25.781, 20, 200, 82.405, 138.92, 20, 200, 200, 29.812, 198.35, 200, 200, 182.71, 200, 200, 200, 200, 200, 200, 99.486, 200	7, 18, 32, 41, 55, 56, 58, 61, 62, 64	20, 52.496, 199.87, 200, 200, 200, 134.93, 197.6, 20, 20	6
	effect on DG and DSTATCOM optimization	5, 6, 7, 8, 11, 14, 16, 17, 19, 22, 25, 26, 38, 50, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 68	200, 200, 142.03, 54.518, 20, 194.65, 200, 20, 184.91, 124.77, 20, 200, 169.63, 156.61, 60.009, 200, 118.44, 142.08, 196.14, 33.444, 187.82, 200, 56.704, 200, 178.01, 187.15, 200, 148.75, 200	8, 9, 24, 45, 57, 59, 60, 63, 64	26.379, 187.43, 20.342, 20, 96.496, 20, 20, 153.83, 20	7

The maximum SL and total cost of loss and installed units, including the DSTATCOM investment cost, DG investment, and O&M costs, are two parts of the MOFs. The proposed MOF was used in IEEE 33- and 66-bus test systems using multi-objective INFO. The simulation results demonstrate that the total cost increases when SL improves, and vice versa. Therefore, all Pareto front points can be selected as optimum points based on the total cost or SL priority. We obtain the two target functions (maximum SL and minimum cost) as follows:

$$D_i = \sqrt{2\times\left(1/\lambda_{\max_i}\right)^2 + Total\,Cost_i^2} \tag{22}$$

where Di is the distance between the with points and the origin. We calculate Di for all the points of Pareto in the diagram for each state and determine the point with the shortest total origin distance as the optimal point (The less Di = optimal point). Therefore, the point with the minimum distance from the origin can be selected as the optimal point. The above procedure was performed for all evaluated Pareto front points. Fig. 6 represents the results for less Di and total cost. Based on this point, is provided for different modes.



(a)

(b)

Fig. 6. The least D_i values for different modes: a) 33-bus; b) 69-bus test systems.

As shown in Eq. (22), the value of Di is dependent on λ_{max} and total cost. In Fig. 6, Di is calculated for all 7 cases. In Fig. 6a, which is related to the 33-bus system, the highest optimal point for case 6 is equal to 0.9445, and the lowest Di for case 7 is equal to 0.8086. Similarly, for the 69-bus system, the calculation of Di is shown in the diagram of Fig. 6b. The highest optimal point corresponding to case 3 equals 1.4299 and the lowest Di corresponding to case 7 equals 0.7463.

According to Fig. 6, modes 2 to 7 resulted in a more optimal mode that considered the VSI compared to mode 1, which did not consider the VSI. Furthermore, among modes 2 to 7 (with VSI), mode 7 where N_{mm}>0.04 yields the most optimal solution considering the VSI. The least or most optimal value of Di, in this case, is approximately 80% of the lowest value of Di in case 1 without considering the VSI.

5. CONCLUSIONS

This study aimed to optimize the size and location of DG and DSTATCOM based on MOFs with minimum cost and maximum SL issues. The distinguishing feature of the proposed objective function is the use of VSI in MOFs. In other words, the enhancement of the voltage profile is considered. First, the candidate busbar for installation is determined in terms of the VSI, and then, a higher priority is given to these busbars by applying higher weights in the mentioned function. The results indicate more optimal answers than those obtained without considering the VSI.

The location, number, and optimal size of DG and DSTATCOMs in the 33- and 69-bus distribution systems were studied, and VSI-based sensitivity analysis was used to enhance the voltage profile. To determine candidate busbars for installation, we considered the SL and the total cost of an MOF to optimize the sizing and location of the DG and DSTATCOMs. Finally, the proposed MOF was optimized using the INFO algorithm. In continuation of this work, the following topics are proposed for future work: i) the use of other optimization algorithms for the proposed improved MOF, ii) the implementation of the proposed MOF in a generalized model and iii) including various types of renewable energy units, and storage systems.

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