



Voltage Stability Improvement in Optimal Placement of Voltage Regulators and Capacitor Banks Based on FSM and MMOPSO Approach

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ABSTRACT

Installation of Shunt Capacitor Banks (SCBs) and Voltage Regulators (VRs) within distribution system is one of the most effective solutions in reactive power control for improving the voltage profile and reducing power losses along the feeder. However, the presence of the VRs can deteriorate the Voltage Stability Margin (VSM) in distribution feeders. To address this issue, this paper proposes a multi-objective programming model for the simultaneous optimal allocation of VRs and SCBs in the distribution network to improve the voltage profile and to minimize power losses and installation costs. In the proposed model, a Voltage Stability Index (VSI) is considered to prevent voltage instability during SCBs/VRs allocation. A new Modified Multi-Objective Particle Swarm Optimization (MMOPSO) algorithm which includes a dynamic inertia weight and mutation operator is proposed to obtain the optimal solutions as a Pareto set. Thereinafter, a Fuzzy Satisfaction Method (FSM) determines the optimal solution. A practical long radial distribution feeder has been employed to demonstrate the efficiency and efficacy of the proposed model along with a comparison between the proposed MMOPSO and the original MOPSO.

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1. INTRODUCTION

Long feeders are prevalent in practical distribution grids as they deliver energy to scattered consumers and, mainly, areas with low population density. Considerable voltage sag and power losses are common issues of such feeders. Voltage drop is one of the major contributors to increases in network losses and feeders' operation at full load capacity is often impossible due to the voltage drop. In some cases, this issue leads to reducing feeder loading to less than 10% of feeder rated capacity [1]. In contrast, the design and construction of new HV substations and MV networks close to the demand side are not feasible for reasons such as low demand or due to economic limits of investment. Therefore, it is necessary to find alternative solutions to tackle these problems and ensure stability, reliability, and quality of the electric power supply [2].

To date, many different approaches have been proposed to resolve the issues mentioned above. Installing Shunt Capacitor Banks (SCB), as the reactive power compensators, is a well-known and common solution [3-5]. Further, voltage control can be effectively achieved using in-line automatic voltage regulators (VR), which consists of an autotransformer fitted with a tap-changing mechanism [6-8]. VR's advantages, such as controlling the voltage magnitude within standard ranges, have persuaded utilities to utilize it in distribution grids [9]. These methods each have their own advantages and disadvantages. For example, the main advantage of utilizing SCB is its simplicity and low implementation cost. However, in the case of overvoltage situations, which may occur in feeders with a high penetration level of Distributed Generation (DG) or light-load conditions, VRs are more capable of controlling conditions compared to SCB [10-12]. Although, inappropriate

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installation of VRs in long distribution feeders might have devastating effects on voltage stability, and it may lead to voltage collapse.

The benefits of voltage control and loss reduction can best be realised with the optimal allocation of this type of equipment. In fact, inappropriate placing of SCBs or VRs along with improper sizing, may lead to even higher system losses or voltage violations.

Due to the complexity of the problem of locating voltage control devices, like SCBs or VRs, the use of optimization techniques, with goals such as loss reduction and voltage improvement, is widespread in the literature [6, 11-16]. Articles published in this field can be easily divided into two general categories:

The first group discusses the allocation of various control devices, such as SCBs, VRs, DGs, and the goals that must be met in the allocation (such as reducing losses and emission and improving network voltage) [17]. Further, in the second category, different optimization algorithms are presented, knowing that the optimal allocation problem with different objectives is a complex problem. For example, extensive literature [4, 18-21] address SCBs allocation in the distribution network for voltage control and energy losses minimization. The optimal allocation of SCBs based on two optimization techniques, i.e., water cycle algorithm (WCA) and grey wolf optimizer (GWO) have been addressed [22]. Hocks et al. [8] have described in detail the performance of the VR in improving the power quality of the network. Optimal placement and sizing of VRs in a radial distribution network have been discussed in literature [13, 14]. The literature [7, 23, 24] have suggested the simultaneous allocation of SCBs/VRs in order to take advantage of both devices. Further, in some research, hybrid placement and sizing of SCBs/DGs to improve power losses and voltage profile of the distribution network and minimization of investment cost have been considered [11, 25-27]. To enhance the real Egyptian distribution system's performance, optimal placement of the combined SCBs, DGs, and VRs has been introduced in literature [28-30] based on the PSO algorithm. Although literature [28] provides a comprehensive overview of system performance improvement techniques, it has not examined the impact of placement on network stability.

Although the methods presented in the articles mentioned above for SCBs/VRs allocation lead to grid performance improvement, one of their drawbacks is ignoring the network voltage stability during the optimal allocation. The voltage collapse phenomenon is critical in long feeders, which has been the subject of many papers [1, 31-33]. It is a fact that VRs increase injected reactive power to the feeder, which results into lower lag power factor, and consequently, lower Voltage Stability Margin (VSM). In contrast, SCBs as reactive power sources, can improve the VSM. Due to the different

effects of these two elements on the VSM, the voltage stability studies should be factored in the simultaneous installation of VRs and SCBs. Given the above shortcoming, this paper introduces a voltage stability index to prevent the feeder's voltage collapse while optimal allocating of the SCB/VRs.

Franco et al. [7] have carried out research by using the Mixed Integer Linear Programming (MILP) model for optimal placement of SCBs/VRs in a distribution system. Tolba et al. [19] hybridization of Particle Swarm Optimization besides a Gravitational Search Algorithm (PSOGSA) is suggested for solving the optimal allocation of SCBs. Oliveira et al. [34] have applied Mixed Integer Non-Linear Programming (MINLP) model to obtain the optimum size of the SCBs. Evolutionary and nature inspired techniques, like Genetic Algorithm [24, 35] or Particle swarm optimization (PSO) [23], Harmony Search Algorithm (HSA) [36], Water Cycle Algorithm [11], have also extensively used for solving allocation problems due to their specificity in solving the optimization problem.

As already discussed, the problem of SCBs/VRs is a complicated multi-objective problem, which due to being trapped in local optima and the possibility of premature convergence, the simple or original class of heuristic methods may not be sufficient to find the optimal solution. In this regard and as the second contribution, a novel Modified Multi-Objective PSO (MMOPSO) is proposed, which obtains optimal Pareto set as optimal solutions. Thereinafter, the Fuzzy Satisfaction Method (FSM) is employed to determine the best optimum solution. The main features and contributions of this research study are highlighted as follows:

- Optimal allocation of the SCBs/VRs to enhance technical and economic issues of distribution systems.
- Introducing a voltage stability index (VSI) as one of the objective functions during allocation, in addition to power losses, voltage deviation, and SCBs/VRs installation costs. The advantage of considering VSI is to prevent the voltage collapse of long feeders after the VRs installation.
- Proposing a Modified Multi-Objective PSO (MMOPSO) algorithm to find optimal solutions for optimal allocation of SCBs/VRs program.
- Applying a Fuzzy Satisfaction Method (FSM) for determining the optimum solution among the non-dominated Pareto set.
- Applying the proposed method to a real radial distribution system.

2. PROBLEM FORMULATION

This paper introduces a multi-objective programming model to optimally allocate the SCBs/VRs within a long feeder. According to the model presented, SCBs/VRs are

positioned along the feeder to optimally improve all operating criteria such as losses and voltage indices. In this section, the objective functions (OFs) and related constraints are introduced.

2. 1. Power Losses Minimization of the total feeder losses after installation of SCBs/VRs is technically considered as an objective function in optimal allocation of SCBs/VRs [37, 38]

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

where R_{ij} stands for the resistance of each line section within the feeder, and I_{ij} indicates current flow through them.

2. 2. Voltage Deviation In the second OF, minimization of total voltage deviation in 20kV feeders is considered as follows:

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

In this paper, the desired and reference voltage (V_{ref}) has not been considered a constant value, e.g., 1 p.u.; in contrast, it has been assumed to be a range of standard voltages. In other words, the voltage magnitude at each terminal must be maintained within specified limits as follows:

$$0.95 \leq V_{ref} \leq 1.05 \tag{3}$$

As per the above constraint, voltage deviation happens whenever the voltage of any terminal (V_n) along the feeder is out of this allowable range. One of the benefits of using such a function is to avoid unnecessary installation of SCBs/VRs to reduce the total costs. In other words, by considering 1 p.u. for V_{ref} , the optimization method would result in higher capacity or number of SCBs/VRs as it tries to reduce deviated voltage from V_{ref} .

2. 3. Installation Cost of SCBs/VRs Due to the limited budget of distribution companies, allocating SCBs/VRs are not possible without considering the economic parameters. Thus, one of the essential objective functions that are generally considered in the optimization problem is an economic OF. This OF aims to optimally determine the number of allocated SCBs/VRs from the viewpoint of cost.

$$\min C = \sum_{i=1}^{N_{cap}} Cap_Kvar_i \times Cost_{cap} + N_{VR} \times Cost_{VR} \tag{4}$$

As stated in Equation (4), the total cost imposed by the SCBs/VRs installation depends on their capacity/number. According to price inquiry from different suppliers, two values of 4.5 US\$/kVAR and US\$45000 have been considered, respectively, for evaluation of $Cost_{cap}$ and $Cost_{VR}$ terms in Equation (4). In this paper, the capacity of each SCB is considered

200KVAR. Due to the limited budget in implementing SCBs/VRs, the maximum number of SCBs is limited to 10 and 20 (In two different studied scenarios in simulation results), and the number of VRs is limited to 3.

2. 4. Voltage Stability Index Unlike during normal operating conditions where a slight increase in load causes a slight decrease in voltage, if the feeder loading exceeds a certain value, then an increase in load will result in a rapid decrease in voltage and, eventually, voltage collapse. Installing the SCBs/VRs without consideration of this issue, despite its other advantages, can bring the network closer to the voltage instability point. Conversely, properly installation of SCBs/VRs can save the network from voltage collapse by changing the flow of active/reactive power.

Given the above description, and considering the ever-growing load demand in distribution networks, it is imperative to consider the stability issue along the feeder while allocating the SCBs/VRs. This issue, to the best of the authors' knowledge, has been overlooked in the literature. Hence, a voltage stability index (VSI), which has been derived based on the research reported in literature [32], is presented that should be minimized in the optimal allocation problem.

$$\min VSI = 4 \left[(x_{eq} P_{Deq} - r_{eq} Q_{Deq})^2 + x_{eq} Q_{Deq} + r_{eq} P_{Deq} \right] \tag{5}$$

Since the practical distribution network consists of many lines and laterals, the stability index is obtained based on the single-line method for reducing a distribution network and extraction of the equivalent Thevenin's parameters.

In this equation, P_{Deq} and Q_{Deq} are total real and reactive loads in the distribution network. Also, equivalent resistance (r_{eq}) and equivalent reactance (x_{eq}) for a single line are defined as follows:

$$r_{eq} = \frac{\sum P_{Loss}}{\{(P_{Deq} + \sum P_{Loss})^2 + (Q_{Deq} + \sum Q_{Loss})^2\}} \tag{6}$$

$$x_{eq} = \frac{\sum Q_{Loss}}{\{(P_{Deq} + \sum P_{Loss})^2 + (Q_{Deq} + \sum Q_{Loss})^2\}} \tag{7}$$

where

$$P_{Loss} = R_{ij} \frac{P_{ij}^2 + Q_{ij}^2}{V_n^2} \tag{8}$$

$$Q_{Loss} = X_{ij} \frac{P_{ij}^2 + Q_{ij}^2}{V_n^2} \tag{9}$$

where (P_{ij}, Q_{ij}) are the active/reactive power of each line, which are altered by utilizing SCBs/VRs along the feeder.

It should be noted that theoretically, in a stable system, the VSI index has to be below 1. If the feeder is

loaded beyond the critical limit, at this circumstance, the voltage will collapse.

In addition to the mentioned objective functions, distribution system constraints such as a line's loading capacity are considered in the problem.

3. SOLUTION APPROACH

The problem of SCBs/VRs allocation is a complicated multi-objective problem that should be solved via a multi-objective optimization algorithm. Therefore, heuristic methods, like PSO and GA, have been commonly used in the literature [8, 13, 36, 38]. However, the original or simple class of these kinds of methods are susceptible of being trapped into local optimum and also premature convergence and may not be sufficient to find the optimum solution, especially within practical distribution networks that have numerous long feeders. In this regard, a novel modified Multi-Objective PSO for finding an optimal Pareto set of non-dominated solutions is proposed as the paper's second contribution. Moreover, the FSM technique for determining the optimum solution among the Pareto set is presented.

3. 1. Modified Multi-objective PSO (MMOPSO)

Multi-objective problem optimization is a class of complex problems with objective functions, which can be incomparable or contradictory. In these problems, it is impossible to find a single global optimum solution. Contrary to the single-objective optimization scenario, there is an optimal set of solutions or alternatives, called the Pareto optimal set. Expert analysis and trade-off can, therefore, describe the optimal solution among the Pareto set. The aim of the multi-objective model proposed in the present research is to find the optimal size and site of SCBs and the location of VRs along the distribution feeders.

However, solving the MOPs with mathematical or linear programming methods is difficult due to the necessity of optimizing several objective functions. Metaheuristic algorithms, such as PSO, are therefore suitable because of 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 strategy inspired by bird flocking or fish schooling social behaviour [39] and extended by authors of [40, 41] as multi objective PSO. Consider $X_i (X_{i,1}, X_{i,2}, \dots, X_{i,d})$ denotes an n-dimensional decision variable vector which moves with a velocity $V_i (V_{i,1}, V_{i,2}, \dots, V_{i,d})$. The particles positions are restored as nondominated vectors in the repository (REP). The historical record of a particle's best solutions is used for storing non-dominated solutions. Each particle is associated with its best solution achieved, $X_{best-i} (X_{best-i,1}, X_{best-i,2}, \dots, X_{best-i,d})$, 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 the leader from the RES is done based on the hypercube method and applying the Boltzmann and roulette-wheel selection algorithm [41].

The particle's new position is controlled by updating its position attributes and velocity (10 and 11). A modified version of the classical PSO (MPSO) based on literature [42] has been used in this paper to ensure the optimal solution in the allocation problem. The third term of the Equation (10) is a randomly applied intermediate crossover in the MPSO to prevent particles from becoming lazy in the swarm after a while.

$$V_i^{iter+1} = W \times V_i^{iter} + c_1 \times \text{rand} \times (X_{best-i}^{iter} - X_i^{iter}) + c_2 \times \text{rand} \times (X_i^{REP} - X_i^{iter}) + c_{1c} \times \text{rand} \times (X_i^{iter} - X_{not-best}^{iter}) \quad (10)$$

$$X_i^{iter+1} = X_i^{iter} + V_i^{iter+1} \quad (11)$$

where W is the inertia weight, c_1 and c_2 are cognitive and social acceleration coefficients, and $X_{not-best}^{iter}$ reflects the worst particle experience.

Two modifications are implemented in this paper to solve the proposed multi-objective model and to improve the MPSO 's efficiency in finding the global optimum. These modifications improve the algorithm's convergence capability and searchability. The following describes these modifications, respectively.

3. 1. 1. Dynamic Inertia Weight

The particles inertial behaviour causes a partial restriction of the particle velocity variations so that the particles from the search space don't change their direction quickly to the best swarm experience; thus, fast convergence of the algorithm is prevented. At the start of random search algorithms, such as PSO, an exploration or global search is required to find the optimal search space, so the diversity of the population in the initial iterations should be preserved. The particles should also explore the entire search space that is met by selecting a relatively high value for inertia weight. Setting too high values for inertial weight causes a problem in that the algorithm in the final iterations cannot correctly converge to the X_{Gbest} experience. Thus, the inertia weight should be selected as a balance between exploration and exploitation so that the algorithm addresses both issues. In this paper, a dynamic inertia weight factor is introduced as follows to resolve these issues and to maintain the balance between exploration and exploitation:

$$W = \left(\frac{\text{iter}_{max} - \text{iter}}{\text{iter}_{max}} \right) \quad (12)$$

As per (12), with increasing repetitions, gradually and dynamically, the weight of inertia decreases as the

algorithm converges to the optimal point and the best group experience. Besides, the inertia weight has characteristic randomness to maximize the particle variety.

3.1.2. The Proposed Mutation Mechanism

In a problem with a vast search space, like the problem of optimal SCBs/VRs allocation, in which every node along the feeder could be a candidate, it is possible that the initial population is far from the optimum solution. Under such a case, the MPSO's exploration capability degrades, and therefore the particles move rapidly to a false Pareto front, which may be a local optimum under global optimization, leading to premature convergence. A mutation operator (Equation (13)) is introduced to tackle this issue, which causes particles to move in different directions during the optimization process and enhance the algorithm's exploration.

$$X_i^{\text{iter}} = X_i^{\text{iter}} + W \times \frac{1}{\pi\gamma} \left[\frac{\gamma^2}{(X_i^{\text{iter}} - \theta)^2 + \gamma^2} \right] \quad (13)$$

The proposed operator is multiplied by the inertia weight (W), which in the beginning increases the step size of the mutation and thus increases the opportunity to search for new areas. In this way, the explorative behaviour of the algorithm is improved. By comparison, as the current best solution reaches an optimum solution in subsequent iterations, the mutation's step size is reduced to improve the accuracy of convergence. The mutation, on the other hand, should be done at random; thus, when a particle is selected for mutation, a random disturbance is applied to its current position. The probability in this paper is determined on the basis of the Cauchy distribution function, which is multiplied by W. The scale parameter (γ) and location parameter (θ) are set to 0.5 and 0, respectively, in the distribution function.

3.2. Fuzzy Satisfaction Method (FSM)

The equations called membership functions are used to define the fuzzy sets. These functions show membership level in certain fuzzy sets using values from 0 to 1 [43]. The membership value '1' presents compatibility totally, while the number '0' means full incompatibility with the set.

In this study, fuzzy sets are defined for all the objective functions discussed in section 2. We assume that all objective functions' maximum and minimum values can be defined based on the base case scenario and other aforementioned technical constraints. By taking account of the individual minimum and maximum values of each objective function, the membership function $\mu(R_i)$ for each objective function in section 2 can be determined in a subjectively manner as expansion (14), Where R_{\min}^i and R_{\max}^i are the minimum and maximum values of i th objective function in which the solution is expected.

$$\mu(R_i) = \begin{cases} 1 & R_i < R_i^{\min} \\ \frac{R_i^{\max} - R_i}{R_i^{\max} - R_i^{\min}} & R_i^{\min} \leq R_i \leq R_i^{\max} \\ 0 & R_i > R_i^{\max} \end{cases} \quad (14)$$

For calculating the membership functions, the minimum and maximum values of objective functions must be defined first. The maximum values of losses and total voltage deviation are set according to the data resulting from the base case simulation at the test case feeder. This is because the values for losses and total voltage deviation in the base case are the worst between Pareto solutions, and the optimization methods are aimed to reduce these values. The minimum values for these two objective functions theoretically could reach the value '0'. In a stable system, the VSI index has to be below 1, thus the maximum and minimum values of this objective function are defined '1' and '0', respectively. Due to the limited budget in implementing SCBs/VRs, the maximum numbers of these elements are limited to the mentioned values in section 2. Therefore, the maximum values of the installation cost of SCBs/VRs are calculated as the maximum number of SCBs/VRs multiplied by the stated prices in section 2. The minimum values of the installation cost for SCBs/VRs are zero.

The membership functions' value indicates how much (in scale from 0 to 1) a solution is satisfying the objective. The minimum value of all membership functions for a specific combination represents the optimality value of the combination. Therefore, a combination with a larger minimum value of membership functions is more favourable since it can lead to more objective functions tending to their individual optimum values. Thus among all possible optimum solutions, one should seek a combination for which the minimum value of all the membership functions is maximum. Hence for a multi-objective optimization problem with N objective functions, the following index (φ) can be calculated for every Pareto solution in the repository.

$$\varphi \equiv \text{Max}\{\min(\mu(R_i))\} \quad i = 1, \dots, N \quad (15)$$

According to the relation (15), the Pareto set's optimal solution would be the Pareto solution for which φ is the maximum.

4. SIMULATION RESULTS

To verify the performance of the proposed algorithm in obtaining the optimal placement and capacity of SCBs/VRs, a practical 20 kV distribution network located in Semnan (Figure 1) is used as a test system. For verification of the proposed approach's efficacy, a long feeder (about 180 km) is selected for the allocation of SCBs/VRs. Feeder information in the base case (where

there are no SCBs/VRs within the feeder) are shown in Table 1. In Figure 1, all feeders are shown in different colours. The main advantage of choosing a practical 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 it also works for smaller systems.

It was possible to access hourly load information of the test system over the past year, which is one of the algorithm implementation requirements.

The proposed MMOPSO starts optimizing the problem with a population of 60 particles, a repository size of 15 particles; and finally, the algorithm stops after 100 iterations. It should be noted that, in the proposed MMOPSO, the related parameters are set based on the values obtained in the literature [44, 45]. To evaluate the effectiveness of the simultaneous allocation of SCBs/VRs, two scenarios are studied for the purpose of discussion.

In the first scenario, the optimal simultaneous allocation of SCBs/VRs based on the proposed formulation is obtained, while, in the second one, the optimum allocation of SCBs without considering the VRs is done to evaluate the effect of the VRs on the network operation. In both scenarios, the implementation

TABLE 1. Power flow data of studied feeder in the base case

Active Power (MW)	Reactive Power (Mvar)	Nominal Voltage (KV)	Input Current (A)	Losses (MW)
3.53	1.85	20	115	0.796

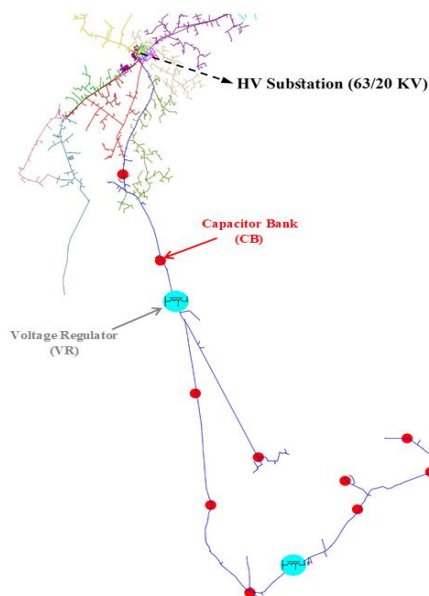


Figure 1. Location of SCBs/VRs in scenario 1 in Semnan distribution network in DlgSILENT

of the proposed MMOPSO in finding optimum solutions is evaluated in contrast to the original multi-objective PSO.

4. 1. Scenario 1. Simultaneous Allocation of SCBs/VRs

As already mentioned, in this scenario, the optimal allocation of SCBs/VRs and their impacts on improving the operation of the grid is assessed. The repository consists of 5 Pareto optimal solutions for solving the problem, which are reported in Table 2. The optimal location of the allocated VRs and SCBs based on the obtained results (for the solution with the maximum φ in Pareto set - solution 4 in Table 2) are also depicted in Figure 1. For the sake of comparison, some operating indices and objective functions in the base case are also inserted in this table. In all Pareto solutions, the optimum number of VRs was 2. So, the number and capacity of SCBs, as the difference between Pareto solutions, have been inserted in this table instead of installation cost.

As per the results of Table 2, in the simultaneous allocation of SCBs/VRs, the maximum number of SCBs that can be placed is 10. Nevertheless, all five reported solutions improve network performance in terms of voltage improvement and loss reduction compared to the base case. However, none of the solutions is dominated. The FSM method is employed to determine the best solution in this table. By calculating index φ , it can be found that solution 4 satisfies Equation (15), and it is the best solution in the Pareto set. The value of φ in this solution is 0.2977.

The obtained results verify the performance and effectiveness of the proposed method, as follows:

- In all of the Pareto solutions, all of the objective functions' values are more optimal than the base case.
- The individual values of objective functions (except voltage deviation index) in solution 4 are not the best between all solutions, but calculating index φ shows that solution 4 is the best. In fact, there is a compromise between different objective functions in this solution.
- The losses amount in solution 4 is decreased to 0.559 MW, as given in Table 2. However, it is not the minimum value in all solutions, which indicates the non-domination of different solutions in the Pareto set. The best solution from this viewpoint is solution 3.
- Voltage deviation happens whenever the voltage of any terminal (V_n) along the feeder is out of the allowable range. As stated in Equation (2), the total voltage deviation equals the summation of the voltage deviations at all feeder busses. As illustrated in Table 2, the total voltage deviation of the feeder in scenario 4 considerably decreases from 253.53 p.u. to 0 p.u. In this regard, the minimum voltage value is increased to 0.954 p.u., which indicates that the voltage of all terminals is controlled within the permissible range, compared to the base case. To compare the network operation conditions, Figure 2 and Figure 3 illustrate the voltage profile of the test case

TABLE 2. The optimal allocation of SCBs/VRs (scenario 1)

Optimum Solution	MMOPSO Results					Original MOPSO Results				
	Losses (MW)	Total Voltage Deviation (p.u)	VSI	Total installed SCBs (Mvar)	Number of SCBs	Losses (MW)	Total Voltage Deviation (p.u)	VSI	Total installed SCBs (Mvar)	Number of SCBs
Base case	0.796	253.53	0.632	0	0	0.796	253.53	0.632	0	0
1	0.549	0	0.563	1.67	10	0.541	6.98	0.554	1.95	10
2	0.533	11.84	0.547	1.51	10	0.554	24.58	0.576	1.55	9
3	0.531	19.00	0.589	1.46	10	0.569	12.25	0.561	2	10
4	0.559	0	0.556	1.39	10	0.576	42.35	0.581	1.2	8
5	0.589	66.70	0.567	1.1	8	0.552	5.23	0.572	1.8	10

feeder in the base case and scenario 4, respectively. It is clear that the feeder voltage profile is improved under the simultaneous allocation of SCBs/VRs conditions.

- Another salient feature of the proposed methodology is to increase the voltage stability criterion, following optimal SCBs/VRs allocation. The results show that the VSI index is strengthened relative to the base case, which allows for more loading of the feeder if needed. It should be noted that when the VSI approaches one, it indicates that the system is close to the voltage collapse condition. It is worth noting that although the power losses in solution 1 is lower than 4, but it is the VSI in scenario 4 that is better than 1, resulting solution 4 is the best in this scenario.

- In Table 2, the optimal solutions obtained by the original MOPSO are also reported, comparing them with the results of the proposed MMOPSO. The obtained results show that the value of ϕ in the original MOPSO is 0.2764, which is lower than the ϕ in MMOPSO case. It demonstrates the feasibility and efficiency of the MMOPSO algorithm in terms of allocation of SCBs/VRs, and so improved operating conditions.

4. 2. Scenario 2- Allocation of SCBs To examine the effect of the VRs on improving feeder performance, in the second scenario, only the optimal allocation of SCBs is discussed. In other words, in this case, the VRs are eliminated and the MMOPSO and original MOPSO methods are applied to optimize the site and size of SCBs only. The maximum number of allocated capacitors is increased from 10 to 20 in this scenario to distinguish the results better.

The 5 Pareto optimal solutions are reported in Table 3. The obtained results can be summarised as follows:

- The MMOPSO allocates the SCBs along the feeder in order to satisfy the objective functions of the voltage control and loss reduction; however, it has not been able to adjust the feeder voltage compared to scenario 1 optimally.

- Depicted in Table 4, the ϕ values for discussed scenarios indicate that the ϕ values in scenario 1 for both algorithms are more optimal than the ones in scenario 2.
- Based on statistics seen in Table 4, solution 1 in MMOPSO is the best in this scenario, where the total capacity of 2.61 MVar capacitors are allocated, and the minimum voltage of feeder terminals is obtained 0.922 p.u., which is outside the permissible range. Also, in this case, the total voltage deviation is calculated by 140.54 p.u., which is not acceptable.

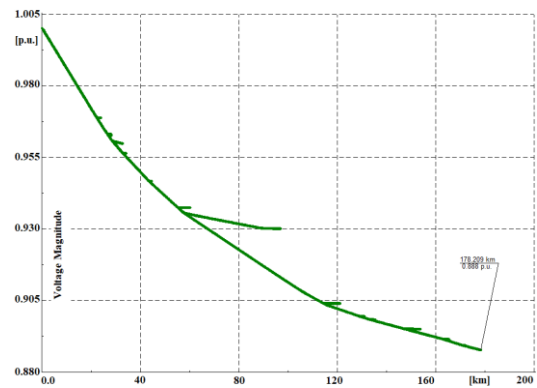


Figure 2. Voltage profile of test case feeder in the base case

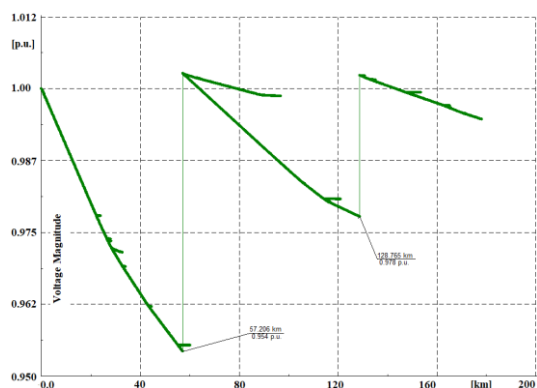


Figure 3. Voltage profile of test case feeder in the scenario 1

TABLE 3. The optimal allocation of SCBs (scenario 2)

Optimum Solution	MMOPSO Results					Original MOPSO Results				
	Losses (MW)	Total Voltage Deviation (p.u)	VSI	Total installed SCBs (Mvar)	Number of SCBs	Losses (MW)	Total Voltage Deviation (p.u)	VSI	Total installed SCBs (Mvar)	Number of SCBs
Base case	0.796	253.53	0.632	0	0	0.796	253.53	0.632	0	0
1	0.591	140.54	0.508	2.61	17	0.754	102.34	0.592	3.12	18
2	0.788	87.72	0.601	3.46	19	0.651	194.76	0.536	0.98	13
3	0.667	207.38	0.544	0.78	12	0.642	189.23	0.538	1.24	14
4	0.636	191.78	0.530	1.16	10	0.602	153.75	0.522	2.85	19
5	0.650	199.74	0.536	1.01	12	0.612	132.24	0.541	2.91	18

• Analyzing the average values of VSI in both scenarios reveals that implementing VRs deteriorates the voltage stability status in distribution grids, especially in long feeders. Therefore, voltage stability indices should be taken into account as one of the critical objectives in allocating VRs.

To conclude, it is clear that the allocation of capacitors alone cannot solve the problem of operating long feeders. On the other hand, it is not technically correct to install too many SCBs along the feeder as placing capacitors in a system could cause harmonic resonance and/or switching transients and may cause equipment damage due to high voltage, excessive thermal problems, and current circulation between the capacitor and the system. Finally, the results of Table 3 confirm that the proposed MMOPSO algorithm is more successful and more reliable in finding the optimal solution than the original MOPSO.

The main finding from the obtained results can be summarized as follows:

In long feeders without use of VRs and only with the use of SCBs, it is not possible to adjust the voltage of the feeder properly. In fact, in the medium voltage networks, due to the predominance of R over X, increasing the capacitance of SCBs in the network can not fix the issue of network voltage drop.

On the other hand, by comparing the VSI values in Tables 2 and 3, it can be seen that in general, in the first scenario and in the presence of VRs, the voltage stability

index has worse conditions than the second scenario (without the presence of VRs). This means that in allocating such equipment, it is very important to consider the voltage stability index as one of the decision criteria. Obviously, if these conditions are not taken into account, a solution may be chosen that, despite improvements in other parameters, will bring the feeder closer to the voltage collapse condition. For example, a comparison of solutions 1 and 4 in Table 2 indicates that solution 1 is superior to solution 4 in terms of losses and has the same conditions in terms of voltage deviation. But in terms of voltage stability index, Solution 4 is superior to Solution one.

5. CONCLUSION

In this paper, a multi-objective programming model is presented to determine the optimal size and site of VRs and SCBs in long distribution feeders. In this regard, an MMOPSO is employed to solve the proposed model, and the obtained results have been compared with an original MOPSO.

This paper's main aims are voltage level adjustment, loss reduction, voltage profile improvement, voltage stability enhancement, and installation cost minimization. Several important observations can be concluded as follows:

- Utilizing shunt capacitors cannot address the voltage stability margin issues. As a result, the simultaneous implementation of VRs and SCBs is necessary .
- The VSI index of the distribution system faces enormous difficulties by installing VRs, so it is vital to consider the VSI criteria in an optimal allocation of VRs .
- The power losses of the distribution system can be effectively reduced.
- Using proposed MMOPSO leads to more optimal solutions than the original MOPSO.

TABLE 4. The φ Values for different scenarios

Scenario No.	MMOPSO		Original MOPSO	
	φ	Solution No.	φ	Solution No.
1	0.2977	4	0.2764	4
2	0.2575	1	0.2437	4

6. REFERENCES

- Chakravorty, M. and Das, D., "Voltage stability analysis of radial distribution networks", *International Journal of Electrical Power & Energy Systems*, Vol. 23, No. 2, (2001), 129-135. DOI: doi.org/10.1016/S0142-0615(00)00040-5
- Liang, R.-H. and Wang, Y.-S., "Fuzzy-based reactive power and voltage control in a distribution system", *IEEE Transactions on Power Delivery*, Vol. 18, No. 2, (2003), 610-618. DOI: 10.1109/TPWRD.2003.809740
- Gu, Z. and Rizy, D.T., "Neural networks for combined control of capacitor banks and voltage regulators in distribution systems", *IEEE Transactions on Power Delivery*, Vol. 11, No. 4, (1996), 1921-1928. DOI: 10.1109/61.544277
- Baran, M.E. and Wu, F.F., "Optimal capacitor placement on radial distribution systems", *IEEE Transactions on Power Delivery*, Vol. 4, No. 1, (1989), 725-734. DOI: 10.1109/61.19265
- Diab, A.A.Z. and Rezk, H., "Optimal sizing and placement of capacitors in radial distribution systems based on grey wolf, dragonfly and moth-flame optimization algorithms", *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, Vol. 43, No. 1, (2019), 77-96. DOI: 10.1007/s40998-018-0071-7
- Batmani, Y. and Golpîra, H., "Automatic voltage regulator design using a modified adaptive optimal approach", *International Journal of Electrical Power & Energy Systems*, Vol. 104, (2019), 349-357. DOI: org/10.1016/j.ijepes.2018.07.001
- Franco, J.F., Rider, M.J., Lavorato, M. and Romero, R., "A mixed-integer lp model for the optimal allocation of voltage regulators and capacitors in radial distribution systems", *International Journal of Electrical Power & Energy Systems*, Vol. 48, (2013), 123-130. DOI: org/10.1016/j.ijepes.2012.11.027
- Hock, R.T., Novaes, Y.R.d. and Batschauer, A.L., "A voltage regulator for power quality improvement in low-voltage distribution grids", *IEEE Transactions on Power Electronics*, Vol. 33, No. 3, (2018), 2050-2060. DOI: 10.1109/TPEL.2017.2693239
- Siahi, M., Porkar, S., Abbaspour, T.A., Poure, P. and Saadate, S., "Competitive distribution system planning model integration of DG, interruptible load and voltage regulator devices", *Iranian Journal of Science & Technology, Transaction B: Engineering*, Vol. 34, No. B6, (2010), 619-635. Retrieved from <https://www.sid.ir/FileServer/JE/8542010B603.pdf>
- Mohammadi, M., Parsa, M., Alinejad-Beromi, Y. and Moradi, A., "Optimal locating and sizing of unified power quality conditioner-phase angle control for reactive power compensation in radial distribution network with wind generation", *International Journal of Engineering, Transactions B: Applications*, Vol. 31, No. 2, (2018), 299-306. DOI: 10.5829/ije.2018.31.02b.14
- El-Ela, A.A.A., El-Schiemy, R.A. and Abbas, A.S., "Optimal placement and sizing of distributed generation and capacitor banks in distribution systems using water cycle algorithm", *IEEE Systems Journal*, Vol. 12, No. 4, (2018), 3629-3636. DOI: 10.1109/JSYST.2018.2796847
- Chamana, M. and Chowdhury, B.H., "Optimal voltage regulation of distribution networks with cascaded voltage regulators in the presence of high pv penetration", *IEEE Transactions on Sustainable Energy*, Vol. 9, No. 3, (2018), 1427-1436. DOI: 10.1109/TSTE.2017.2788869
- Efkarpidis, N., Rybel, T.D. and Driesen, J., "Optimal placement and sizing of active in-line voltage regulators in flemish lv distribution grids", *IEEE Transactions on Industry Applications*, Vol. 52, No. 6, (2016), 4577-4584. DOI: 10.1109/TIA.2016.2599148
- Safigianni, A.S. and Salis, G.J., "Optimum voltage regulator placement in a radial power distribution network", *IEEE Transactions on Power Systems*, Vol. 15, No. 2, (2000), 879-886. DOI: 10.1109/59.867188
- Moradian, S., Jadid, S. and Homaei, O., "Optimal allocation of capacitors with stand-alone var control systems in radial distribution networks", *International Transactions on Electrical Energy Systems*, Vol. 25, No. 7, (2015), 1333-1348. DOI: org/10.1002/etep.1911
- Pamshetti, V.B. and Singh, S.P., "Optimal coordination of pv smart inverter and traditional volt-var control devices for energy cost savings and voltage regulation", *International Transactions on Electrical Energy Systems*, Vol. 29, No. 7, (2019), e12042. DOI: org/10.1002/2050-7038.12042
- Cao, Y., Wang, Q., Wang, Z., Jermittiparsert, K. and Shafiee, M., "A new optimized configuration for capacity and operation improvement of cchp system based on developed owl search algorithm", *Energy Reports*, Vol. 6, (2020), 315-324. DOI: <https://doi.org/10.1016/j.egy.2020.01.010>
- Dixit, M., Kundu, P. and Jariwala, H.R., "Optimal integration of shunt capacitor banks in distribution networks for assessment of techno-economic asset", *Computers & Electrical Engineering*, Vol. 71, (2018), 331-345. DOI: <https://doi.org/10.1016/j.compeleceng.2018.07.014>
- Niknam, T., Ranjbar, A., Ostadi, A. and Shirani, A., "A new approach based on ant algorithm for volt/var control in distribution network considering distributed generation", *Iranian Journal of Science & Technology, Transaction B, Engineering*, Vol. 29, No. B4, (2005), 385-398. Retrieved from <https://www.sid.ir/FileServer/JE/8542005B405.pdf>
- Montazeri, M. and Askarzadeh, A., "Capacitor placement in radial distribution networks based on identification of high potential busses", *International Transactions on Electrical Energy Systems*, Vol. 29, No. 3, (2019), e2754. DOI: <https://doi.org/10.1002/etep.2754>
- Tolba, M.A., Zaki Diab, A.A., Tulsy, V.N. and Abdelaziz, A.Y., "Vlci approach for optimal capacitors allocation in distribution networks based on hybrid PSO/GSA optimization algorithm", *Neural Computing and Applications*, Vol. 31, No. 8, (2019), 3833-3850. DOI: <https://doi.org/10.1007/s00521-017-3327-7>
- Kola Sampangi, S. and Thangavelu, J., "Optimal capacitor allocation in distribution networks for minimization of power loss and overall cost using water cycle algorithm and grey wolf optimizer", *International Transactions on Electrical Energy Systems*, Vol. 30, No. 5, (2020), e12320. DOI: <https://doi.org/10.1007/s40998-018-0071-7>
- Attar, M., Homaei, O., Falaghi, H. and Siano, P., "A novel strategy for optimal placement of locally controlled voltage regulators in traditional distribution systems", *International Journal of Electrical Power & Energy Systems*, Vol. 96, (2018), 11-22. DOI: <https://doi.org/10.1016/j.ijepes.2017.09.028>
- Szuvovivski, I., Fernandes, T.S.P. and Aoki, A.R., "Simultaneous allocation of capacitors and voltage regulators at distribution networks using genetic algorithms and optimal power flow", *International Journal of Electrical Power & Energy Systems*, Vol. 40, No. 1, (2012), 62-69. DOI: <https://doi.org/10.1016/j.ijepes.2012.02.006>
- Das, S., Das, D. and Patra, A., "Operation of distribution network with optimal placement and sizing of dispatchable dgs and shunt capacitors", *Renewable and Sustainable Energy Reviews*, Vol. 113, (2019), 109219. DOI: <https://doi.org/10.1016/j.rser.2019.06.026>
- Elmitwally, A. and Eldesouky, A., "An approach for placement and sizing of capacitor banks in distribution networks with distributed wind generation", *International Transactions on*

- Electrical Energy Systems*, Vol. 23, No. 4, (2013), 539-552. DOI: <https://doi.org/10.1002/etep.1611>
27. Haghghat, H., "Energy loss reduction by optimal distributed generation allocation in distribution systems", *International Transactions on Electrical Energy Systems*, Vol. 25, No. 9, (2015), 1673-1684. DOI: <https://doi.org/10.1002/etep.1907>
 28. Elsayed, A.M., Mishref, M.M. and Farrag, S.M., "Distribution system performance enhancement (egyptian distribution system real case study)", *International Transactions on Electrical Energy Systems*, Vol. 28, No. 6, (2018), e2545. DOI: <https://doi.org/10.1002/etep.2545>
 29. Mishra, A., Farzinfar, M., Bahadornajad, M. and Nair, N.C., "Evaluating the impact of different pv control strategies on distribution network operation", In 2014 Australasian Universities Power Engineering Conference (AUPEC), (2014), 1-6. DOI: 10.1109/AUPEC.2014.6966591
 30. Farzinfar, M., Shafiee, M. and Kia, A., "Determination of optimal allocation and penetration level of distributed energy resources considering short circuit currents", *International Journal of Engineering, Transactions C: Aspects*, Vol. 33, No. 3, (2020), 427-438. DOI: 10.5829/IJE.2020.33.03C.07
 31. Aolaritei, L., Bolognani, S. and Dörfler, F., "Hierarchical and distributed monitoring of voltage stability in distribution networks", *IEEE Transactions on Power Systems*, Vol. 33, No. 6, (2018), 6705-6714. DOI: 10.1109/TPWRS.2018.2850448
 32. Jasmon, G.B. and Lee, L.H.C.C., "New contingency ranking technique incorporating a voltage stability criterion", *IEE Proceedings C - Generation, Transmission and Distribution*, Vol. 140, No. 2, (1993), 87-90. DOI: 10.1049/ip-c.1993.0012
 33. Gubina, F. and Strmcnik, B., "A simple approach to voltage stability assessment in radial networks", *IEEE Transactions on Power Systems*, Vol. 12, No. 3, (1997), 1121-1128. DOI: 10.1109/59.630451
 34. Tolba, M.A., Diab, A.A.Z., Tulsy, V.N. and Abdelaziz, A.Y., "Vlci approach for optimal capacitors allocation in distribution networks based on hybrid PSO/GSA optimization algorithm", *Neural Computing and Applications*, Vol. 31, No. 8, (2019), 3833-3850. DOI: <https://doi.org/10.1007/s00521-017-3327-7>
 35. de Oliveira, L.W., Carneiro Jr, S., De Oliveira, E.J., Pereira, J., Silva Jr, I.C. and Costa, J.S., "Optimal reconfiguration and capacitor allocation in radial distribution systems for energy losses minimization", *International Journal of Electrical Power & Energy Systems*, Vol. 32, No. 8, (2010), 840-848. DOI: <https://doi.org/10.1016/j.ijepes.2010.01.030>
 36. Haghifam, M.-R. and Malik, O., "Genetic algorithm-based approach for fixed and switchable capacitors placement in distribution systems with uncertainty and time varying loads", *IET Generation, Transmission & Distribution*, Vol. 1, No. 2, (2007), 244-252. DOI: 10.1049/iet-gtd:20045267
 37. Ali, E.S., Abd Elazim, S.M. and Abdelaziz, A.Y., "Improved harmony algorithm for optimal locations and sizing of capacitors in radial distribution systems", *International Journal of Electrical Power & Energy Systems*, Vol. 79, (2016), 275-284. DOI: <https://doi.org/10.1016/j.ijepes.2016.01.015>
 38. de Araujo, L.R., Penido, D.R.R., Carneiro, S. and Pereira, J.L.R., "Optimal unbalanced capacitor placement in distribution systems for voltage control and energy losses minimization", *Electric Power Systems Research*, Vol. 154, (2018), 110-121. DOI: <https://doi.org/10.1016/j.epsr.2017.08.012>
 39. Nazarpour, D. and Sattarpour, T., "Assessing the impact of size and site of dgs and sms in active distribution networks for energy losses cost", *International Journal of Engineering, Transactions A: Basics*, Vol. 28, No. 7, (2015), 1002-1010. DOI: 10.5829/idosi.ije.2015.28.07a.06
 40. Kennedy, J. and Eberhart, R., "Particle swarm optimization", In Proceedings of ICNN'95 - International Conference on Neural Networks. Vol. 4, (1995), 1942-1948. DOI: 10.1109/ICNN.1995.488968
 41. Coello, C.A.C., Lamont, G.B. and Van Veldhuizen, D.A., "Evolutionary algorithms for solving multi-objective problems, Springer, Vol. 5, (2007). Retrieved from <https://link.springer.com/content/pdf/10.1007/978-0-387-36797-2.pdf>
 42. Coello, C.A.C., Pulido, G.T. and Lechuga, M.S., "Handling multiple objectives with particle swarm optimization", *IEEE Transactions on Evolutionary Computation*, Vol. 8, No. 3, (2004), 256-279. DOI: 10.1109/TEVC.2004.826067
 43. Moravej, Z., Jazaeri, M. and Gholamzadeh, M., "Optimal coordination of distance and over-current relays in series compensated systems based on MAPSO", *Energy Conversion and Management*, Vol. 56, (2012), 140-151. DOI: <https://doi.org/10.1016/j.enconman.2011.11.024>
 44. El-Hawary M E, M.G.A.N., "Stochastic optimal load flow using newton raphson iterative technique", *Electric Machines Power Systems*, Vol. 15, (1988), 371-380. DOI: <https://doi.org/10.1080/07313568808909347>
 45. Carlisle, A. and Dozier, G., "An off-the-shelf PSO" In Proceedings of the Workshop on Particle Swarm Optimization, Indianapolis, USA, (2001), 1-6. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.589.485&rep=rep1&type=pdf>

Persian Abstract

چکیده

نصب بانک‌های خازنی و رگولاتورهای ولتاژ در شبکه‌های توزیع برق از جمله راهکارهای موثر در کنترل توان راکتیو به منظور بهبود پروفیل ولتاژ فیدرها و کاهش تلفات شبکه به حساب می‌آید. با این حال، بهره‌برداری از شبکه‌های توزیع در حضور رگولاتورهای ولتاژ ممکن است منجر به عدول پارامترهای پایداری ولتاژ از مقادیر مجاز و استاندارد گردد. به منظور رفع این مشکل، در این مقاله یک مدل جدید بر مبنای یک مسئله بهینه‌سازی چندهدفه پیشنهاد شده است که قادر به مکان‌یابی همزمان بهینه بانک‌های خازنی و رگولاتورهای ولتاژ با هدف بهبود پروفیل ولتاژ، کاهش تلفات و همچنین کاهش هزینه‌ها می‌باشد. در مدل پیشنهادی، از یک شاخص پایداری ولتاژ به منظور جلوگیری از ایجاد ناپایداری ولتاژ در شبکه توزیع هنگام جایابی ادوات کنترلی استفاده شده است. همچنین، برای حل مدل پیشنهادی یک الگوریتم PSO اصلاح شده، مبتنی بر وزن دهی دینامیکی ذرات و استفاده از عملگر جهش ارایه شده است. در ادامه به منظور انتخاب بهترین راه‌حل‌ها از مجموعه جواب‌های پرتو، الگوریتم استنتاج فازی بکار گرفته شده است. به منظور بررسی کارایی الگوریتم پیشنهادی، یک سیستم تست واقعی مورد استفاده قرار گرفته است. تصدیق کارایی الگوریتم MMOPSO پیشنهادی با انجام مقایسه با جواب‌های بهینه حاصل از الگوریتم MOPSO انجام شده است.
