

Pareto Local Search Function for Optimal Placement of DG and Capacitors Banks in Distribution Systems

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ABSTRACT:

DGs and capacitor banks are installed to optimize the performance of many distribution networks. Typically, the problem of optimizing the overall performance of the distribution network is examined with multi-objective purposes. Network optimization purposes are usually varied and sometimes contradictory. Therefore, the problem search space is very large due to the variety of purposes. This paper presents a modified Pareto local search function for optimal placement of DGs and capacitor banks. To limit the search space and find Pareto points, a new combination method including Pareto chart and a weight function has been used. The optimal operation of the distribution network is performed by three single objective functions related to the voltage stability index, voltage profile of buses and power loss. In this method, a modified per-unit system is presented to align single objective functions and their weighting coefficients. The network is studied with three different loads. So that, the network is examined in the final stage by increasing the load and reaching bus voltage stability margins. The particle swarm optimization method is applied to solving placement problems. In addition, locating and sizing DG and capacitor banks, tap setting of on load tap changer transformer is adjusted by the proposed method. To show the effectiveness of the proposed method, simulations are applied to 69 bus radial system. The results indicated the favorable advantage of the proposed method to improve the overall performance of the distribution network.

KEYWORDS: Capacitors Placement, DG Placement, Loss Reduction, Multi-objective Function, On Load Tap Changer Transformer, Particle Swarm Optimization, Voltage Stability Index.

1. INTRODUCTION

Today, to enhance the overall power operation of the distribution systems, Capacitor Banks (CBs) and Distribution Generators (DGs) play an important role [1]. CBs and DG can bring many economical and technical benefits [2].

1.1. Literature Review of CB and DG Placement

The first capacitor placement was performed to reduce electricity losses about seventy years ago [3]. In addition, DGs have been widely used in the last few decades. DGs and CBs, by injecting active and reactive power, have made many effective changes in the network [4]. However, proper placement and setting of the DGs and CBs to optimize the overall performance of the network require the analysis of a multi-objective

problem. On the other hand, powerful methods are needed for analysis, which could achieve various and sometimes conflicting objectives in distribution networks. Performance objectives can be economic and technical, such as reducing fuel costs, improving voltage profile, reducing loss, and so on.

In the past decades, many methods for DG and CBs placement have been introduced for different purposes in power systems and distribution networks. For example in some papers, the simultaneous reconfiguration with optimal allocation of capacitor and DGs has been performed [5-7]. Objectives in [5] are to minimize power loss and operating costs and to improve The Voltage Stability Index (VSI). To achieve those, several intelligent algorithms in different scenarios are compared in [5]. However, in that article

there are no solutions suggested to regulate the voltage of the buses to be within the allowable range. In [6], DGs and capacitors are placed to reduce power loss, and reduce operation costs of DG units and capacitors. However, the voltage indices have not been studied. In [7], a multi-Objective purpose includes active power loss, annual operation costs and pollutant gas emissions are investigated. Nevertheless, their Multi-Objective Functions (MOF) are in the same direction and do not conflict with objective functions. M. Suresh and et.al in [8] have used a hybrid technique to optimize the position and size of DG units to reduce losses and to improve the voltage profiles in the power distribution network. But they only studied voltage profiles and other network purposes were not achieved. It should be noted that improving the network status with a single-purpose function may lead to undesirable levels for the other important factors in network quality. In addition, [7, 8] only used DG to improve distribution network conditions, while they could also use capacitors to improve the voltage profile and reduce losses. For DGs and CBs placement purposes in [9-11], the combined heuristics method with Monte-Carlo simulation method [9], neural network method [10] and the water cycle algorithm [11] have been used, respectively for the purposes of reducing investment cost and increasing network reliability [9], reduce the annual energy loss [10] and minimize power losses, voltage deviation, and electrical energy cost. In articles [8-11], VSI is not considered. Nonetheless, VSI is always one of the main purposes of distribution network operators. Placement DGs and CBs in a probabilistic model are proposed in [12]. Objective functions in that article are reducing power losses, current imbalances, and improving network reliability. They have simulated uncertainty models of DGs and load by Monte Carlo simulation. Although the Monte Carlo method is accurate for simulation, it requires a lot of analysis and is very time consuming. In [13], large-scale DG placement is proposed to reduce the load of heavily loaded lines and to improve the reliability of the power grid in a probabilistic model. However, in the mentioned article, objective functions of voltage and losses have not been studied. DG placement for reducing grid's power losses are produced by particle swarm optimization algorithm in [14]. However, the objective function is a Single Objective Function (SOF) and the voltage objective functions are not considered. In [15], DG placement based reactive power control is recommended to reduce capital cost, improve the voltage profile and voltage stability. Reactive power is controlled by a doubly-fed induction generator in [15]. Nevertheless, the objective function of line losses has not been investigated.

1.2. Literature Review of Multi-objective Proposes for Capacitor and DG Placement

In [16], a comparison between three mixed integer programming analytical methods and genetic algorithm method is used to the placement of DGs. In [17], a mixed-integer linear programming approach is suggested to improve a Multi-Objective Problem (MOP) including minimizing active power losses and reliability indices. In addition, the ϵ -constraint technique is used for finding Pareto points. As reviewed in [16, 17], the capabilities of the mixed integer programming methods are well considered in contrast to the main intelligent search methods such as genetic algorithms. But no comparison has been made between and modified smart methods such as local search algorithms. An exchange market algorithm has been accomplished for placement DG in [18]. The MOFs include reducing line loss, improving voltage profile, and reliability. However, in [18], two search operators search the entire search space to optimize the objective function and find the global point. In [19], the effect of DG placement on reducing network losses and bus voltages has been investigated using several intelligent methods. It should be noted that, in all methods, no attempt has been made to narrow down the search space. A non-dominated genetic algorithm has been presented for placement DG in [20]. Their MOFs include line loss, voltage deviation, and VSI margin. Paper [20] searches an optimal global solution for multi-objective optimization.

It is necessary to mention, most evolutionary algorithms and analytical methods are used for MOPs to find a large range of Pareto points. A huge amount of analysis is carried out to find these responses. In [21], a hybrid algorithm of Pareto-fuzzy dominance with a shuffled frog leaping algorithm is presented that defines Pareto frontiers for analyzing a distribution network. In [21], the search space using hybrid methods is significantly reduced. Despite all the modifications, it is still necessary to find all Pareto answers. Nonetheless, in most cases not all responses need to be found and a limited number of responses are sufficient and one or more Pareto points can be selected.

1.3. Literature Review of Local Search Method

Nowadays, researchers are using new and sophisticated methods to analyze various optimization problems in power systems and distribution networks. Most evolutionary algorithms and analytical methods for analyzing MOP problems find a wide range of Pareto points. Nevertheless, simpler methods with less complexity but more efficiency can be used to analyze optimization problems. A huge amount of analysis is carried out to find these responses. Nonetheless, Pareto local search (PLS) algorithms have been proposed since 2004 for solving MOPs [22]. In recent years, stochastic local search algorithms have been widely

used to solve decision-making and optimization problems in a wide range of applied sciences. A variety of articles with different local search methods for optimization purposes are listed in [23]. The local search methods have been used extensively for siting and sizing DGs and CBs in distribution networks problems. For example, in [24], a momentum incorporated gradient local search and a rotational movement method using shark odor capability has been used to locate CBs to reduce cost of the energy loss in a distribution network. But in the [24] method, due to creating many random primary variables to simulate the rotational movements of sharks and gradient calculations, there is a lot of complexity. However, the local answers obtained are likely to be far from the global answers.

A hybrid local search genetic algorithm has been used to place DGs/CBs for minimizing total real power losses and the total voltage deviation in the radial systems in [25]. In [25], with changes in genetic algorithm techniques, an attempt has been made to reduce the search space for local and global answers, but the search space has not been significantly limited. In general, the genetic algorithm has a slow convergence. Article [26] has used the local search PSO method for a DG placement problem in the distribution network to reduce network total power loss. They have compared PSO local search and heuristic search techniques. In [27] the Chaotic Lightning Search algorithm, a local search method, is used to locate DG and DSTATCOM to minimize active power losses. Despite all the advantages of [26, 27], they have explored placement issues with SOFs. It should also be noted that there are very few articles that have also set on load tap changer transformer (OLTC) in addition to DG placement. In [28], by using a photovoltaic system (a type of DG), the OLTC is also adjusted and the purpose is to regulate the network voltage, but the general purpose and its subject are different from the topics of this article. Their objective is to minimize the number of tap operations.

1.4. The Procedure and Innovations

Most researchers, in the first part of the analysis, look for all Pareto answers to analyze placement problems. However, in most placement problems, a limited number of answers are sufficient for the problem. Therefore, in the PLS method, one or more Pareto points are selected by narrowing the search space.

In this paper, for optimal placement DG and CB and setting the tap of OLTC, a Pareto local search function (PLSF) is introduced, which includes three different SOFs. These functions are bus voltage SI, load voltage profiles, and power loss. The Prato chart is used to determine the coefficients of the SOF functions. In this

way, the search space to find Pareto points becomes narrower and a local search has been performed. Therefore unlike many papers, there is no need to find all Pareto points using conventional methods. This reduction in the number of Pareto points is one of the important advantages of the method presented in this paper. In addition, DGs and CBs are placed and adjusted and the taps of OLTC are set. To show the effectiveness of the proposed method, it is applied to 69 bus radial system and simulation results showing the improvement of all three objective functions are described.

The main contributions of the proposed method are as follows:

- Per-unit values in all objective functions are determined so that a proper comparison can be made between inconsistent SOFs.
- Using the Pareto chart, the weighting coefficients of the MOF are determined to narrow the search space, and a limited number of Pareto answers are selected.
- DG and CB placement and setting OLTC are performed simultaneously to optimize three SOFs.

The overall power operation with different loads up to the bus VSI margins is investigated. Prioritization of objective functions and determining the degree of importance of each function in different electrical loads have been accomplished.

1.5. Comparison between Reviewed Literature and Current Study

In the literature review sections, a number of articles were reviewed for the placement of DGs and CBs in distribution networks. Objectives of the reviewed articles include: reduction of network line losses, reduction of bus voltage deviation, increase of bus voltage SI, increase of network reliability, reduction of network operation costs, and reduction of pollutant emissions. In some articles, network reconfiguration has been done to further improve the objectives of the study [5-7]. In some articles, single-objective proposes have been studied. A number of articles have also studied the multi-objective functions and try to improve the condition of the network using a variety of objectives. Some of these articles have used sophisticated analytical methods such as Mixed Integer and some other smart methods with very large search space such as algorithm genetics and PS methods to analyze the optimization problem. A limited number of articles have used multi-objective functions with limited methods and local search to analyze the problem [14], [26], [27]. There are very few articles

where OLTC and DG settings are performed simultaneously. Paper [18] is about setting up OLTC and DGs in the distribution network, but its purposes are different from the one covered in this article. In this paper, to analyze the problem of multi-objective optimization, the local search method using the weight function by Pareto diagram is used, which has not been performed in any other article. Table 1 is prepared to review published articles in this field, which use exploratory optimization methods. In this table, a conceptual and qualitative comparison is made between the literature review articles and this article, which includes: analysis method, equipment used to optimize network performance, objective functions used, experimental systems and the main innovation of each article.

1.6. Paper Organization

The next sections of this article are as follows. Section 2 presents the multi-objective problem formulation for a set of conflicting objective functions and the proposed local search method is introduced. Section 3 shows how the PSO algorithm is used to place DGs and CBs and adjust the transformer. In addition, Section 3 shows how the proposed algorithm limits the search space using the weighted sum method and Pareto chart. Section 4 describes two models for demonstrating the effect of the active and the reactive compensators and OLTC in the distribution network. Section 5, includes the comparison of the results of the proposed methods with other papers. Finally, Section 6 is the conclusion of this paper.

2. MULTIOBJECTIVE PROBLEM FORMULATION

2.1. Multi-objective Function Definition

The optimization of a MOP is performed simultaneously with a set of conflicting objective functions. Optimization may include maximizing some functions and minimizing some other functions. The objective function is formulated as [29],

$$\begin{aligned} & \text{Optimized } F(x) = \{f_1(x), \dots, f_n(x)\} \\ & \text{Subject to } x \in S \end{aligned} \tag{1}$$

Where, S is the feasible set of decision vectors $F: S \rightarrow R^n$ consists of n real value objective functions. For the PLSF, given a set of n independent variable and a set of functions, each variable consists of a set of operations $x = \{x_1, \dots, x_n\}$, where x_{ik} represents the operation of variable i on function k . The processing of variable $x_i = x_{\text{new}}$ on functions j is denoted by P_{ij} ($i = 1, \dots, n; j = 1, \dots, m$). A feasible solution scheduling sequence is denoted by $x = \{x_1, \dots, x_n\}$, Let $C(x_i, m)$ denotes the completion time of variable x_i on function m . a feasible solution $x^1 \in S$ is said to dominate another solution $x^2 \in S$, if

$$\begin{cases} f_i(x^1) \leq f_i(x^2) & \text{for all indices } i \in \{1, 2, \dots, k\} \\ f_j(x^1) < f_j(x^2) & \text{for at least index } j \in \{1, 2, \dots, k\}. \end{cases} \tag{2}$$

Table 1. Comparison between reviewed literature and current study.

Ref	Method	Placement			Adjusting	Functions				Test system	The main innovation
		DG	CB	OLTC		Voltage	SI	Loss	Other		
[5]	Several intelligent algorithms	√	-	-	-	√	√	√	69-bus 33-bus	Compare the results of 5 intelligent methods for placement problems.	
[6]	Dedicated Genetic Algorithm	√	√	-	-	-	√	√	69-bus	Network rearrangement using DGs and CBs, Optimization various objective function and cost reduction	
[7]	A fuzzy set theory	√	-	-	-	-	√	√	33-bus	Distribution network reconfiguration simultaneously with the DG location and sizing	
[8]	Mixed Grasshopper Optimization Algorithm and Cuckoo Search technique	√	-	-	√	-	√	-	69-bus 33-bus	Introducing a hybrid method for locating DGs	
[9]	A mixed integer nonlinear optimization and a Hybrid heuristics-Monte Carlo simulation method	√	√	-	-	-	-	√	90-bus	Discussion of the impact of the method to estimate the reliability indexes on the optimization process	
[10]	Neural network method	√	√	-	√	-	√	√	2 nodes 37 nodes 123 nodes	Training the neural network with 6 years of wind data and its practical use for seasonal forecasting of wind turbine power	
[11]	Water cycle algorithm	√	√	-	√	√	√	√	69-bus 33-bus East Delta	Locating DGs and CBs and maximizing technical, economic, and environmental benefits in a real part of Egyptian system	

									network	
[12]	PSO algorithm and preference order ranking-based multi-objective planning model, Monte Carlo simulation	√	√	-	-	-	√	√	34-bus 123-bus	Introducing different probabilistic models for grid components with uncertainty and solving DGs and CBs placement problem
[13]	A probabilistic method	√	-	-	-	-	-	√	5-bus 30-bus	Investigation of probabilistic load models and DG placement to reduce the load of the heavily loaded transmission lines
[14]	Local-PSO algorithm	√	-	-	-	-	-	-	30-bus 33-bus	Using a local search method to locate DG
[15]	Introducing a new squirrel cage induction generator	√	-	-	√	√	-	√	30-bus	Introducing a new combination of squirrel cage induction generator and doubly-fed induction generator based DG configuration
[18]	Exchange market algorithm	√	-	-	√	-	√	√	69-bus 33-bus	Introducing a technique to extract the optimal global point in the DGs placement problem
[19]	Several intelligent algorithms	√	-	-	√	-	√	-	118-bus 85-bus	Compare the results of 4 intelligent methods for placement problems.
[20]	Non-dominated genetic algorithm	√	-	-	√	√	√	-	33-bus	Introducing the shortening strategy for GA algorithm and its application in placement problems
[26]	PSO algorithm	√	-	-	-	-	√	√	33-bus	Using modified PSO algorithm to find local and global answers
[27]	Chaotic Lightning Search algorithm	√	-	-	-	-	√	√	69-bus 33-bus	Introducing a new local search method
[28]	-	√	-	√	√	-	-	√	-	Minimizing the number of tap operations
This study	Pareto local search	√	√	√	√	√	√	-	69-bus	Using the Pareto chart-weighting coefficients of the MOF to narrow the search space, and a limited number of Pareto answers, Using DGs, CBs and OLTC simultaneously

A solution $x^* \in S$ is Pareto optimal. The set of optimal Pareto results is often called the Pareto front. If Pareto points are limited, the Pareto front is bounded by a nadir objective vector and an ideal objective vector. An objective vector $z^{nad} = (z_1^{nad}, \dots, z_m^{nad})^T$ constructed with worst value of objective functions in the complete Pareto-optimal set P^* is called a nadir objective vector. The ideal point $(z_1^*, z_2^*, \dots, z_m^*)^T$ can be found by optimizing each objective individually over the feasible set S .

The MOF, which is formulated through SOFs, is described as follows,

2.1.1 Bus Voltage Stability Index

M. Chakravorty and et.al in presented an index for SI in the distribution network. SI of bus (i) is given by Eq. (3) [30].

$$SI_i = |V_s|^4 - 4\{P_r x_{ij} - Q_r r_{ij}\}^2 - 4\{P_r r_{ij} - Q_r x_{ij}\}|V_s|^2 > 0 \quad (3)$$

Where, SI_i , V_s , P_r , Q_r , r_{ij} and x_{ij} are the bus VSI, sending bus voltage, total active power loads at receiving end, total reactive power loads at receiving end, the resistance of the line i - j and the reactance of the line i - j , respectively. For stable operation, the value of each bus

SI should be greater than zero. The objective function is given by [30],

$$f_1 = \text{Min} (SI_i) \quad (4)$$

The f_i is the SI value of the bus with the worst SI (WSI) in the distribution network.

2.1.2 Voltage Improvement Function

Voltage constraint of load buses is shown as [31]:

$$V_i^{min} \leq V_i \leq V_i^{max} \quad i = 1, 2, \dots, N_b \quad (5)$$

Where, N_b stands for the total number of buses. V_i , V_i^{min} and V_i^{max} are i 'th bus voltage magnitude, lower and upper boundaries of i 'th bus, respectively. The objective function is formulated as:

$$f_2 = \sum_{i=1}^{N_b} (V_i - V_n)^2 \quad (6)$$

Where, V_n is the nominal voltage value, which is considered one per-unit for all buses in this paper.

Loss Reduction Function

In the power distribution networks, loss is caused by power transmission through currents on the line resistance. The power flow equations can be formulated as [31]:

$$P_i = V_i \sum_{j=1}^n Y_{ij} V_j \cos(\delta_i - \delta_j - \gamma_{ij}) \quad (7)$$

$$Q_i = V_i \sum_{j=1}^n Y_{ij} V_j \sin(\delta_i - \delta_j - \gamma_{ij}) \quad (8)$$

Where, P_i and Q_i are active and reactive power of the i 'th bus, respectively, V_i is the i 'th bus voltage, and Y_{ij} is the admittance between bus i and j link. δ is the bus voltage angle, and γ is the angle of the system admittance matrix. The objective function can be defined as:

$$f_3 = P_{loss} = \sum_{i=1}^n P_{Gi} - \sum_{i=1}^n P_{Di} \quad (9)$$

This objective function (f_3) shows the total line loss in the entire system (P_{loss}). P_{Gi} is the injected active power from power system to distribution network or i 'th bus generated power by i 'th DG. P_{Di} represents the total connected load.

2.2. Pareto Local Search Method

Generally, in analyzing MOPs, some objective functions are more important than others. In a MOP, sometimes, a change to improve a problem can cause significant changes in the overall state of all problems. This change may in some cases have a positive effect and in some others a negative effect [32].

$$\text{Optimized } F(x) = \begin{cases} w_1 f_1(x), \dots, w_n f_n(x) \\ w_i = \frac{N_i}{\sum_{j=1}^n N_j} \\ \sum_{i=1}^n w_i = 1 \end{cases} \quad (10)$$

Subject to $x \in S$

Where, F , f_1, \dots, f_n and w_1, \dots, w_n are PLSF, SOFs and weight coefficients of f_1, \dots, f_n . N_i is the number of each worst-case objective function for any of the functions determined by the Pareto chart (PC).

3. RESEARCH METHOD

3.1. PSO Algorithm to Determine the Base Values of Functions

In this paper, the PSO attempts to locate DG, CBs and set the tap of OLTC. In addition, PSO is used to determine the values of DG active powers and CB steps. By proper selection of all variables using PSO, the PLSF can be optimized. The PLSF is combined by all SOFs. However, the differences between the optimized numerical values of SOFs are considerable [31]. Therefore, to unify the difference results between SOFs, a modified per-unit system is introduced in this paper. At the separate solutions, the problem is solved by SOFs, so that the best values of each function are found. These best values are used as the base values of SOFs. During each execution of load flow analyses, by

SOF, real values of SOFs are found. Per-unit values of SOFs are achieved using mentioned base values. Therefore, these per-unit values of SOFs are currently comparable. Thus, optimizing of PLSF, results in optimizing of SOFs individually. The per-unit transfer function and the SOF defined in this paper are described as Eq. (11).

$$f_{i-pu} = \frac{f_{i-real}}{f_{i-base}} \quad i = 1, \dots, n \quad (11)$$

f_{i-pu} , f_{i-real} and f_{i-base} are per-unit, real and base values of SOFs. To obtain f_{i-pu} by the above method, a new method is defined in f_{i-base} in this article. Therefore, regardless of the value of each of the SOFs, the values of each SOF are normalized and comparable.

3.2. Weighted Sum Method and Limiting Search Space by Pareto Chart

Most multi-objective methods find a large range of Pareto points. However, in most cases it is sufficient to find a limited number of Pareto points. By giving more weight to the function with more critical conditions, the solution is being searched among fewer values. Then one of the Pareto points is obtained which further optimizes the desired function.

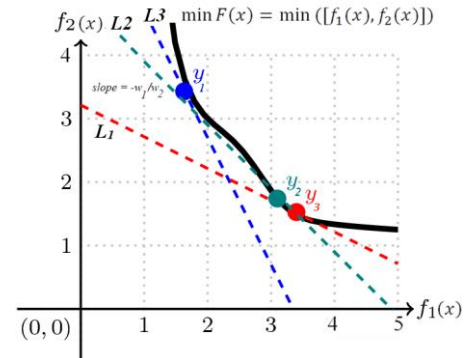


Fig. 1. Method of limiting the search space for Pareto points.

According to Fig. 1, a limited number of Pareto points are found because of tangent points of line with the MOF. This is done by adjusting the slope of each line, which is set by the weight of functions. Weighting method misses some Pareto points in some cases even with the change of slope. However, in most cases similar to ϵ -constraint method [17, 33], if all constraints are considered, the local solutions are acceptable.

In the proposed method, the search space for Pareto points is limited and a local search is performed. By precisely assigning the weight of the SOFs to the PC, one of the lines finds the answers.

$$F(x) = \begin{cases} -\max(w_1 f_1(x)) + \min(w_2 f_2(x)) + \min(w_3 f_3(x)) \\ w_i = \frac{N_i}{\sum_{j=1}^3 N_j} \\ \sum_{i=1}^3 w_i = 1 \end{cases} \quad (12)$$

Where, F , f_1 , f_2 , f_3 and w_1 , w_2 , w_3 are PLSF, The SI value of the bus with the WSI, the voltage deviation function, the total line loss in the entire system, and weight coefficients of f_1 , f_2 , f_3 . N_i is the number of each worst-case objective function for any of the functions determined by the PC.

4. COMPENSATOR AND OLTC EFFECTS ON TWO-BUS NETWORK

Two models are presented for illustrating the effect of the active and the reactive compensators placement and OLTC setting in the distribution network. Fig. 2 assumes a simple two-bus network without any reactive compensators and OLTC.

Fig. 3 shows a simple two-bus network with an OLTC in bus 1 and active and reactive compensators in bus 2.

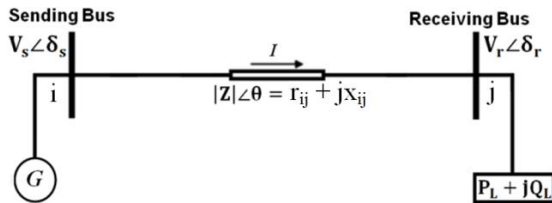


Fig. 2. A simple two-bus network.

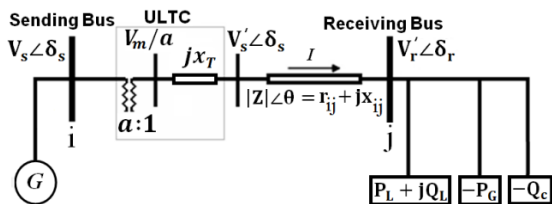


Fig. 3. The simple two-bus network with compensators and OLTC.

Phasor diagram of the two-bus network with compensators and OLTC is shown in Fig. 4. In general, DGs active power and CBs reactive power inject in distribution networks, so they are shown with a negative sign in Fig. 3.

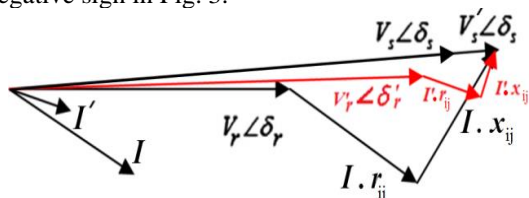


Fig. 4. Phasor diagram of the two-bus network with compensators and OLTC.

Mathematical formulations for the two-bus network can be written as:

$$I = \frac{V_s \angle \delta_s - V_r \angle \delta_r}{r_{ij} + x_{ij}} \quad (13)$$

$$S = P_L + jQ_L = I^2 (r_{ij} + x_{ij}) \quad (14)$$

From Eqs (12 and 13) resulted in Eq. (14)

$$|V_r \angle \delta_r - V_s \angle \delta_s|^2 = (P_L + jQ_L)(r_{ij} + x_{ij}) \quad (15)$$

The OLTC increases or decreases the magnitude of sending voltage profile. It is shown in Fig. 4. by V'_s . The compensators reduce the active and the reactive power loads as Eqs (16 and 17).

$$P'_L = P_L - P_G \quad (16)$$

$$Q'_L = Q_L - Q_C \quad (17)$$

The active and reactive line flows, are reduced, while V_s remains constant, therefore V_r increases as shown with Eq. (10) and Fig. 4. In distribution networks, Eq. (18) can be assumed as follows:

$$r_{ij} \gg x_{ij} \quad (18)$$

Therefore, Eq. (1) is approached to Eq. (19)

$$SI_i = |V_s|^4 - 4\{Q_r r_{ij}\}^2 - 4\{P_r r_{ij}\}|V_s|^2 \quad (19)$$

In addition, with increasing voltage by OLTC and reducing the active and reactive load by compensators, using Eq. (19) is changed to Eq. (20).

$$SI'_i = |V'_s|^4 - 4\{(Q_r - Q_c) r_{ij}\}^2 - 4\{(P_r - P_G) r_{ij}\}|V'_s|^2 \quad (20)$$

By comparing Eq. (20) and Eq. (1), it is shown that SI'_i is more than SI_i , therefore, VSI can be improved.

Eqs (21 and 22) show power loss.

$$P_{Loss} = I^2 r_{ij} \quad (21)$$

Eqs (13 and 20) give Eq. (22)

$$P_{Loss} = r_{ij} \frac{P_L + jQ_L}{(r_{ij} + jx_{ij})} \quad (22)$$

Eq. (22) shows that, with reducing active and reactive power by compensators, power loss is reduced.

5. RESULT AND DISCUSSION

The proposed solution methodology has been applied in 69 bus radial system. The network data and structure of this system are presented in [20].

In this paper, one DG and four CBs are located in the network. The DG size constraint is shown as [34]:

$$0 \leq \text{size of DG } (P_{DG}) \leq \sum P_{\text{load}} \quad (23)$$

Where, PDG is the power generation value of DG and Pload is the total load of buses.

Each CB is considered as four discrete sizes of 150 kVAr [34, 35]. The total reactive power injection of these CBs can be maximum (1600 kVAr). It is not allowed to exceed the total reactive power demand. The tap numbers of OLTC are 6 taps and minimum and maximum output voltage of OLTC are 0.95, 1.05 volts, respectively [31].

5.1. Comparing the Results of the Proposed Methods

The first section of the simulation has two steps. In this section, the network is on the nominal load without using any DG or CBs. Therefore, only an OLTC transformer controls the network. In the first step, load flow analysis is performed on the 69 bus radial system. Many researchers typically use standard IEEE 69-bus [8], [36], [37], [38] and 33-bus [5], [8], [38] systems to simulate similar studies. In this paper, a larger size system (69-bus) is used to demonstrate the efficiency of the proposed algorithm. In this simulation, the OLTC is set to one to see the effect of the transformer not adjusting the OLTC. Power loads in the distribution network are supplied only by bus one where it connects to the power system. The numerical results of this section are shown in the second column of Table 2. The (WSI) is an acceptable value. The worst voltage deviation (WVD) of buses is out of the constraints range as shown by Eq. (2). Total Power Loss (TPL) obtains about 6.25% of total demand. In the second step, because of the optimization of PLSF, the OLTC sets on the maximum tap and load flow analysis executes again. The WSI slightly improved, but as shown in Fig. 5, some voltages of buses are not in the acceptable range. However, the TPL is also slightly improved.

In the second section by increasing the load to about 275% of the nominal load, the network approaches on the edge of VSI condition in spite of setting the OLTC tap. In other words, the network has been studied in the worst case scenario, which is rarely considered in other articles. The results of this section are shown in the 4th column of Table 2. WSI bus is on edge of VSI condition and WVD is unacceptable value. WVD is the maximum value of Voltage Deviation of the nominal voltage (Upward, UVD or downward, DVD) as is shown in Fig. 5). TPL is about half of the total demand. Fig. 5 shows the bus voltage profiles with OLTC tap setting without DG and CB. As can be seen, some buses have voltage below 0.8 p.u. This is unrealistic and unacceptable for distribution system operation.

Therefore, to improve overall performance of the network, the active and reactive compensators are required. Accordingly, in the next section, compensators are added.

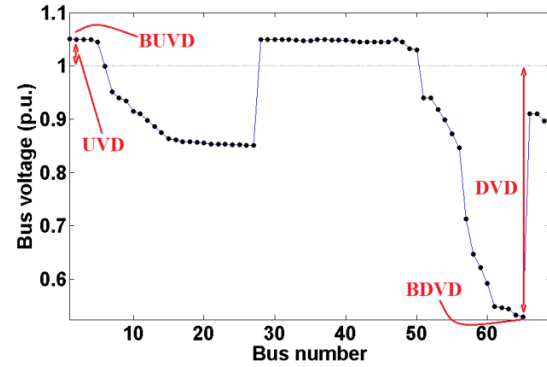


Fig. 5. Bus voltage profiles with OLTC, without DG and CB.

In the third section, load flow analysis runs by adding a DG, four CBs and setting OLTC tap in the network. In the first, second and third steps, the PSO algorithm attempts to optimize three SOFs individually, by proper locating and sizing of DG and CBs and setting of OLTC. Main fitness functions of each step are f_1 (Eq. 2), f_2 (Eq. 3) and f_3 (Eq. 6).

Optimization includes maximizing the values of f_1 and minimizing the values of f_2 and f_3 . The results are shown in 5th, 6th and 7th columns of Table 2. Main fitness functions of each step are highlighted with gray color. By comparing columns 5th with 6th and 7th, it is shown that in the 5th column, SI (f_1) is higher than other columns. In the 6th column, the UVD (which is affected by f_2) is lower than other columns. In the 7th column, TPL (which is affected by f_3) is lower than other columns. However, according to the mentioned results, using SOFs only improves one factor on network performance. For improving the overall state of the network, a PLSF is needed.

The base values of functions are determined by results of the first, second and third steps.

$$\begin{cases} f_{1-\text{base}} = 0.9240 \\ f_{2-\text{base}} = 0.0574 \\ f_{3-\text{base}} = 195 \end{cases} \quad (24)$$

The population is initially generated over the search space, randomly. Random values are selected for the transformer tap and the location and size of DGs and CBs. As a result, the per-unit values in all objective functions are determined using these random values. In the proposed method, the number of worst-case objective functions is counted at each step and put on the PC, which has not been presented in the similar

papers. The weighting coefficients are determined by the PC and are used to prioritize the objective functions.

Fig. 6 shows the number of undesirable objective functions. Each function captures the weighting

coefficient proportional to the number of undesirable functions

Table 2. Multi-objective and single objective optimization results.

Load	$\lambda = 1$		$\lambda = 2.75$				
	Section 1		Section 2	Section 3			
	Step 1	Step 2	Step 1	Step 1	Step 2	Step 3	Step 4
V_{trans} (PU)	1.00	1.05	1.05	1.05	1.04	1.05	1.04
DG_{Place}	-	-	-	Bus 61	Bus 63	Bus 61	Bus 62
CB_1_{Place}	-	-	-	Bus 19	Bus 18	Bus 60	Bus 60
CB_2_{Place}	-	-	-	Bus 23	Bus 22	Bus 61	Bus 61
CB_3_{Place}	-	-	-	Bus 27	Bus 25	Bus 63	Bus 63
CB_4_{Place}	-	-	-	Bus 64	Bus 65	Bus 64	Bus 65
WSI	Bus 65	Bus 65	Bus 65	Bus 22	Bus 23	Bus 27	Bus 27
$BDVD$	Bus 65	Bus 65	Bus 65	Bus 65	Bus 21	Bus 27	Bus 27
UVD (PU)	-	0.0499	0.0498	0.0499	0.0399	0.0499	0.0499
DVD (PU)	0.1223	0.0652	0.5344	0.0200	0.0309	0.0526	0.0526
TPL (%)	6.25	5.60	33.82	4.20	4.78	1.84	1.85
f_1	0.5919	0.7621	0.0387	0.9240	0.8822	0.8060	0.9242
f_2	0.1770	0.0994	2.6261	0.0727	0.0574	0.1057	0.1049
f_3	253	225	5330	457	489	195	197
F	-	-	-	0.9240	0.0574	195	0.9020 pu

WSI : The Worst SI bus
 UVD : Value of Upward Voltage Deviation
 $BUVD$: The Bus with Upward Voltage Deviation on Bus 2
 DVD : Value of Downward Voltage Deviation
 $BDVD$: The Bus with Downward Voltage Deviation
 TPL : The Total Power Loss percentage
 WVD : The Worst Voltage Deviation (The maximum value of UVD or DVD)

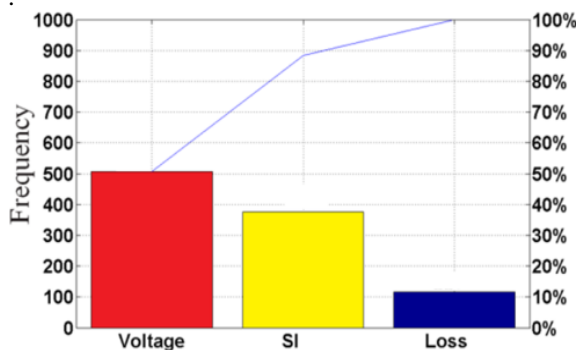


Fig. 6. The Pareto chart with the proposed method.

In the fourth step, load flow analysis was running again similar to the third step, using the achieved coefficients. However, in this step the PSO algorithm

attempts to optimize the PLSF instead of SOF. For aligning the results of three different SOFs, the proposed per-unit system and weight coefficients are used. The PC is shown that if loss is controlled in this network, the SI index and voltage profile will be in proper condition, too. Placement results are presented in the 8th column of Table 2, which, f_1 , f_2 and f_3 are normalized values of three SOFs. By comparing the gray marked values with similar values of previous columns, it can be shown that using PLSF improves each of three functions to acceptable values. According to these results, PLSF can improve the overall network status. Magnitude of the bus voltage using the proposed method is shown in Fig. 7.

5.2. Comparison PLS Method Result with Other Papers

There has been a lot of research on CB and DG placement in various papers. For example, in articles [37, 38] a CB has been installed on the 69 bus radial system and improving voltage profile and reducing power loss have been investigated. To have a better comparison between our results and results from other reference papers, following adjustments have been applied. Table 3 shows the adjusted results for CB placement, improved worst voltage deviation, and reduced grid loss. In the present study, the load is approximately 275% of the nominal load (i.e. $\lambda = 2.75$, λ is defined as the load coefficient).

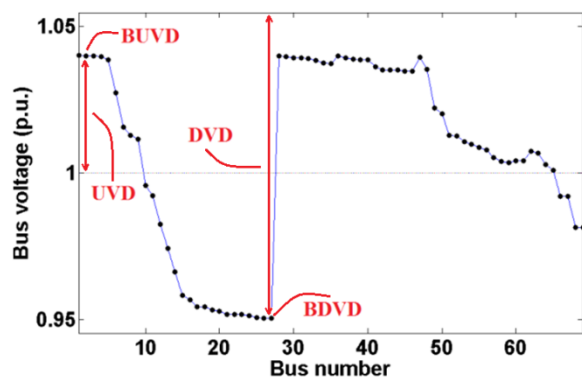


Fig. 7. Magnitude of the bus voltage using the proposed method.

Table 3. Comparison between PLS and other methods in CB placement and network performance metrics.

	[37]	[38]	PLS Method
	$\lambda = 1$	$\lambda = 1.6$	$\lambda = 2.75$
$P_{DG} (kW)$	-	2293.6	3800
$Q_{CB} (kVAr)$	1113	1982.5	1600
$P_{loss-Before\ placement} (kW)$	202.28	225	1630
$P_{loss-after\ placement} (kW)$	151.53	112.7	162
$\Delta P_{loss} (kW)$	50.75	112.3	1468
$\Delta P_{Loss} / Q_{CB} (kW / kVAr)$	0.046	0.057	0.918
$V_{WVD-Before\ placement} (PU)$	0.9092	0.9092	0.7388
$V_{WVD-after\ placement} (PU)$	0.9309	0.9933	0.9505
$\Delta V_{WVD} (\%)$	2.39	8.41	21.17

6. CONCLUSION

In this paper, a new approach for locating of DG and CBs and the tap setting of OLTC has been presented. A new PLSF is proposed for placement DG and CBs. The optimization leads to increasing voltage SI, improving the bus voltage profiles and reducing the total power loss. For aligning three SOFs, a modify per-unit system has been proposed. The proposed weighting coefficients of three SOFs are determined by the PC. A new hybrid method includes a Pareto chart and a weight function is used to limit the search space for Pareto points. In other words, the overall network status

has been improved by multi-objective optimization based on PLSF. Simulation results using the PLSF applied to the 69 bus radial system have validated the effectiveness of the proposed approach.

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