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Determination of Optimal Allocation and Penetration Level of Distributed Energy Resources Considering Short Circuit Currents

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ABSTRACT

The integration of Distributed Energy Resources (DER) in the distribution network has plenty of advantages if their allocation and Penetration Level (PL) are done appropriately. Hence, the challenge of finding the best allocation and PL of DERs in large distribution networks is an important but intricate problem. This paper proposes a novel methodology to simultaneously determine the optimal location/capacity and PL of DERs based on both power losses and voltage deviation minimization, while constraints of voltage profile of feeders under light loading and short circuit capability of the CBs are met. Moreover, a Multi-Objective Mutation based PSO (MOMPSO) is presented that by introducing two modifications of dynamic inertia weight and utilizing a mutation operator improves exploration and exploitation searchability as well as convergence capability of the PSO algorithm. The proposed methodology is tested on a practical distribution network to evaluate its effectiveness in finding optimal location and capacity of DERs along with the feeders.

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NOMENCLATURE

X_{best-i}	The best solution of ith particle in PSO	X_i	Decision variable vector
R_{ij}	Line resistance	X_i^{REP}	Variable vector of the leader in repository
I_{ij}	Line current	C1, C2	cognitive and social acceleration coefficients
N_L	Number of independent lines of each feeder	$X_{i\_not-best}^{iter}$	worst experience of the particle
N_b	Number of terminals of each feeder	w	Dynamic inertia weight
V_{ref}	Reference voltage	γ	scale parameter
S_{ij}	Line complex power	θ	location parameter
V_i	Velocity vector		

1. INTRODUCTION

The uptake of Distributed Energy Resources (DER) in the power distribution network has grown increasingly in recent years. DERs encompass a wide range of locally installed power generation units, which can be of both renewable (like Photovoltaic-PV) and conventional types (like Synchronous based unit). DERs have plenty of advantages such as a reduction in energy transfer costs, voltage profile improvement, and reduction in losses and loading on main feeders [1, 2]. Nonetheless, the presence of the DERs, particularly in the case of inappropriate capacity and location, may bring some issues in distribution networks, which should be addressed. The main issues are as follows:

- They change one-way power flow to two-way, which disrupts the operation of the passive designed power distribution networks and so increases the voltage of feeder, particularly in the time of light loads.

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- Improper capacity and location of DERs may also cause an increase in power losses and voltage stability problems.
- They also may cause some issues in the protective system by affecting the short circuit level of the network. Moreover, this issue may result in considerable costs to replace Circuit Breaker (CB) or related switches and instruments such as CT and PT.

Based on these facts, accurately locating and capacity of DERs are vital from the operation point of view. Therefore, the sizing and placement of the DERs should be done in such a way to maximally reducing the abovementioned disadvantages. Hence, the challenge of identifying the best allocation for DERs has attracted significant research efforts. However, in large and practical distribution networks, solving this problem considering all advantages and disadvantages is complicated. To deal with this issue, utilizing optimization methods in optimal sizing and siting of the DERs is the right candidate which has been employed by various references [3-7], in which several techniques have been studied.

Most of the research conducted in the literature can be categorized based on three distinct approaches: finding optimal locations for known DER capacities, finding optimal DER capacities at predetermined locations, and finding both optimal locations and capacities simultaneously [8-11]. In those papers, various objectives with a variety of constraints have been employed. These objectives include real and reactive power loss minimization, improving voltage profile, and planning for spinning reserve power. On the other hand, evolutionary and nature-inspired techniques, like Genetic Algorithm (GA) or Particle swarm optimization (PSO), are commonly used for solving allocation problems. A comprehensive review of the optimal allocation of DER and related models and methods can be found in literature [3, 12].

It has optimally obtained the allocation of multiple DERs for distribution network; however, the optimization has been carried out only based on minimizing losses [13, 14]. In other words, a single-objective optimization has been used, which is relatively simple to handle. However, ignoring other objectives such as voltage profiles may lead to an inappropriate and non-optimal solution. In work reported by Ameli et al. [15], a multi-objective PSO to find the optimal placement and capacity of DERs is presented. Improving voltage profile, power-loss reduction, and reliability enhancement are the objectives of this work. Zhao et al. [16] have constructed a multi-objective model for allocation optimization incorporating uncertainties to find the DER siting and sizing. It has been reported that optimal Integration of DERs and capacitor banks with objectives of reduction of power losses, voltage profile improvement, and therefore enhancing the overall distribution system performance has been suggested [6]. The optimal problem of DER allocation with the aim of minimization of power loss and voltage deviation has been reported in literature [17, 18], therein GA algorithm has been used for optimization.

In the above researches, because of the complexity of the allocation problem, heuristic methods, like PSO and GA, are commonly used as described. However, the simple or original class of these methods, due to the possibility of premature convergence and being trapped into local optima, might not be sufficient to find the optimum location and capacity of DERs, particularly in the practical distribution networks that have multiple long feeders. On the other hand, although, the operational indices, like power losses and voltage deviation, have been widely studied in the abovementioned papers, to the best knowledge of the authors, optimal siting and sizing of DERs regarding the effects of DERs penetration on the short circuit level have been rarely carried out. This issue, which is one of the negative sides of an increase in DER penetration, may interrupt in coordination among protective devices. Moreover, it can cause the overall fault current to exceed the designed capability level of distribution components, like CBs, and so degrading the reliability [19]. Replacement of all the feeders' CBs of an HV substation may be required in these situations. It should be, however, noted that in most cases, replacing CBs after installing DERs is not solely able to head off the abovementioned issues. Hence, it is crucial tasks to integrate the issue of change of short-circuit level in the optimal problem of placement and sizing of the DERs. Moreover, most reviewed studies have solved the optimal problem of DERs allocation under normal load conditions while the presence of DERs may result in voltage exceeding the permissible limit in the case of light loading of the feeders, which have been rarely mentioned in the literature. This issue may lead to insulation failures of the components, unwanted tripping of the voltage relays, degrading reliability of the system, and reduction in the quality of power delivered to consumers.

In the view of shortcoming of the recent literature, this paper proposes a novel methodology by introducing two main contributions to the optimal problem of DER allocation. First, in the proposed algorithm, determining optimal placement and capacity of the DERs is carried out concerning the effects of optimal solution on both voltage profile (under peak and light loading conditions) and short circuit level of the system. For this purpose, a multi-objective problem (MOP) is defined that while minimizing power losses and voltage deviation, it can optimally alter the size and type of located DERs to meet predetermined requirements of voltage profile of feeders under light loading and short circuit current rating of the CBs.

Furthermore, in this paper, in order to solve MOP of DER allocation and to improve the performance of the PSO in finding global optimum, a new Multi-Objective Mutation based PSO (MOMPSO) is presented. In the proposed MOMPSO, by introducing two modifications of dynamic inertia weight and utilizing a mutation operator, exploration and exploitation searchability and convergence capability of the algorithm is enhanced. In summary, the main contributions of this paper are explicit as follow:

1. Modeling the optimal siting and sizing problem of DERs in a distribution system by a multi-objective programming approach considering power losses and voltage deviation as the objective functions.
2. Specifying optimum solutions regarding short circuit current rating of the CBs in different feeders of an HV substation.
3. Considering both peak and light load conditions to determine the optimum solutions, regarding the voltage increase issue in light loading condition.
4. Introducing a new MOMPSO algorithm for solving the proposed model and comparing the results with the conventional MPSO.

2. MULTI-OBJECTIVE PROBLEM OF OPTIMAL ALLOCATION OF THE DERS

Generally, the studied objective functions include power losses and voltage deviation in the feeder [3, 12, 20, 21]. The used objective functions of the paper are stated in (1) and (2). In fact, in the utilized multi-objective problem, the minimization of both power losses and voltage deviation in the case of DER integration is considered. It is worth noting that the proposed model is applied in peak load conditions.

$$\min P_{Loss} = \sum_{ij=1}^{N_L} R_{ij} \times I_{ij}^2 \tag{1}$$

$$\min \sum_{n=1}^{N_b} \left| V_{ref} - V_n \right| \tag{2}$$

Equation (1) explains the total ohmic feeder losses, which should be minimized in which R_{ij} and I_{ij} parameters show the line resistance and line current, respectively. In this equation, N_L stands for the number of independent lines of each feeder, which should be considered in the calculation of the total power losses. In the second equation, the minimization of total voltage deviation in 20kV feeders has been considered, where the number of terminals of each feeder is N_b. It is worth to note that here, the desired and reference voltage (V_{ref}) has not been considered a constant value, e.g., 1 p.u. Furthermore, in contrast, it has been assumed to be a range of voltages, i.e., [0.975-1.025] p.u. Therefore, voltage deviation happens whenever voltage is out of this allowable range. One of the benefits of using such a function which is used in this paper is to avoid unnecessary installation of higher capacity generators to reduce the costs. In other words, by considering 1 p.u. for V_{ref}, the optimization method would result in a higher capacity of DERs as it tries to reduce the deviated voltage from V_{ref}.

Besides, the constraints should be met during optimization to ensure that the operational or design requirements stay within limits while finding the optimal location and capacity of DERs. In this paper, the most essential and common constraints, including loading of the feeder, voltage range constraint, DER power output constraint, the short circuit current capability of the CBs are considered. In equation (3), minimum and maximum capacity of DER has been determined, in 500 kW increments, and the number of installable DER in each feeder has been determined too. In this model, the constraint for the maximum capacity of feeders has been explained by equation (4). This inequality states that the complex power through any feeder must be less than its rating value.

$$0.5^{\mathrm{MW}} \le \mathrm{DER}_{\mathrm{Capacity}} \le 5^{\mathrm{MW}} \tag{3}$$

$$\mathrm{S}_{\mathrm{ij}} \le \mathrm{S}_{\mathrm{ij}}^{\max} \qquad \forall\ \mathrm{ij} \in \mathrm{N}_{\mathrm{L}} \tag{4}$$

It is noteworthy that since the load flow output of the network (via DIgSILENT software) is used during the optimization process, the equality Constrain of power balance is also met in solving the problem.

3. PROPOSED METHODOLOGY

In order to optimally determine the location and capacity of the DERs along the feeder, this paper proposes a new methodology by introducing two main contributions to the optimal problem of section 2, which are illustrated as follows:

3. 1. The Proposed Strategy for Modifying the Optimal Capacity of DERs and Determining the Penetration Level (PL) of DERs

As already mentioned, determining optimal placement and capacity of the DERs should be performed with regard to the effects of optimal solution on voltage profile of the light loaded feeders and short circuit level of the system; otherwise, the network might face some challenges in the presence of the DERs. In this regard, this paper proposes a new strategy which with the aim of meeting predetermined requirements of voltage profile and short circuit level, which can optimally alter the size and type of located DERs optimally. The proposed strategy integrates both optimization (through MOMPSO) and simulation (through DIgSILENT software) studies to find the optimal location and capacity of the DERs. Two common types of DER, i.e., Synchronous Gas Turbine (hereafter called SGT) and Photovoltaic (hereafter called PV), are studied in this paper, as they are good representative for all kind of DERs. Flowchart of the proposed algorithm, consisting of three subroutines, has been illustrated in Figure 1. A brief description of each subroutine is as follows:

Subroutine 1: conventional optimal placement and capacity of DERs

In this subroutine, first, the results of power flow/short circuit study are obtained when the network is operated without any DERs. For this goal, the test system is completely modeled within DIgSILENT software. Then, similar to the allocation methods used in the previous researches, the optimal placement and capacity of DERs are found. It should be noted that at this stage of the flowchart, the distribution network is modeled under peak loading conditions. In addition, the proposed optimization algorithm (MOMPSO) which is described in Section 3.2, is used to find the exact solutions. In other words, the proposed MOMPSO is applied to the optimal problem of section 2. In this part, a range of voltage, i.e., [0.975-1.025] p.u has been considered to model the multi-objective programming. As mentioned in section 2, this approach avoids the unnecessary installation of higher capacity generators to reduce the costs. The optimal results in this stage include the location and capacity of DERs along with the feeders. For simulation, the worst-case type of DER is assumed to be of SGT.

Subroutine 2: Modifying the optimal results considering the voltage profile of the network under light loading

The network is then simulated in the presence of all optimal located DERs, found in subroutine 1, while the system is operating under light loading, which is an important and effective task during optimal allocation. In this paper to model the light loading condition, the loading data of a real distribution network for the past year were analyzed, and the lowest normal loads of feeders were extracted. It should be noted that the lowest normal load of feeders is determined based on the data which have been recorded at least 10 times over the past year. This is for the exclusion of the bad data that might be recorded in the case of a faulty network or maneuvered condition.

Further, the obtained results are analyzed in terms of voltage profiles and the highest allowable voltage value, i.e., 1.05 p.u. If the voltage violation due to DER integration occurs, the MOMPSO is employed to find a new solution. However, given that small changes around the optimum solutions lead to solving the issue of voltage violation, the search space of the algorithm is bound to the region of [G_{best}-20%G_{best}, G_{best}+20%G_{best}].

Further, the inertia weight of the MOMPSO is set here to zero to prevent velocity updating. This feature results in the fast convergence of the algorithm to a new global optimum. Also, the probability of trapping into local optimum becomes zero. Moreover, in rerunning MOMPSO in this stage, only the size dimension of the initial particles is updated, and the obtained optimal location in the last iteration is not initialized. The reason is, changing the capacity of DERs solves the issue of overvoltage in the light loading condition.

Subroutine 3: Modifying the optimal results considering the designed short circuit capability of the CBs

Contribution of the DERs (particularly SGTs) during fault conditions can cause the overall fault current to exceed the designed capability level of distribution components, like CBs. In this case, CBs are subjected to increased stresses and are thus more prone to failure to operate when desired. Hence, in this subroutine, the short circuit study in the case of occurrence of a three-phase fault at the beginning of each feeder is performed. Evaluation of maximum fault current passing through the CBs of the DERs integrated network (I_{sc}) is the purpose of such a study, which yields to maximum short circuit current. Note that, as per the IEC60900 standard, the CBs are sized based on 80% of their maximum interrupting rating (I_{th}). After that, a comparison between I_{sc} and I_{th} is made and based on the result, if I_{sc} is higher than I_{th}, the obtained results are not optimized from the point of view of short circuit studies, and again the MOMPSO algorithm must be implemented in order to find new solutions. Subsequently, the two following steps are performed separately according to the flowchart presented.

Step 1: The SGT (or SGTs) with the maximum contribution to the fault is identified, and then a repetitive change of type to PV is taken through MOMPSO until the condition is met. Pareto set found in this step are optimal from the perspective of DER effects on voltage profile, power losses, and short circuit capability of the C.B. Finally, the optimal capacity of SGTs and PVs will be divided by total capacity of the DERs to determine the penetration level (PL1) of each type of located DER.

Step 2: Although the results obtained in the first step are the optimum allocation of DERs with taking into account all the effective parameters, but as explained earlier, obliging operators or DERs owner to install a particular type of DER (SGT or PV) at specified locations might not be reasonable from a standpoint of issues such as technical constraints, availability of suitable land and other infrastructure. To address this, in the flowchart of the proposed algorithm, a short circuit study on DERs with the least contribution is also performed separately to calculate the penetration levels under this condition. Similarly, the penetration level of DERs in this step is also calculated as PL2.

The advantage of the implementation of both steps is that it assures the calculated penetration levels are independent of places of the DERs and loading. Note that in this subroutine also the inertia weight of the MOMPSO is set here to zero, and again only the size dimension of initial particles is updated.

3. 2. Multi-Objective Mutation based PSO (MOMPSO)

As discussed in section 2, the problem of allocating DERs in the distribution network, i.e., finding optimal location and size of DERs along with outgoing feeders, is a Multi-Objective Problem (MOP). MOP optimization is a class of complicated problems with the objective functions that may be incomparable or conflicting with each other. In such problems, finding a single global optimum solution is impossible, and solutions in contrast to the single-objective optimization case, there is a set of optimal solutions or alternatives, which is called Pareto optimal set. However, the optimal solution among the Pareto set can be defined by expert analysis and trade-off. The purpose of the proposed multi-objective model of the present work is finding optimal placement and size of DERs along with outgoing feeders of an HV substation. To do so, two parameters are considered for every DER; one is the place for the installation, and the second is its capacity. It should be noted that for optimal placement of DERs, candidate locations are assumed to be in the 500-meter distance far from each other.

It is difficult to solve MOPs with mathematical or linear programming methods due to the necessity of optimizing several objective functions, e.g., minimizing power loss and voltage violation in the allocation problem of this paper. Hence, metaheuristic algorithms, like PSO, are suited due to their ability to synchronously search for multiple Pareto optimal solutions and perform better global exploration and local exploitation of the search space. PSO is a population-based optimization technique inspired by social behavior of bird flocking or fish schooling [22] and extended by Coello et al. [23, 24] as multi-objective PSO. Consider Xi ($xi1$, $xi2$ . . . xid) denotes a n-dimensional decision variable vector which moves with a velocity Vi ($vi1$, $vi2$ . . . vid). The positions of the particles, as nondominated

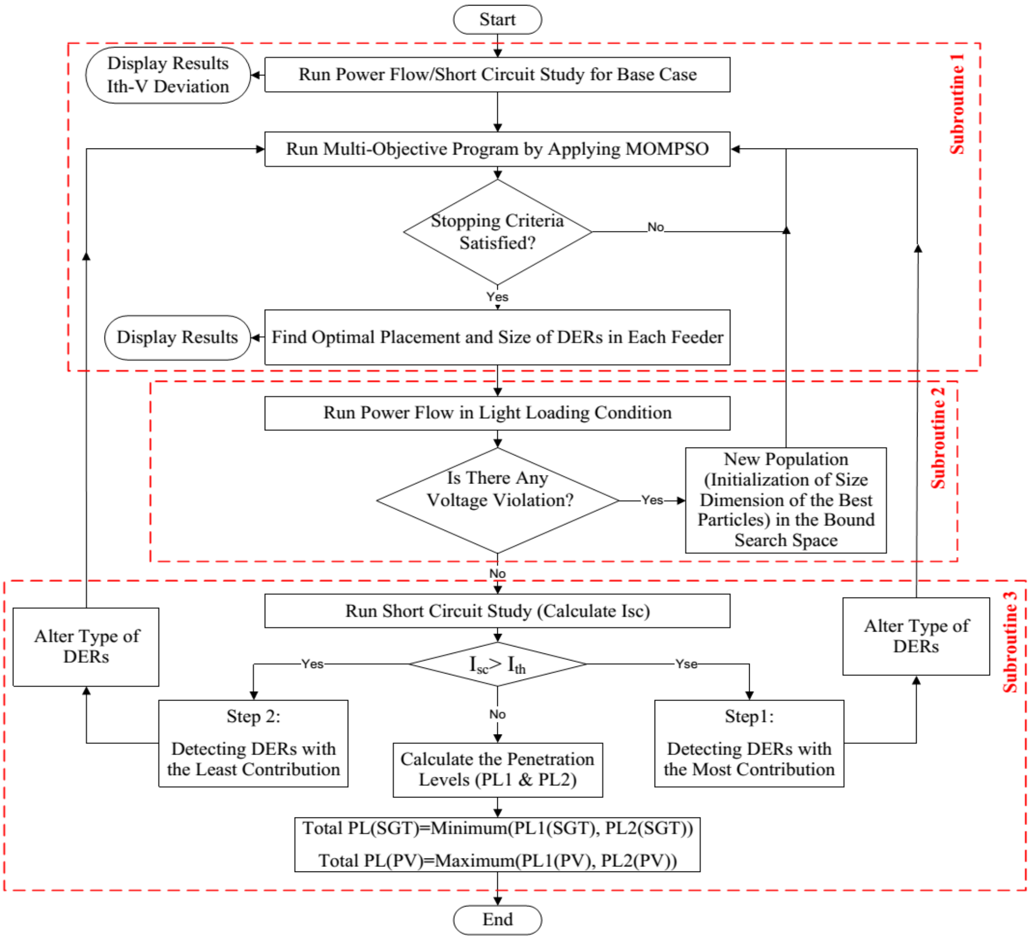

Figure 1. Flowchart of the proposed methodology in the optimal allocation of DERs

vectors, are restored in the repository (REP). The historical record of best solutions found by a particle is commonly used to store nondominated solutions. Each particle is associated with its best solution achieved, X_{best-i} (X_{best-i} 1, X_{best-i} 2 . . . X_{best-i} d) which is defined by its own best performance in the swarm. Further, each particle in its movement selects a member of REP randomly as its leader (X_i^{REP}). In this paper, the selection of leader form RES is done based on the hypercube method and applying a Boltzmann and roulette-wheel selection algorithm [24].

The new position of the particle is governed by updating its velocity and position attributes as per (5 and 6). Note that, in order to guarantee the finding optimal solution in the allocation problem, a modified version of classical PSO (MPSO) has been employed in literature [25, 26]. The third term of the Equation (5) is an intermediate crossover which is applied randomly in the MPSO to prevent particles from becoming lazy in the swarm after a while.

$$\begin{aligned} V_i^{iter+1} &= W \times V_i^{iter} + c_1 \times rand() \times (X_{best-i}^{iter} - X_i^{iter}) + \\ & c_2 \times rand() \times (X_i^{REP} - X_i^{iter}) \\ & + c_{1c} \times rand() \times (X_i^{iter} - X_{i\_not-best}^{iter}) \end{aligned} \tag{5}$$

$$X_i^{iter+1} = X_i^{iter} + V_i^{iter+1} \tag{6}$$

where W is the inertia weight, c_1 and c_2 are cognitive and social acceleration coefficients and $X_{i\_not-best}^{iter}$ represents the worst experience of the particle.

Furthermore, in this paper, in order to solve the MOP of DER allocation and to improve the performances of the MPSO in finding a global optimum, two modifications are introduced. These modifications enhance the exploration and exploitation of searchability and convergence capability of the algorithm. These modifications are described in the following, respectively.

- *Dynamic inertia weight*

The inertial behavior of the particles causes the particle velocity variations to be partially constrained so that the particles from the search space do not rapidly shift their direction to the best experience of the swarm, thus preventing the rapid convergence of the algorithm. On the other hand, at the beginning of the random search algorithms, like PSO, a global search or exploration is needed to identify the optimal space search, so population diversity should be preserved in the initial iterations. Moreover, the particles should explore the whole of the search space that is met by choosing an inertia weight at a relatively high value. However, setting high values for inertial weight causes a problem, which is that the algorithm in the final iterations cannot correctly converge to the X_{Gbest} experience. So, to balance between exploration and exploitation, the inertia weight should be selected so that the algorithm deals with both issues. To address these issues and to keep the balance between exploration and exploitation, in this paper, a dynamic inertia weight factor is introduced as follows:

$$W = \left(\frac{iter_{\max} - iter}{iter_{\max}} \right) \times rand() \tag{7}$$

As per (7), gradually and dynamically, with increasing repetitions, the inertia weight decreases as the algorithm converges to the best group experience and optimal point. Moreover, the inertia weight has a randomness characteristic to increase the diversity of the particles.

- *The proposed mutation mechanism*

In the problem with vast search space, like the problem of optimal DER location, which every node along the feeder could be a candidate, the initial population probably locate far away from the real optimal solution. In such a situation, the exploration capability of the MPSO degrades, and so the particles quickly move towards a false Pareto front, which could be a local optimum in global optimization, and lead to premature convergence. To address this issue, a mutation operator (Equation (8)) is introduced, which causes particles to move in a different direction during the optimization process and enhance the exploration of the algorithm.

$$X_i^{iter} = X_i^{iter} + W \times \frac{1}{\pi\gamma} \left[\frac{\gamma^2}{(X_i^{iter} - \theta)^2 + \gamma^2} \right] \tag{8}$$

The proposed operator is multiplied by inertia weight (W), which increases the step size of the mutation at the beginning, and in this way, increases the chance of searching for new areas. In this way, the explorative behavior of the algorithm is improved. In contrast, when the current best solution approaches to optimum solution in subsequent iterations, the step size of the mutation is minimized to increase the convergence accuracy. On the other hand, the mutation should be done randomly; therefore, when a particle is chosen to mutate, a random disturbance is added to its current position. In this paper, the probability is calculated based on Cauchy distribution function, which is multiplied by W. In the distribution function scale parameter (γ) and location parameter (θ) are set to 0.5 and 0, respectively.

4. TEST SYSTEM AND SIMULATION RESULTS

4. 1. Description of the Test System

To verify the effectiveness of the proposed algorithm in obtaining optimal placement and capacity of DERs, a real 20 kV distribution network is used as a test system, which is shown in Figure 2. The HV substation (63/20 kV) of the test system has a peak loading of 40 MW and consists of 13, 20kV feeder, 2, 40MVA 63/20KV transformers, 371, 20/0.4 kV transformers. Also, according to the data provided by the NASA meteorological center, Global Horizontal Irradiance (GHI) in Semnan is 1959 kWh/m^2, which is used in the PV plant simulations [27]. In this figure, feeders are shown in different colors. The main advantage of choosing a real test system includes:

- A large and vast power system is more complex, so if the proposed algorithm could obtain suitable solutions, it can be assured that for smaller systems also work.
- It was possible to access hourly load information of the test system over the past year, which is one of the requirements of the algorithm implementation.

However, it is noteworthy to mention that the proposed algorithm has been derived in such a way that it can be implemented in any other case study. In the present study, modeling of the test system and also the simulation routine and different analyses are fulfilled accurately in the DIgSILENT environment.

4. 2. Optimal Results and Discussion

Table 1 reports the data of all branched feeders from the HV substation in the base case, i.e., when there is no DER within the system. In this table, the feeder currents have been inserted in the case of peak loading. In the present study, to verify the proposed methodology, and for discussion, two different scenarios are considered. In the first scenario, the operation of the proposed MOMPSO in finding optimal location and size of DERs and in contrast to MPSO is evaluated. In the second scenario, the performance of the proposed algorithm in optimal modifying DER capacity and determining the DER penetration level is assessed.

Scenario 1. The operation of the MOMPSO in optimal placement and capacity of DERs

By implementing the proposed optimization algorithm, as formulated in sections 2 and 3.1, Pareto-optimal set or a set of optimal solutions are obtained which identify the optimized location and capacity of DERs along each feeder. It is worth to mention that the Pareto-optimal set stands for a set of solutions that are non-dominated to each other but are superior to the rest of the solutions in the search space. However, the best solution in terms of power loss and voltage deviation is selected for each feeder. The selected optimal results have been shown in Table 2. The results in this table have been sorted based on the degree of effect on reduction in the losses. In this table, the suggested capacity of DERs, minimum and maximum voltage in the presence of allocated DER, the improvement in feeder losses, and also in voltage deviation has been noted. For the sake of comparison, the obtained results based on MPSO are also reported in Table 2. The optimal placement of DERs along each feeder based on MPSO and MOMPSO has also been depicted in Figure 2 with red and black dots, respectively. Further, the optimal location of the allocated DER in feeder 5 based on two algorithms is shown in Figure 3.

The results have shown that:

- The capacity and place for installation of a DER, as well as its effect in the feeder, is related to feeder loading, length/ types of the feeder, and as well as the distribution of the load along the feeder. For instance, the feeder 10 has more length and loading than feeder 7, but the power loss is less in feeder 10. This means that long and heavy loaded feeders are not necessarily good candidates for installing DERs, particularly in terms of losses improvement. Again with a look at Table 2, it can be seen that in feeder 5, although it has less loading than feeder 2, it experiences more loss reduction
- The effect of DER installation on the voltage of a feeder is related to the length of the feeder. As can be concluded from the results of Table 2, feeder 5 is the longest one and, therefore, has most voltage drops in the base case, when no DER is installed (0.962 p.u. in Table 1). Nonetheless, the presence of a DER with a capacity

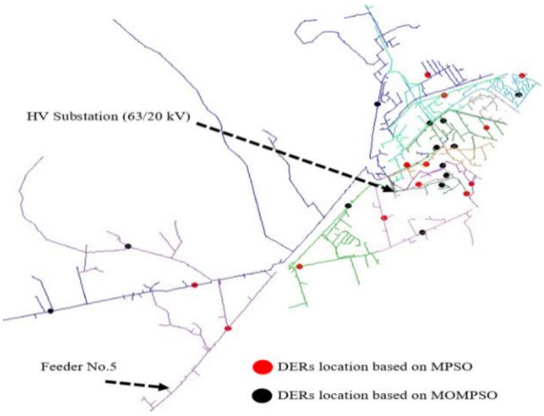

Figure 2. Single line diagram of the test system and outgoing feeders

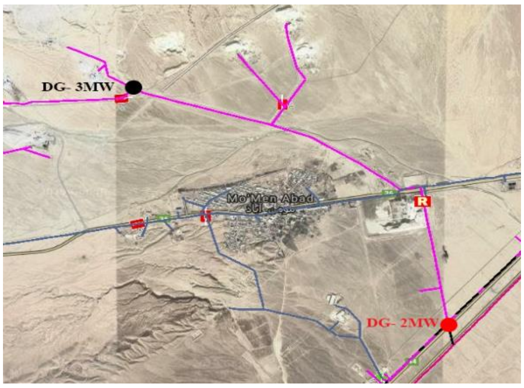

Figure 3. The optimal location of the allocated DER in feeder 5 based on two algorithms

TABLE 1. Data of outgoing feeders (Base Case)

Feeder No.	Length (KM)	Load (A)	Loss (MW)	Min Voltage (p.u.)	Max Voltage (p.u.)	Total V-Deviation (p.u.)
1	3.3	50.7	0.02289	0.999	1	0
2	27.5	136.7	0.1268	0.974	1	0.0048
3	18.1	75.5	0.05145	0.994	1	0
4	9.7	46.7	0.02868	0.998	1	0
5	48	98	0.16575	0.962	1	1.1198
6	6.5	143	0.07025	0.997	1	0
7	9.1	163.7	0.139	0.996	1	0
8	4.8	57.4	0.0283	0.999	1	0
9	24.3	131	0.1257	0.991	1	0
10	19	177.8	0.13	0.994	1	0
11	3	105.4	0.087	0.998	1	0
12	32.8	72.6	0.0561	0.974	1	0.0027
13	9.5	95	0.061	0.995	1	0

TABLE 2. The optimal allocation of DERs in each feeder based on MPSO and MOMPSO

Feeder No.	Obtained Results from MOMPSO					Obtained Results from MPSO				
	DER (MW)	Min Voltage (p.u.)	Max Voltage (p.u.)	Loss Improvement (MW)	V-Deviation Improvement (p.u.)	DER (MW)	Min Voltage (p.u.)	Max Voltage (p.u.)	Loss Improvement (MW)	V-Deviation Improvement (p.u.)
7	4.5	0.996	1	0.0466	0	4	0.991	1	0.0436	0
5	3	0.994	1	0.04225	1.1198	2	0.973	1	0.03595	0.9725
10	4.5	0.994	1	0.0317	0	3.5	0.99	1	0.01963	0
2	3.5	0.988	1	0.0226	0.0048	2.5	0.981	1	0.01621	0.0048
6	3	0.997	1	0.01575	0	4	0.999	1	0.0089	0
3	3	0.994	1	0.00515	0	2.5	0.986	1	0.00305	0
9	2.5	0.991	1	0.0271	0	3	0.994	1	0.02625	0
13	2.5	0.995	1	0.0128	0	1	0.986	1	0.00431	0
11	2.5	0.998	1	0.0072	0	3	0.988	1	0.00472	0
12	1.5	0.994	1	0.0253	0.0027	2	0.995	1	0.02401	0.0027
1	1.5	0.999	1	0.00239	0	1.5	0.999	1	0.00239	0
8	1.5	0.999	1	0.0019	0	1	0.997	1	0.0011	0
4	1	0.998	1	0.00248	0	1	0.998	1	0.00248	0

of 3 MW at the optimum location has compensated the voltage profile totally. In such a case, the minimum voltage has improved to a suitable level of 0.994 p.u. To prove this matter, the voltage profile of feeder 5, in the base case and scenario 1, have been depicted in Figures 4 and 5, respectively. As seen in Figure 4, in the base case, the minimum and maximum voltages in feeder 5 are 0.962 and 1 p.u. while the minimum voltage is the lowest voltage in all feeders and happens in the end of feeder (most far point of feeder related to HV substation). On the other hand, installation of 3 MW DERs in this feeder (based on presented results in Table 2 by using MOMPSO algorithm) leads to voltage profile improvement, as seen in Figure 5. In this circumstance, the minimum volatge of feeder 5 increases to 0.994 p.u. in the end point of feeder.

It should be noted, however, that studies in this scenario have been carried out in high loading of the network, and as stated earlier, the presence of optimized DERs in the light loading conditions can lead to an increase of the feeder voltage beyond the allowable level. This illustrates the necessity of modifying the DER capacity during the optimization process by modeling the light load conditions. Addressing this issue, which is one of the outstanding novelties of this research, is discussed in scenario 2 (following section).

***Scenario 2**. The operation of the proposed algorithm in modifying the optimal capacity of the DERs and determination of penetration levels*

As already discussed, in solving the optimal allocation of DERs, the voltage violation in the light loading conditions and also a violation of allowable short circuit current should be investigated; otherwise, the obtained results might be non-optimal in some locations. For example, by installing 3 MW DER along the feeder 5, according to optimal results of Table 2, the maximum voltage of this feeder in the light loading condition, would level up to 1.056 per unit, which is out of the allowed range. However, the reduction of the capacity to 2 MW will solve the problem as the maximum voltage is calculated 1.045 that is in the normal range. Hence, modifying the optimal capacity considering the light loading of the feeders is vital, which this issue is covered by applying the proposed flowchart of Figure 1. Moreover, in the proposed algorithm, capacity corrections are done during the optimization process to ensure that the short circuit current of the DER integrated network is also preserved under the permissive interrupting rating of the CBs. However, in the case of a short circuit violation, changing the type of DER from SGT to PV is suggested.

The following discussions are carried out briefly to show the importance of considering the short circuit study in an optimal allocation of DERs. In the test system under study, the designed short circuit current for the distribution CBs is 18 kA, and based on the IEC standard, the maximum current passing through it should be 20% lower (i.e., 14.4 KA). Note that the three-phase fault which is occurred near the HV substation is the basis of all short circuit studies. In the base case of the network and in the absence of the DERs, the maximum short circuit current (Isc) and power (Skss) are calculated as 12.08 kA and 418.53 MVA, respectively, which are lower the allowable values. However, in the presence of all optimal allocated DERs in scenario 1, Isc is calculated to equal to 16.7356 KA, which is higher than 14.4 kA, as allowed current. This means that although optimal placement and capacity of DERs reported in Table 2 are the best solutions in terms of power losses and voltage deviation, and these results can cause the overall fault level to exceed the designed fault level of distribution equipment, like CBs. In this case, CBs are subjected to increased stresses and are thus more prone to failure to operate when desired, which is a significant issue.

To overcome this issue, whenever the fault current is exceeded, the type of DER is changed to PV during the optimization process, as illustrated in Figure 1. It is known that the inverter-based DERs, like PV, have a low contribution to the fault and is limited by the maximum current level of the applied inverters. In the final step of the methodology, the penetration level of SGTs and PVs is also calculated. However, as explained earlier, obliging operators or DERs owner to install a particular type of DER (SGT or PV) at specified locations might not be reasonable from the standpoint of issues such as technical constraints, availability of suitable land and other infrastructure. To address this, in the proposed algorithm short circuit studies on DERs with the most and least contribution is also performed separately in step 1 and 2 (see the flowchart of Figure 1) to calculate the penetration levels under this condition.

The results for implementing step 1 of the algorithm (altering SGTs with the most contribution to PV) are summarized in Table 3. As per this table, it can be concluded that from 34 MW located DERs in different feeders, the optimal share of SGTs and PVs are 13 MW and 21 MW, respectively. Accordingly, the penetration level for SGTs and PVs, i.e., PL1(SGT) and PL1(PV) are obtained equal to 38.24 and 61.76 %., respectively.

The results for implementing step 2 of the algorithm (altering SGTs with least contribution to PV) are reported in Table 4. It can be here concluded that from 34 MW located DERs in different feeders, the optimal share of SGTs and PVs are 12.5 MW and 21.5 MW,

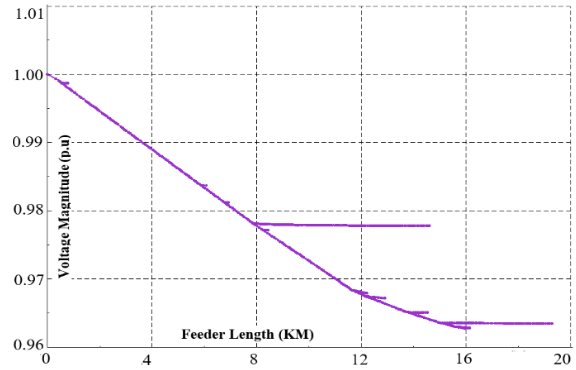

Figure 4. Voltage profile of feeder 5 in the base case

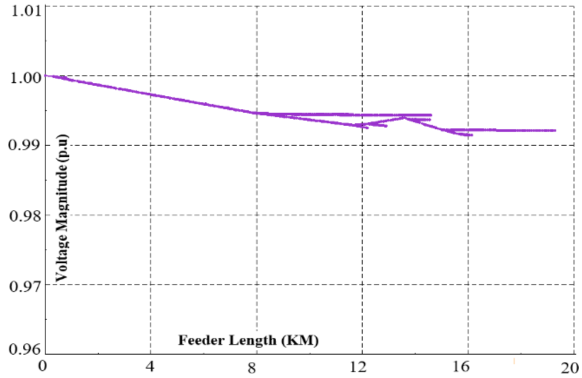

Figure 5. Voltage profile of feeder 5 based on MOMPSO

TABLE 3. Optimal allocation of DERs based on step 1 of the flowchart

Feeder No.	DER Type	DER Capacity(MW)	I_{Kss}(KA)	S_{Kss}(KA)
Grid	-	-	12	415.84
7	PV	4.5	0.1123	3.89
10	PV	4.5	0.1113	3.85
2	PV	3.5	0.0857	2.97
6	PV	3	0.0728	2.52
3	PV	3	0.0728	2.52
9	PV	2.5	0.0607	2.10
13	SGT	2.5	0.3511	12.16
5	SGT	2.5	0.3536	12.25
11	SGT	2.5	0.3401	11.78
12	SGT	1.5	0.2015	6.98
1	SGT	1.5	0.2007	6.95
8	SGT	1.5	0.1985	6.88
4	SGT	1	0.1458	5.05
	Sum	34	14.3069	495.74

respectively. Accordingly, the penetration level of SGTs and PVs, when altering DERs with least contribution, PL2(SGT) and PL2(PV), is considered, are obtained equal to 36.76 and 63.24 %., respectively.

TABLE 4. Optimal allocation of DERs based on step 2 of the flowchart

Feeder No.	DER Type	DER Capacity(MW)	I_{Kss}(KA)	S_{Kss}(KA)
Grid	-	-	12	415.84
7	SGT	4.5	0.6429	22.27
10	SGT	4.5	0.6424	22.25
2	SGT	3.5	0.4991	17.29
6	PV	3	0.0749	2.59
3	PV	3	0.0749	2.59
9	PV	2.5	0.0618	2.14
13	PV	2.5	0.0618	2.14
5	PV	2.5	0.0618	2.14
11	PV	2.5	0.0618	2.14
12	PV	1.5	0.0367	1.27
1	PV	1.5	0.0367	1.27
8	PV	1.5	0.0367	1.27
4	PV	1	0.0245	0.85
	Sum	34	14.3162	496.08

The proximity of the results in the two above steps, which show the optimum size and location of all types of DERs taking into account all the effective parameters, confirms the effectiveness of the proposed methodology in an optimal allocation of the DERs.

5. CONCLUSION

Integration of DERs has plenty of advantages such as voltage profile improvement and reduction in losses and loading on main feeders, which only on condition of appropriate allocation are obtained. To this end, optimization methods are commonly used to solve the complicated problem of DER allocation. Given the importance of this issue and in order to find optimal placement and capacity of DERs, this paper proposed a new methodology, including two main contributions. First, a multi-objective problem (MOP) was defined that while minimizing power losses and voltage deviation along with the feeders, it can optimally alter the size and type of located DERs to meet predetermined requirements of voltage profile of feeders under light loading and short circuit capability of the CBs. Second, for solving such a problem, a new Multi-Objective Mutation based PSO (MOMPSO) was presented. Two modifications of dynamic inertia weight and utilizing a mutation operator help the algorithm to improve its exploration and exploitation searchability and convergence capability. The obtained optimal results regarding applying the proposed methodology on a practical distribution network demonstrated its effectiveness in finding the best and optimal allocation of DERs.

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Determination of Optimal Allocation and Penetration Level of Distributed Energy Resources Considering Short Circuit Currents

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چکیده

نصب منابع تولید انرژی پراکنده در شبکه‌های توزیع در صورتیکه دارای جایابی و ضریب نفوذ مناسبی باشند، مزایای بسیاری را بدنبال دارد. ازینرو چالش یافتن تخصیص و ضریب نفوذ بهینه منابع تولید پراکنده در شبکه‌های بزرگ جزو مسایل مهم و البته پیچیده است. در این مقاله یک متدولوژی جدید به منظور تعیین همزمان موقعیت/ظرفیت بهینه منابع‌و نیز سطح نفوذ منابع و با هدف کاهش شاخصهای تلفات و انجراف ولتاژ ارایه میگردد. قیود پروفیل ولتاژ شبکه در شرایط بارگذاری سبک و نیز قابلیت عبور جریان اتصال کوتاه بریکرها در روش پیشنهادی مقاله بررسی میگردند. علاوه بر این، یک الگوریتم بهبودیافته چندهدفه PSO با معرفی دو تکنیک ضریب وزنی دینامیکی و نیز بکارگیری عملگر جهش ارایه میگردد که در بهبود دو فاکتور اکتشاف و استخراج و نیز قابلیت همگرایی الگوریتم موثر است. متدولوژی ارایه شده بر روی یک شبکه توزیع واقعی اعمال شده است.

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