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Optimal Capacitors Allocation and Sizing in Radial Distribution System for Power Losses Reduces

Erita Astrid[1]*, Muhammad Dani Solihin[2], Rosma Siregar[3], Bakti Dwi Waluyo[4]
[12] Prodi Teknik Elektro, Universitas Negeri Medan
[3] Prodi Pendidikan Teknologi Informatika dan Komputer, Universitas Negeri Medan
[4] Prodi Pendidikan Teknik Elektro, Universitas Negeri Medan
*)Corresponding author, email: eritaastrid@unimed.ac.id

Abstract

The use of capacitors in electrical systems is widely known for their function to improve power factor and voltage profile while minimizing power losses. It results from the reactive power correction provided by capacitors within the system. It is believed that proper placement and size of capacitors can enhance the electricity quality in power systems. Therefore, numerous methods have been developed regarding the allocation and sizing of capacitors. In this research, a meta-heuristic method, Particle Swarm Optimization (PSO) is applied to find the optimal allocation and sizing of capacitors in order to reduce losses. The method has also been improved by modifying the value of inertia weight to optimize the algorithm's performance in finding the solution. The method is tested on an IEEE 34 bus radial distribution system to observe its performance and effectiveness in identifying the solution. The power loss in the distribution system plays the most important role in the economic operation of the power system. It will be used as a fitness function for each particle in the algorithm. The obtained test results include the size of the capacitor and the optimal placement of the capacitor installation.

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I. INTRODUCTION

The distribution system plays a crucial role in the energy infrastructure as it directly impacts the supply of power to users. An efficient and optimal distribution system must exhibit superior performance to ensure the proper and reliable distribution of power, as power quality has a massive impact in maintaining the stability of the electric power system. Power losses significantly contribute to the decline in power quality inside the electrical distribution network because of the value of high comparison R/X parameters present in the network. Moreover, the losses in the system are related to voltage levels and line flows therefore it is necessary to maintain these variables operating in the nominal value. According to studies, almost 10-13% of total power generated is lost as distribution losses. To overcome this problem, an appropriate, fast, and economical solution is required because if it is not addressed in the right way it will affect the reliability and performance of the system and could even result in additional system operating costs [1].

An effective solution to address this issue is by installing capacitors in the network to improve power factor and at the same time to reduce existing power losses. The capacitor here functions as reactive power compensation. It is important to be aware that installing capacitors in inappropriate locations and with inadequate capacity in the distribution network might lead to system instability and an increase in operational expenses. Hence, accurate analysis is required to ascertain the optimal location for capacitor integration and the appropriate capacity of the capacitor to be installed in a distribution system [2].

Capacitor allocation is a combinatorial optimization problem where the space in searching for a solution exponentially arises with the system size [3]. Mathematically, it is a nonlinear problem that solution acquired through non-convex approach model. It may provide different optimal local solutions [4]. The allocation of capacitor issue has been investigated since the 1960s, but in the 1990s some deterministic, heuristic and metaheuristic techniques have been developed. However, heuristic and metaheuristic techniques have gather a lot attentions from researchers so have been intensively developed for capacitor allocation problems such as Genetic Algorithms, Simulated Annealing, Ant Colony Algorithm , Tabu Search and Particle Swarm Optimization

PSO is a metaheuristic technique that has gained attention for its effectiveness in addressing combinatorial issues. PSO has also demonstrated robust in handling problems characterized by non-linearity, non-differentiability, and high dimensionality [3]. Many research findings have been found successfully to solve the capacitor allocation using PSO. G.E Mendoza et all applied PSO to find the best position integration of capacitors with the appropriate capacity to minimize real power losses, and fixed costs operating costs, and, consequently, to enhance voltage quality [5]. Some researchers also tried to figure out how to define the best candidate location of capacitor placement through loss sensitivity factor values [6][7]. Others tried to combine PSO with other heuristic methods to boost the algorithm performance in finding the solutions such as [8] that combine PSO with Harmony Search Algorithm (HSA), [9] which applies Artificial Bee Colony (ABC) combining with PSO, and [10] that analyze optimal capacitor placement and sizing in using Hybrid Approach of PSO-GA. Furthermore, some research to improve the PSO performance has also been done by enhancing and modifying the PSO parameters. The [11] and [12] use accelerated PSO to identify the best candidate bus to integrate capacitors by using the loss sensitivity factor however in [12] the problem is not only to solve the allocation capacitor problems but also the annual saving cost.

This study focuses on optimizing the placement and size of capacitors using the Modified Particle Swarm Optimization (MPSO) algorithm. The MPSO technique is an enhanced version of the Particle Swarm Optimization algorithm, originally developed by James Kennedy and Russell Eberhart. The distinguishing factor of the MPSO approach is the presence of the "inertia weight" parameter in the modified PSO. Optimizing the inertia weight parameter value can expedite and enhance the PSO algorithm's ability to accurately converge on the problem's solution and optimize the algorithm's performance in finding the solution. The MPSO developed in this study, is applied to the IEEE 34 bus radial electrical distribution system to identify to determine the optimal location and size of capacitor installation with the objective of minimizing power losses.

II. RESEARC METHOD

2.1. Modified Particle Swarm Optimization (MPSO)

The PSO method is an algorithm inspired by the social behavior of flocks of birds flying together. Social behavior encompasses the activities of individuals and the impact of other individuals within a group. Every individual or particle exhibits distributed behavior based on its inherent intelligence and is also influenced by the aggregate group. This method was discovered by Kennedy and Eberhart in 1995.

The PSO algorithm begins by creating a population consisting of particles in a search dimension. Each particle's position is determined by $X_i = (x_{i1}, \dots, x_{id})$ and its movement is defined by $V_i = (v_{i1}, \dots, v_{id})$. Let $Pbest_i = \left(x_{i1}^{Pbest}, \dots, x_{id}^{Pbest}\right)$ and $Gbest_i = \left(x_{i1}^{Gbest}, \dots, x_{id}^{Gbest}\right)$ represent the best positions of each particle and the best positions of all particles so far. Using this information, the latest position and velocity for each particle can be found using the equation 1 and 2 below.

$$\mathrm{V_{id}^{k+1}} = \mathrm{W} * \mathrm{V_{id}^{k}} + \mathrm{C_1} * \mathrm{rand_1} * \left(\mathrm{Pbest_{id}^{k}} - \mathrm{X_{id}^{k}}\right) + \mathrm{C_2} * \mathrm{rand_2} * (\mathrm{Gbest_{d}^{k}} - \mathrm{X_{id}^{k}}) \quad (1)$$

$$\mathrm{X_{id}^{k+1}} = \mathrm{X_{id}^{k}} + \mathrm{V_{id}^{k+1}} \quad (2)$$

Where,

V_{id}^{k}	: velocity of particle *i* in iteration *k*;
X_{id}^{k}	: position of particle *i* in iteration *k*;
V_{id}^{k+1}	: updated velocity of particle *i*;
X_{id}^{k+1}	: updated position of particle *i*;
$Pbest_{id}^{k}$	: the best position of particle *i* in iteration *k;*
$Gbest_{d}^{k}$	: the best position obtained by all particles in iteration *k*;
C_1, C_2	: constriction factors
$rand_1$, $rand_2$	: random numbers between 0 and 1
W	: the inertia weight factor

In this research, the inertia weight *(W)* parameter value is modified with the aim of enhancing the convergence speed of the PSO. This is particularly advantageous when PSO is applied to address problems that are very robust with abundant data and several parameters that require conditioning. Inertia weight is a parameter that controls the ability of particles to explore and travel toward their objectives. The inertia weight will directly impact the velocity of the particles in finding the solution. If the value of W is too large, the particle is likely to pass a good solution point. Conversely, if the value is too low, it restricts the particle's ability to explore the search space effectively, resulting in the failure to reach some good solution points.

In order to avoid this situation, several improvements can be made to the inertia weight value, such as utilizing the concept of "a time-decreasing inertia weight" theorem [5]. This concept has the ability to expedite the convergence of particles toward the ideal solution and hence decrease the number of iterations required. The equation expressing the inertia weight for this concept is as follows:

$$W = w_{max} \times \frac{w_{max} - w_{min}}{iter_{max}} + iter \tag{3}$$

The inertia weight value is crucial for the convergence of the PSO method in finding the optimal solution as it directly impacts the simulation runtime. When the value of W is excessively high, the particle is prone to surpassing an optimal solution point. Conversely, if the value is too low, it restricts the particle's ability to traverse the search space effectively, resulting in the failure to reach certain desirable solution locations.

2.2. The Objective Function

The objective function is the goal of optimization or the results to be achieved. In this research, the objective function is to minimize power losses and improve the voltage profile by installing optimal capacitors which can be written as in equation (4).

$$\mathrm{Min}(f(x)) = W_1 \times P_{loss} + W_2 \times Q_{loss} + W_3 \times \sum_{i=1}^{n} (1 - v)^2 \tag{4}$$

Where *Ploss* and *Qloss* are the active and reactive power which refers to network power losses due to the installation of capacitors. n is the total number of allocated capacitors in the distribution network.

The problem formulation above must consider several constraints or limitations in compiling the optimization algorithm as follows:

a. Power balance constraint;

$$\sum_{i=1}^{n} P_{Gi} = \sum_{i=1}^{n} P_{Di} + P_L \tag{5}$$

b. Bus Voltage limits;

$$|V_i|^{\min} \le |V_i| \le |V_i|^{\max} \tag{6}$$

c. Reactive power limits compensation of capacitors;

$$Q_{cap\_i}^{\min} \leq Q_{cap\_i} \leq Q_{cap\_i}^{\max} \quad (7)$$

The calculation of power losses that appear on the network is carried out by applying power flow analysis to the electricity distribution network using the *Bus Injection to Branch Current (BIBC)* and *Branch Current to Bus Voltage (BCBV)* methods [13]. The solution for power flow using this method can be briefly seen in the flowchart of Figure 1.

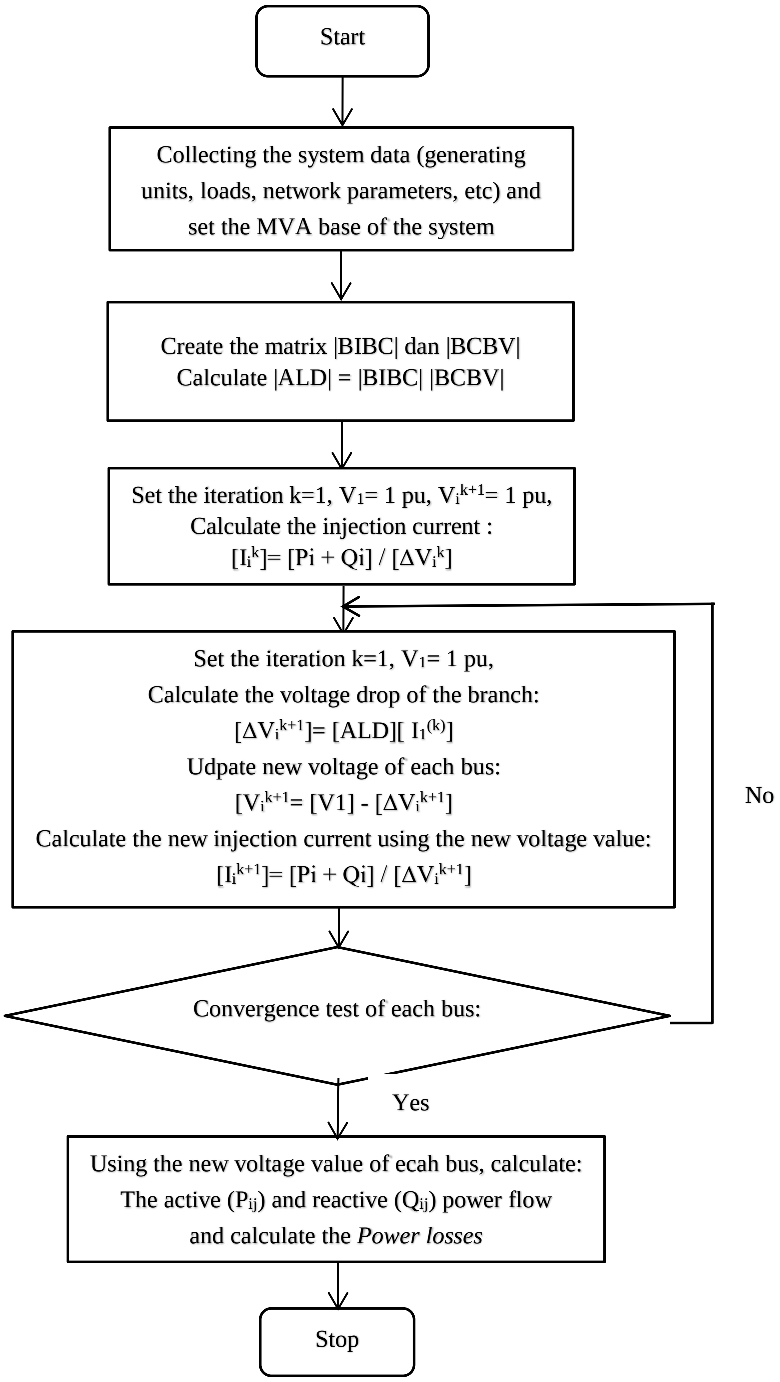

Figure 1. Power flow analysis using BIBC and BCBV to determine power losses in radial distribution networks

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2.3. The Implementation of MPSO to Determine The Optimal Location and Sizing of Capacitors

The MPSO approach involves adjusting various parameters based on the specific problem or optimisation being performed. Table 1 displays the MPSO parameter values utilised to solve the capacitors allocation.

Table 1. Parameter values used in the MPSO method

Min value of inertia weight (Wmin)	Max value of inertia weight (Wmax)	Cognitive parameter	Social parameter	Population size	Iteration
0.4	0.9	2	2	100	100

The following steps must be performed in order to find the best placement and sizing capacitors using MPSO.

1. Input all required system data for load flow analysis inlcuding bus data, load data, generating units, network parameters.
2. Calculate the losses in network using *BIBC* and *BCBV* analysis as described in Figure 1
3. Specify the settings for the MPSO algorithm and determine the placement of capacitors. It should be noted that the capacitors to be located may not always be equal to the variable n. The algorithm aims to minimise the number of capacitors that need to be located.
4. Create an initial population where each particle has random position and velocitie in the search dimension *k.*
5. Set the iteration *k.*
6. For each particle, if the constraints are within the specified limit (equation 5, 6, and 7) then calculate the power losses according to the objective function in this problem (equation 4).
7. For each particle, compare the objective value with the individual best value (P_{best}), if the objective value is lower than P_{best} then set this value as the latest particle value for the next iteration and calculate the value of the particle's latest position.
8. Calculate the inertia weight *(W)* value at iteration k using equation 3.
9. Choose the best P_{best} value among all particles and set that value as G_{best} value.
10. Update the velocity and position values as well as the inertia weight values using equations 1, 2, and 3.
11. If the iteration has reached the specified maximum iteration limit, return to step 9. If not, set *k+1* iterations and return to step 4.
12. Display the optimal solution obtained. The best position includes the optimal location and size of the capacitor. Meanwhile, the objective function represents the minimum power losses, and reactive power produced by the capacitor.

III. Result and Discussion

3.1. IEEE 34 Bus Radial Distribution System

In this research, the MPSO algorithm is constructed using Matlab. Simulation and analysis are conducted on a radial distribution system of IEEE 34 bus. This system comprises 34 buses and 4 feeders. Meanwhile, the total load taken under peak load conditions is 4.64 MW and 6.87 MVar.

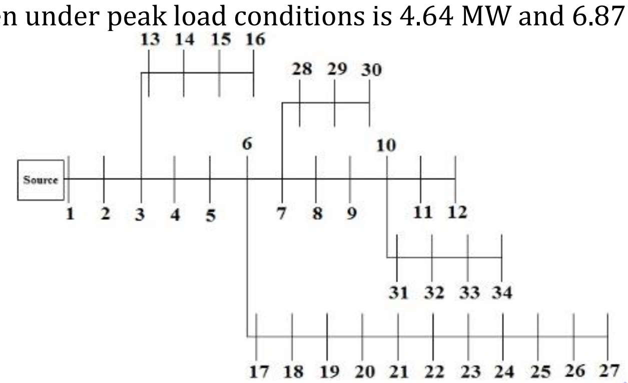

Figure 2. A radial distribution system of IEEE 34 bus

3.2. The Case Study

The capacitor allocation problem in this study includes the optimal location of capacitor installation, the size of the installed capacitor and the number of capacitors used. ment, value, and quantity of capacitors to be fitted. The process of allocating capacitors is stated as an optimization problem, taking into account many factors that need to be considered, including:

a. *Vector x* that describes the location and size of the capacitor to be installed.
b. *Vector x* serves as the input for the objective function in this proble, which is utilized to ascertain the power losses in the network and the voltage profile on each bus.
c. The calculations that is carried out must always be within the specified constraint values.
d. The simulation was carried out using 6 fixed capacitors with the rating of each capacitor ranging from 50 kVar to 1 MVar. The simulation begins by determining the power losses before installing the capacitor, then the capacitors are installed in the system. The utilization of MPSO enables the identification of the most suitable placement for capacitors and the determination of the ideal capacitor size to minimize power losses in the network.

3.3. The Test Results

The by products of the capacitor allocation using the MPSO algorithm are the optimal location and sizing of installed capacitors, the power losses before and after capacitors installation, and the voltage profile of each bus in the system. The location and size of 6 capacitors that have been installed is presented in Table 2. Meanwhile, the results of power losses before and after installing the capacitor can be seen in table 3.

Table 2. The optimal location and size of installed capacitors based on MPSO algorithm

The location of installed capacitor	The size of installed capacitor
Bus 12	670 kVar
Bus 22	70 kVar
Bus 23	68 kVar
Bus 24	675 kVar
Bus 27	670 kVar
Bus 34	675 kVar

Table 3. The power losses before and after capacitors placement

Condition	The total of power losses
Before optimizatio	219 kW
After optimization using MPSO	160 kW
The total reduced losses in the system	26%
The total compensation of power reactive	2850 kVar

The voltage profile on each bus in the IEEE 34 bus radial distribution system is illustrated in Figure 3. It can be seen that the voltage value on each bus is still within the specified limit range, between 0.95 pu to 1.05 pu.

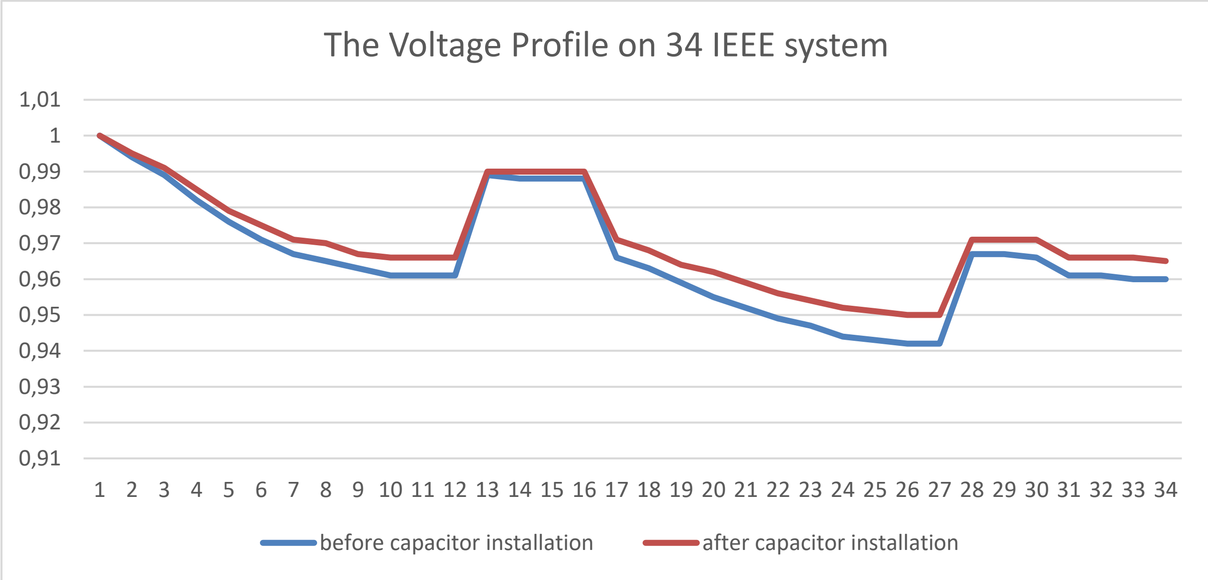

Figure 3. The voltage profile of each bus in the IEEE radial distribution system [14]

IV. Conclusion

This study discusses an optimization strategy for the problem of capacitor allocation in electrical distribution systems. The objective is to minimize power losses in the network and enhance the voltage profile. The approach relies on the utilization of the PSO algorithm, whereby the "inertia weight" parameter is modified to expedite and enhance the particle's ability to explore the search space effectively, resulting in reaching good solution points, called MPSO. This technique is applied to a radial distribution system of the IEEE 34 bus. The testing results revealed that optimizing the placement and size of capacitors can reduce power losses in the system by as much as 26 %, namely from 219 kW to 160 kW. Moreover, this optimization also provides good bus candidates for capacitor installation such as buses 12, 22, 23, 24, 27, and 34.

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