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Optimal Capacitor Allocation and Sizing in Medium Voltage Distribution Networks Using PSO and OpenDSS

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Abstract
The optimal allocation and sizing of capacitors in a Medium Voltage (MV) distribution grid utilizing Particle Swarm Optimization (PSO) for selecting the optimum size and placement of capacitors units can significantly affect the distribution grid. Capacitor installation serves as a standard approach for reactive power compensation. This study focuses on optimizing capacitor allocation and sizing to enhance voltage profiles and minimize power losses. The PSO algorithm, in conjunction with OpenDSS, is used to analyze the power flow outcomes from the IEEE 14 Bus system. To achieve this, the PSO and OpenDSS tools were employed in the research to process the power flow data from the standard IEEE 14 Bus system. The performance of the PSO model was evaluated by presenting the outcomes, demonstrating that the PSO algorithm successfully determines the optimal size and location of capacitors.
index Terms—Capacitor Placement; Particle Swarm Optimization (PSO); Open DSS engines ;Power Loss Minimization.

Introduction

Modern power systems rely on diverse energy sources to enhance efficiency and reliability in electrical distribution networks. Optimal allocation and sizing of these sources significantly impact system performance, voltage stability, and power losses. Various optimization techniques, such as Particle Swarm Optimization (PSO), Ant Colony Optimization, Optimal Power Flow, and Analytical methods, have been utilized to tackle these challenges. Recent advancements incorporate Evolutionary Computation Techniques such as Evolutionary Programming and Genetic Algorithms (GA) to determine ideal configurations for capacitors and energy sources. Combining PSO with tools like OpenDSS provides an efficient solution for allocation problems, reducing computational effort while improving accuracy compared to traditional methods [1-2].

This study demonstrates the application of Various optimization techniques, such as Particle Swarm Optimization (PSO), Ant Colony Optimization, Optimal Power Flow, and Analytical methods, have been utilized to tackle these challenges. . The research also assesses the reduction in power losses achieved through the PSO-based optimization method.

Multiple algorithms have been explored for determining optimal locations and capacities of renewable energy sources, considering factors such as candidate buses, generator sizes, and quantity. Techniques such as PSO, Ant Colony Optimization, Optimal Power Flow, and Analytical methods have been investigated. Recent advancements include Evolutionary Computation Techniques like

Evolutionary Programming and Genetic Algorithms (GA) for solving capacitor placement and sizing problems. PSO, combined with OpenDSS, offers an efficient computational approach, delivering improved results with lower computational effort compared to conventional methods [2-3].

The main goal of this research is to apply the PSO algorithm for optimal placement and sizing of capacitors, leveraging OpenDSS to analyze data from the IEEE Fourteen (14) Bus system. Additionally, the study highlights the effectiveness of PSO in minimizing power losses.

II. Methodology

In this study, the PSO algorithm is applied to identify the optimal placement and sizing of capacitors, as well as the optimal allocation of capacitor. The subsequent subsections detail the methods used to achieve the optimal solution and perform the power flow analysis.

A. Network Modeling

In power systems, conducting an accurate power flow analysis is crucial for determining the power delivered through feeders, transformers, loads, and other components. Therefore, network modeling is the first step, which involves simulating the power grid within a software environment such as OpenDSS, utilized in this research. The IEEE 14 Bus system, illustrated in Figure 1, serves as the test network. System data were sourced from the IEEE database. The system comprises 14 buses, five generators, 16 transmission lines, 11 loads, one shunt, and five transformers [4].

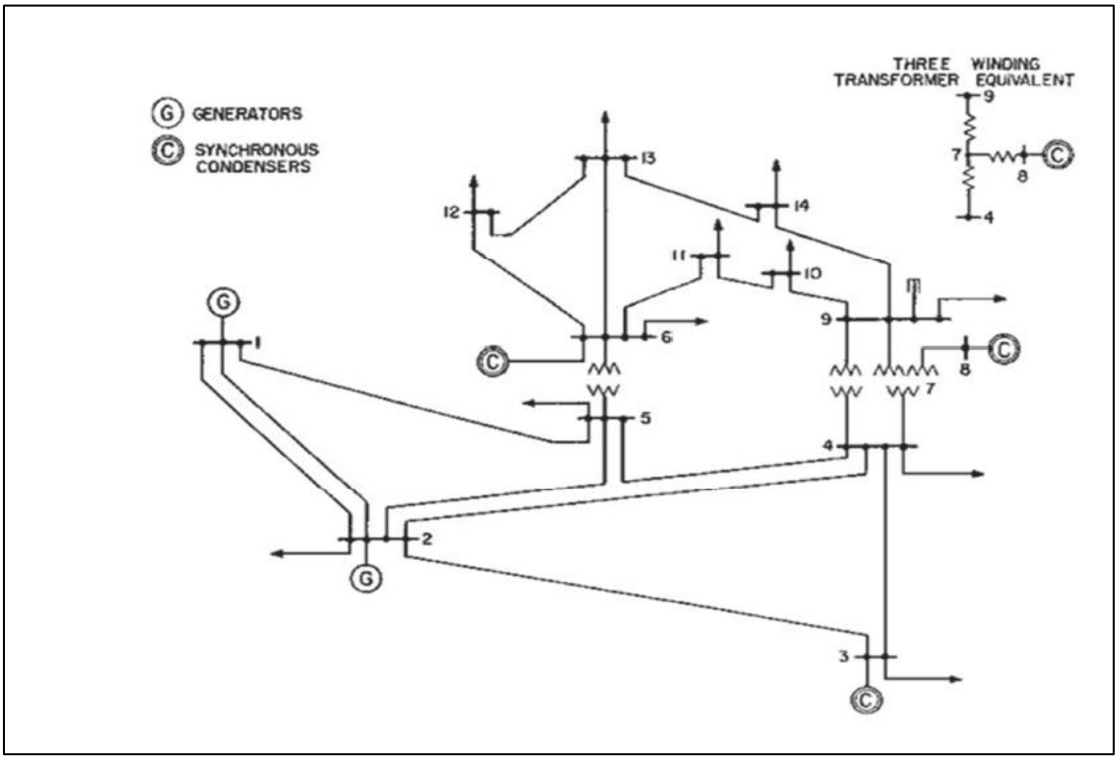


Figure 1: Single-line Representation of the 14-bus system

The process of data collection and the implementation of the power flow engine (OpenDSS) can be segmented into four key stages. First, load demand data are considered, where loads are assumed to supply constant active power (P) and reactive power (Q), as detailed in Table 1, and are not voltage-dependent. Second, the generator "G_0001" serves as the slack bus, with specified voltage magnitude and angle (1.06 p.u., Zero degrees). Generators are configured to control active power injection and sustain voltage magnitudes at their respective buses, as depicted in Tables 2 and 3 Third, the line data are expressed in (p.u), calculated using a system base power of 100 MVA, as summarized in Table 4 Fourth, the transformer data are also presented in per unit (p.u) based on the identical system base power, as depicted in Table 5 .

Tables 4 and 5 summarize the transmission lines and transformers, respectively. The system features 16 lines operating across multiple voltage levels.: buses 1-5 at 132 kV, buses 6 and 9-14 at 33 kV, bus 7 at 1 kV, and bus 8 at 11 kV. The system model comprises five transformers, with parameters specified in per unit on a 100 MVA base.

B. Gathering Data and Executing the Power Flow Analysis Using OpenDSS

Table 1: Load demand (LD)

Load Demand (LD)	Bus Voltage	Active power (P) in MW	Reactive power (Q) in Mvar
LD .2	bus - 2	21.70	12.70
LD .3	bus - 3	94.20	19.00
LD .4	bus - 4	47.80	-3.90
LD .5	bus - 5	7.60	1.60
LD .6	bus - 6	11.20	7.50
LD .9	bus - 9	29.50	16.60
LD.10	bus - 10	9.00	5.80
LD.11	bus - 11	3.50	1.80
LD.12	bus - 12	6.10	1.60
LD.13	bus - 13	13.50	5.80
LD.14	bus - 14	14.90	5.00

Table 2: Generator dispatch (GD)

Generator	Bus Voltage	Active power (P) in MW	Reactive power (Q) in Mvar
Gen - 1	bus - 1	Not Allowed	Not Allowed
Gen - 2	bus - 2	40.00	Not Allowed
Gen - 3	bus - 3	0.00	Not Allowed
Gen - 6	bus - 4	0.00	Not Allowed
Gen - 8	bus - 5	0.00	Not Allowed

Table 3 : Generator Controller Parameters and Settings

Generator	Bus Voltage kind	Voltage in p.u.	Minimum Apparent Power Capability in MVA	Maximum Apparent Power Capability in MVA
Gen -1	Slack-One	1.060	Not Allowed	Not Allowed
Gen -2	PV -Two	1.045	-40.00	50.00
Gen - 3	PV-Three	1.010	0.00	40.00
Gen- 6	PV -Six	1.070	-06.00	24.00
Gen - 8	PV-Eight	1.090	-06.00	24.00

Table 4: Data of transformers given in based on 100 MVA, with rated voltages

Lines	From Bus	To Bus	Un in kV	R in Ω	X in Ω	B in µS
Line - 1- 2/1	1	2	132.0	6.76	20.62	151.6
Line- 1- 2/2	1	2	132.0	6.76	20.62	151.6
Line –1 - 5	1	5	132.0	9.42	38.87	282.0
Line - 2- 3	2	3	132.0	8.19	34.51	251.1
Line - 2- 4	2	4	132.0	10.13	30.73	214.6
Line - 2- 5	2	5	132.0	9.93	30.37	195.1
Line - 3- 4	3	4	132.0	11.80	29.82	198.5
Line - 4- 5	4	5	132.0	2.30	7.34	73.5
Line - 6- 11	6	12	33.0	1.03	2.17	0.0
Line - 6- 12	6	10	33.0	1.33	2.79	0.0
Line - 6- 13	6	13	33.0	0.72	1.42	0.0
Line - 9- 10	9	10	33.0	0.35	0.91	0.0
Line - 9- 14	9	14	33.0	1.39	2.95	0.0
Line - 10- 11	10	11	33.0	0.88	2.18	0.0
Line - 12- 13	12	13	33.0	2.41	2.18	0.0
Line - 13- 14	13	14	33.0	1.87	3.79	0.0

Table 5: Transformer data referenced to a common 100 MVA base.

Transformer	From Bus	To Bus	Ur HV in kV	Ur LV in kV	r in p.u.	X In p.u.	X ohms	Transformer final turns ratio
Transf 4 to 7	4	7	132.00	1.00	0.00	0.2090	36.437	0.978
Transf 4 to 9	4	9	132.00	33.00	0.00	0.5561	96.909	0.969
Transf 5 to 6	5	6	132.00	33.00	0.00	0.2520	43.918	0.932
Transf 7 to 8	7	8	11.00	1.00	0.00	0.1762	0.213	0.000
Transf 7 to 9	7	9	33.00	1.00	0.00	0.1101	1.091	0.000

C- Load Flow Analysis using OpenDSS

Load flow analysis is a numerical computational method essential for power system planning and operational studies. It provides a steady-state solution of the system, yielding critical parameters such as voltage magnitude and phase angle at each bus, as well as active and reactive power flows through all network branches. Load flow analysis in distribution networks is primarily categorized into two methodological frameworks: node-based and branch-based approaches [5]. Node-based methods formulate the problem using bus-level quantities such as active and reactive power injections, current injections, and nodal voltages. In contrast, branch-based methods explicitly model the current or power flow through individual network branches.

This research utilized the Open Source Distribution System Simulator (OpenDSS), a comprehensive electrical power system simulation engine. OpenDSS facilitates the calculation of various grid parameters—including power losses, branch currents, bus voltages, power factor, and active/reactive power flows—by integrating with simulation environments such as MATLAB, C#, and VBA. Specifically, the OpenDSS engine was utilized to perform load flow analysis of the IEEE 14-bus test system is conducted to assess system performance and evaluate the effectiveness of optimal capacitor placement.

D - Particle Swarm Optimization (PSO)

Particle Swarm Optimization (PSO) is a population-based stochastic optimization technique, first developed by Kennedy and Eberhart in 1995 [6-7].It is particularly effective in modeling complex, nonlinear control problems within power systems, including the distribution planning of load and generation components, as well as multi-objective optimization issues with various constraints.

PSO operates through a population of particles, each representing In the Particle Swarm Optimization (PSO) algorithm, candidate solutions (particles) navigate the search space. Their movement is directed by a combination of their own historically best position (personal best) and the best position discovered by any member of the entire swarm (global best). The movement of particles is influenced by their previous velocities, personal experience, and collective intelligence, as described by the equations associated with PSO [8]. Figure 2 illustrates the general movement pattern of particles within the PSO framework, with equations governing their velocity and position updates (shown as Equation 1 and Equation 2).

This algorithm is recognized for its accuracy and efficiency in solving the placement and sizing problems of capacitors, making it an essential tool for optimizing distribution networ

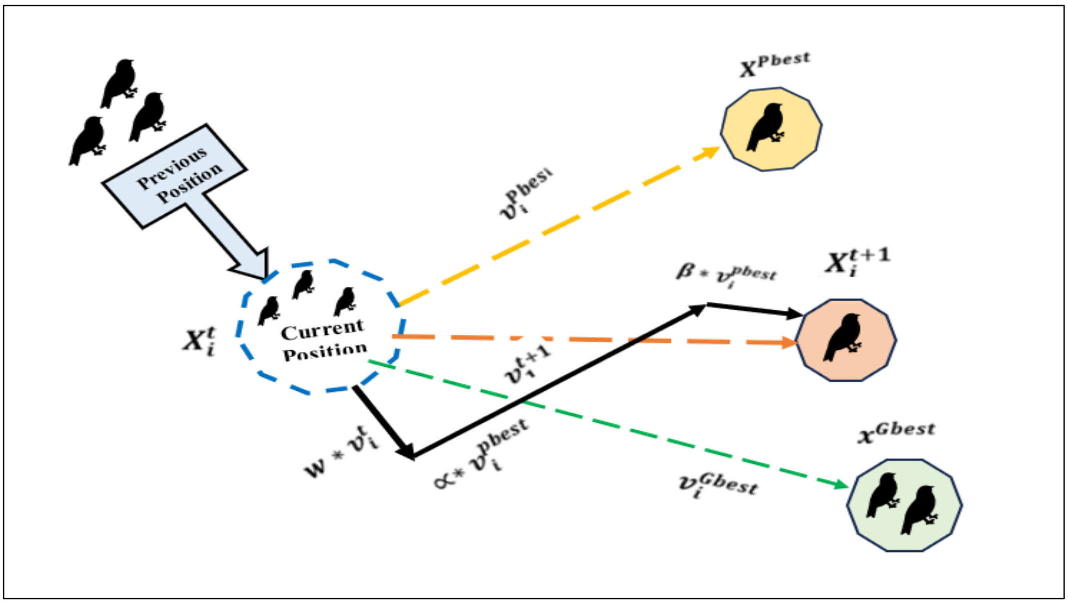


Figure 2: illustrating the structure of the Particle Swarm Optimization (PSO) algorithm.

$$V_t^{t+1} = w \times V_t^t + r_1 \times (x_{pbest} - x_t^t) + C_2 \times r_2 \times \left(x_{gbest-V_i^t}\right) \quad (1)$$

$$x_t^{t+1} = x_t^t + V_t^{t+1} \quad (2)$$

Where:

- V_i^{t+1} represents the velocity of the i-th particle at the next iteration t+1,
- x_i^t The center of a detector or a collision point,
- xpbest is the personal best position,
- xgbest is the global best position,
- w is the inertia weight for the system,
- $C_1 and\ C_2$ are acceleration coefficients for PSO ,
- $r_1 and\ r_2$ are random numbers uniformly distributed in [zero , one].

.

$$X^{pbest} = \begin{cases} X^{pbest(i)} & \text{if} \quad OF^{j+1} \geq OF^j \\ X_i^t & \text{if} \quad OF^{j+1} \leq OF^j \end{cases} \quad (3)$$

$$X^{Gbest} = \begin{cases} X^{Gbest(j)} & \text{if} \quad OF^{j+1} \geq OF^j \\ X^{pbest(j+1)} & \text{if} \quad OF^{j+1} \leq OF^j \end{cases} \quad (4)$$

OF = denotes the Objective Function.

C1= refers to the cognitive factor.

C2 = refers to the social factor, and

r1 and r2~U (0,1) are independently and uniformly distributed random numbers [8].

III. Proposed PSO Algorithm for Capacitor Allocation (CA)

The primary objective of this work is to solve the optimal capacitor allocation (OCA) problem. The problem is formulated as a discrete optimization task with two key decision variables: the identification of suitable candidate buses for capacitor bank placement and the determination of their optimal sizes. The solution thus yields a set of discrete locations and corresponding ratings that optimize the defined network performance criteria.

The problem is solved through a co-simulation framework that integrates MATLAB with the OpenDSS power flow engine. MATLAB initializes the model and directs an iterative optimization process, communicating with OpenDSS at each step to evaluate system performance until the objective function is minimized.

1) Input Data: The input data required for the process are as follows:

(a) The Total number of buses, bus voltage data, load demand (LD) (both P and Q at each bus, line data, and other relevant power system variables.

b) Node Voltage Constraints: Vmin ≤ Vbus ≤Vmax where the minimum voltage is 0.91 p.u. and the maximum is 1.15 p.u., corresponding to a ±6% variation.

(c) Capacitor Range Selection: Choose suitable capacitor sizes from Table 1 such that the reactive power capacity Qic satisfies Qic≤Qmaxc≤Qtotal.

2) From the results, the maximum reactive power (Q) within the system is determined through power flow analysis; subsequently, reactive power injections at each bus are calculated. During this process, the minimum voltage among all buses is identified, and sensitive buses are selected based on their voltage profiles to optimize capacitor placement.

3) initialization

The initialization of PSO parameters includes setting bus data, the number of populations (n), maximum iterations, and line data. Data collected from previous steps, along with PSO-specific parameters such as the number of decision variables, as well as their maximum and minimum bounds, are used. The optimization process begins with the generation of an initial candidate set through a constrained random sampling technique.

4) Estimate:

In this phase, the results are assessed by performing power flow analysis using OpenDSS to determine each particle's personal (pbest) and the overall global best (gbest).

5) Updates: Next, the personal and global bast parameters are updated based on the current evaluation, refining the positions of the particles.

6) PSO Main Loop: These steps (evaluation and updates) are repeated within the main PSO loop until the entire population has been processed. During this loop, the positions and velocities of particles are continually adjusted to find the optimal location, bus, and size for Capacitor in the distribution system [8-9].

Formulation of the Objective Function (OF) for Capacitor Allocation (CA):

In capacitor placemant and sizing, the totel cost includes power losses and the costs of the capacitors. The objactive function (OF) can be expressed as [10]:

$$\min\ OF = \sum_{i=1}^{nb} C_L \cdot P^{i}_{Loss} \qquad (5)$$

Where **OF** represents the total cost task, **CL** denotes the total capacitor cost, and **PLoss_i [kW]** corresponds to the active power losses at bus *i*. The variables **i** and **nb** refer to the bus index and the total number of buses, respectively.

$$P^{i}_{Loss} = \sum[V_i^2 + V_j^2 - 2V_i^2 . V_j^2 \cos(\delta_i + \delta_j)].\, Y_{ij} \cos \theta ij \qquad (6)$$

Element voltages (EV), including directions and angles, are denoted as Vi, δi for bus i, and similarly Vj, δj for bus j. The line admittence's magnitude and phase angle between busas i and j are represented as Yij and θij, respectively.

A. Results of Open-Source Distribution System Simulator (OpenDSS)

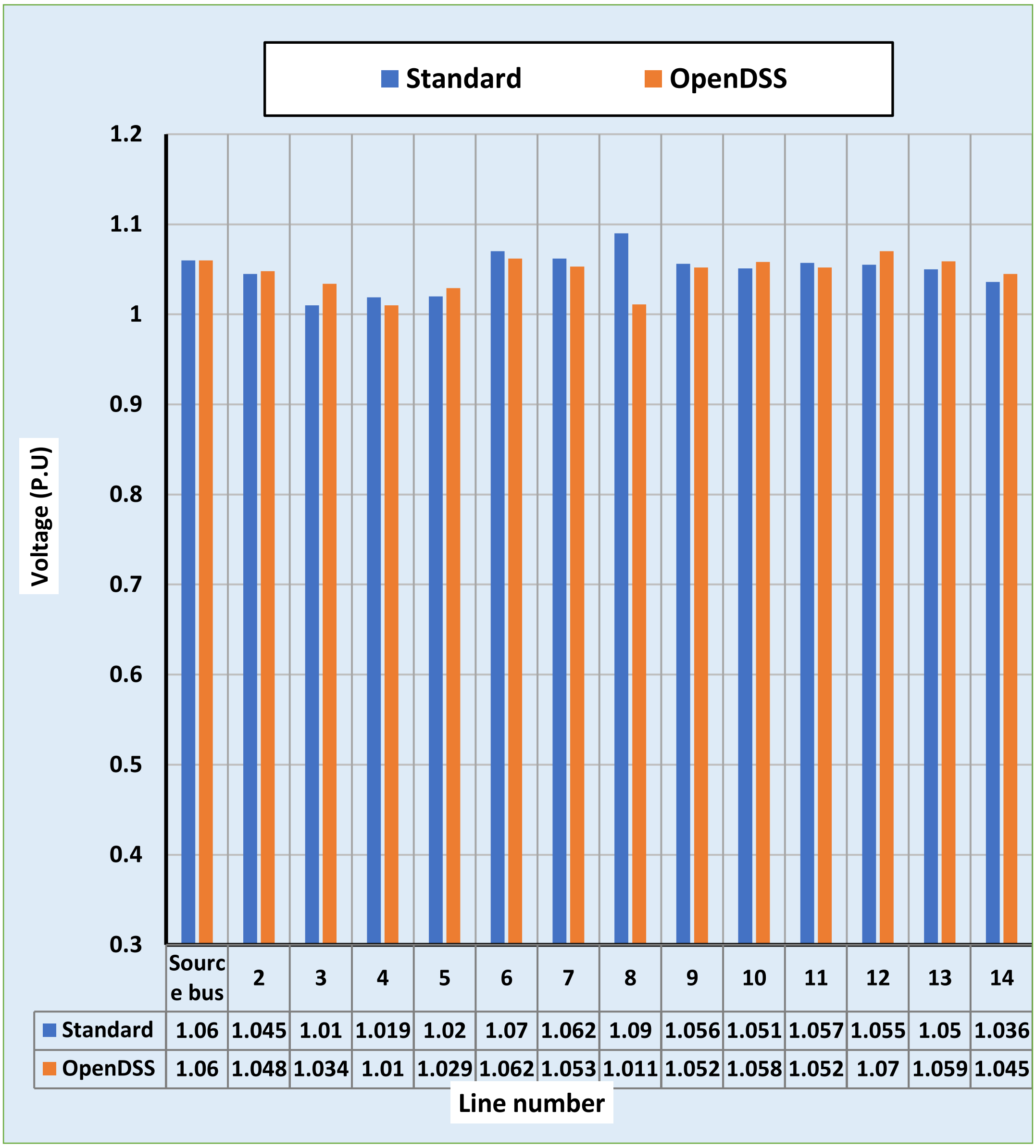
The grid input data are fed into the OpenDSS script environment, which includes generators, loads, transformars, and lines. This is done to get the required parameters of the distribution grid by performing power flow calculations. The results from the OpenDSS engine, such as power losses, voltages, currents, etc., are then compared with the IEEE 14 Bus standard case [10] to validate the functionality of the power flow analysis. The comparison shows minor discrepancies between the OpenDSS results and the standard IEEE 14 Bus results [10], confirming the accuracy of the model.

B. Results After Optimal Capacitor Placement and Sizing Using PSO

The proposed Particle Swarm Optimization (PSO) technique was applied to the IEEE 14-bus test system [10] to determine the optimal locations and sizes of shunt capacitors. The efficacy of the optimization is demonstrated in Figure 5, which compares the system's voltage profile before and after capacitor placement, showing a significant improvement in voltage regulation.. The results show that installing capacitors at the optimal locations not only maintains acceptable voltage levels but also improves voltage profiles in several buses. Notably, at bus 14, the voltage initially exceeded the standard limit with a value of 1.082 p.u., but after installing capacitors at buses 4, 7, 10, and 14 (with sizes of 3960, 1070, 4260, and 5890 kVAR, respectively), the voltage was reduced to 1.0273 p.u. Additionally, the overall power losses in the system decreased after capacitor installation, as shown in Figure 6and Table 8. Specifically, total power losses were reduced from 13413.3kW to 13278.16 kW, amounting to a loss reduction of approximately 135.14 kW. Figure 7 depicts the minimization of the cost function during the PSO iterations, highlighting the convergence towards the optimal solution.

Table 6: Voltage comperison between Standard Case and OpenDSS

Bus name	Standard Case	OpenDSS
Source bus	1.06	1.06
2	1.045	1.048
3	1.01	1.034
4	1.019	1.01
5	1.02	1.029
6	1.07	1.062
7	1.062	1.053
8	1.09	1.052
9	1.056	1.052
10	1.051	1.058
11	1.057	1.052
12	1.055	1.07
13	1.05	1.059
14	1.036	1.085



	Source bus	2	3	4	5	6	7	8	9	10	11	12	13	14
Standard	1.06	1.045	1.01	1.019	1.02	1.07	1.062	1.09	1.056	1.051	1.057	1.055	1.05	1.036
OpenDSS	1.06	1.048	1.034	1.01	1.029	1.062	1.053	1.011	1.052	1.058	1.052	1.07	1.059	1.045

Figure 3: Voltage comparison between OpenDSS and standard results

Table 7: Losses comparison between Standard Case and OpenDSS

Line number	Standard Case	OpenDSS	Difference (kW)
Line.1	2147	2147	49.00
Line.1-1	2147	2147	49.00
Line. 2	2764	2764	40.00
Line.3	2320	2320	86.00
Line.4	1677	1677	24.00
Line.5	902.3	902.3	26.30
Line.6	371.4	371.4	2.50
Line.7	516.5	516.5	8.40
Line.11	54.7	54.7	15.84
Line.12	71.7	71.7	12.10
Line.13	211.5	211.5	30.80
Line.16	13.1	13.1	8.29
Line.17	116.8	116.8	99.40
Line.18	12.3	12.3	5.11
Line.19	6.2	6.2	0.55
Line.20	53.6	53.6	82.70
Total Losses	13304.73 kW	13413.3 kW	-108.57 kW

Figure 4: power losses comperison between OpenDSS and standerd Case results

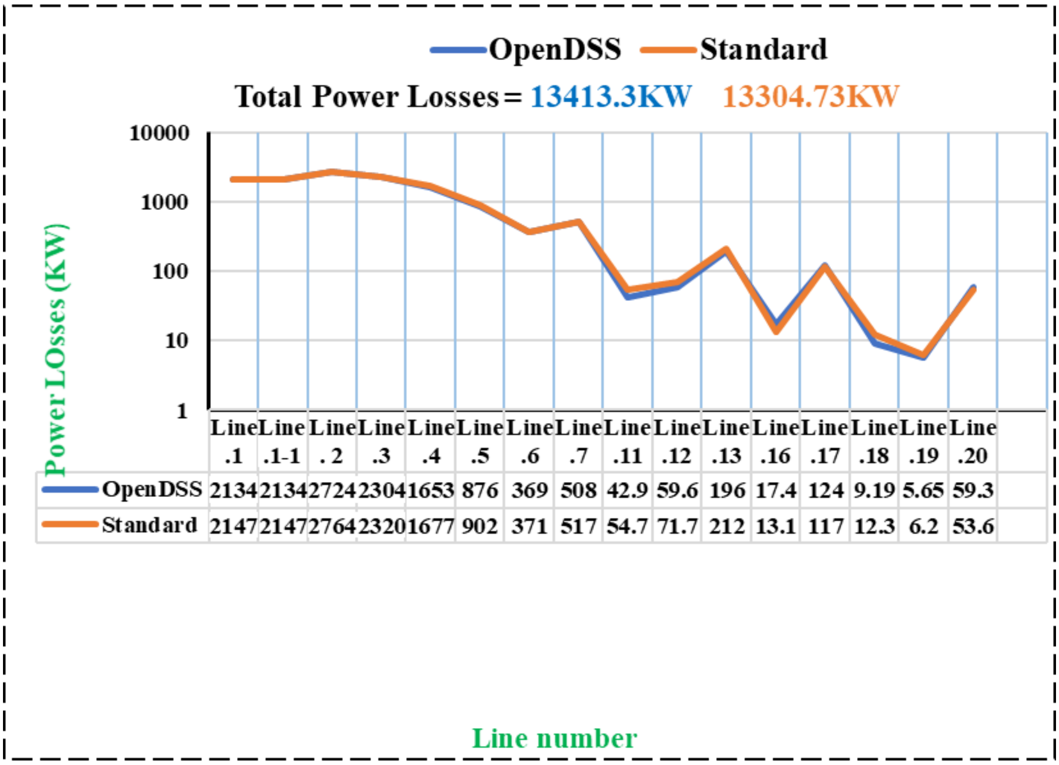
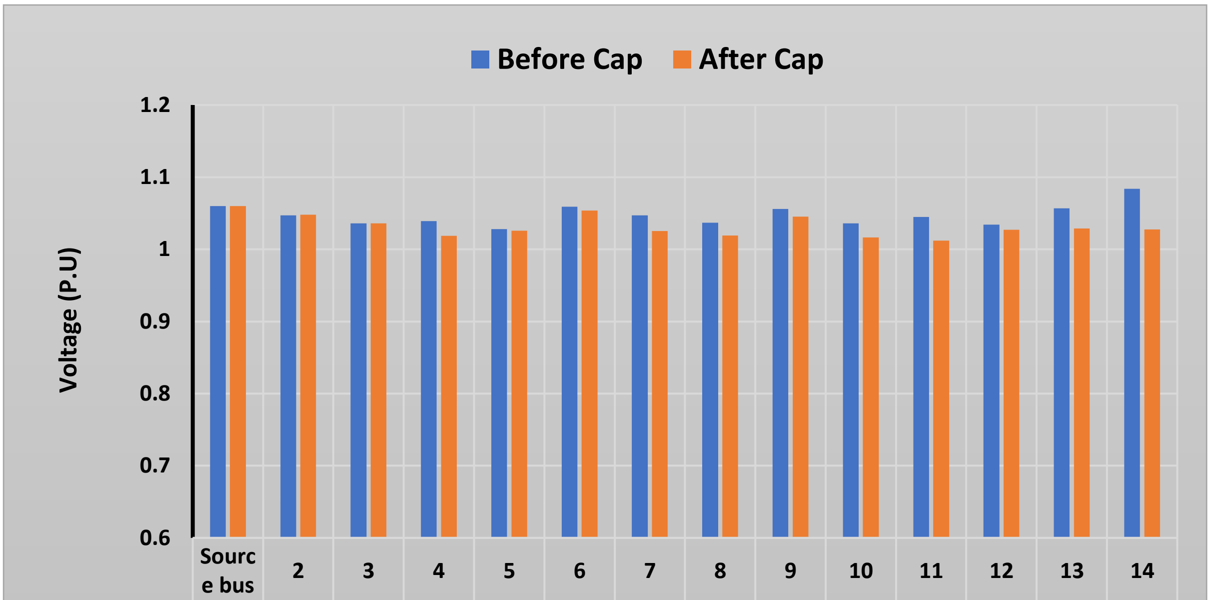


Table 8 shows the summery of the results that could be

Types	Selected Bus	size (KW)	Total (KW)	Line Loss at standard case (KW)	Line Loss after installation (KW)	Power loss reduction saving
Capacitor	4	3960	17880	13314.45	13278.16	12.04
	7	1070				
	10	4260				
	14	5890				



	Source bus	2	3	4	5	6	7	8	9	10	11	12	13	14
Before Cap	1.06	1.047	1.036	1.039	1.028	1.059	1.047	1.037	1.056	1.036	1.045	1.034	1.057	1.084
After Cap	1.06	1.048	1.0359	1.0185	1.0257	1.0535	1.0251	1.0189	1.0453	1.0165	1.012	1.0271	1.0287	1.0273

Figure 5: Voltage comparison between before and after capacitor placement and sizing

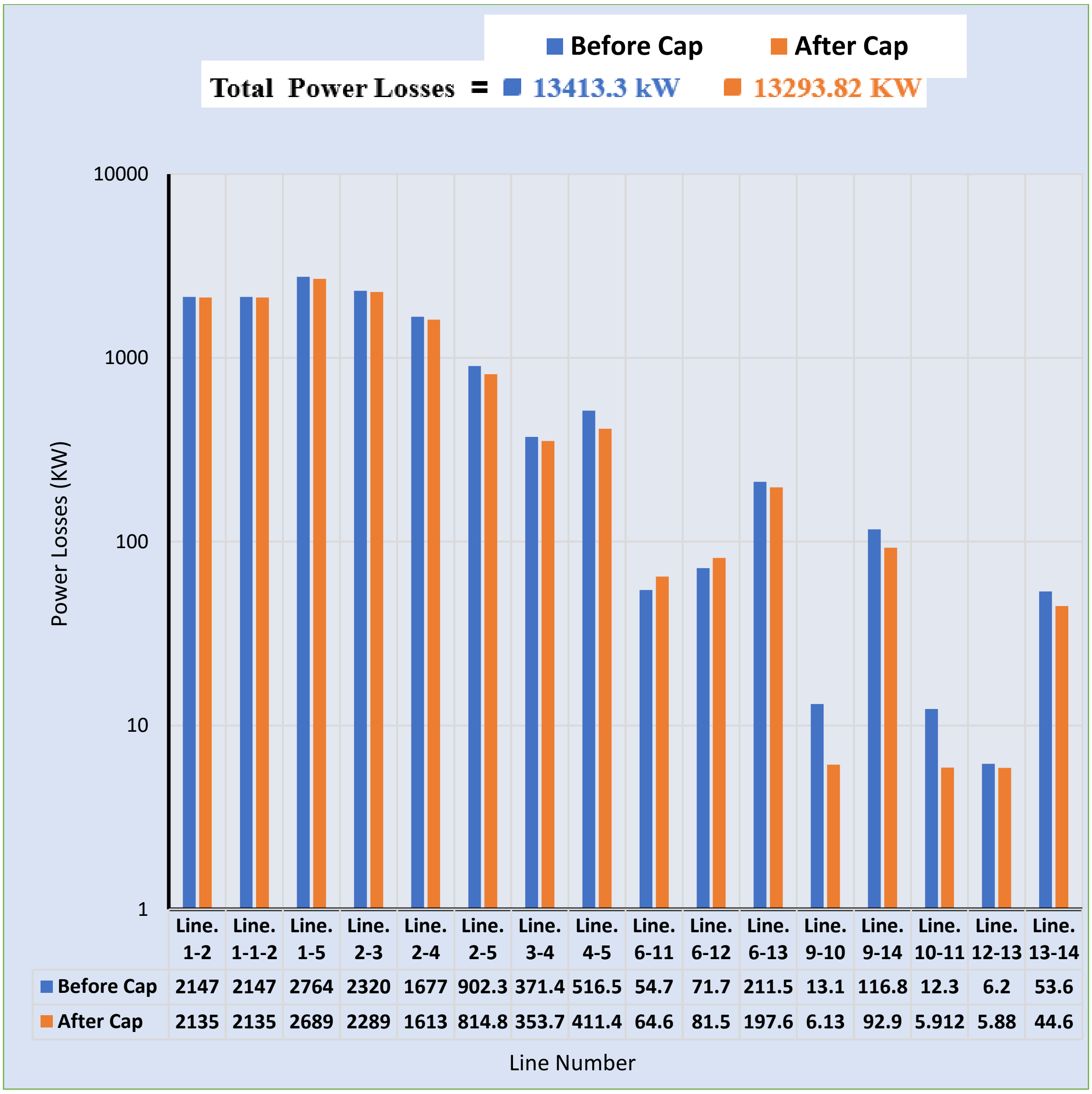


Figure 6: Power losses comperison between before and after capacitor placement and sizing

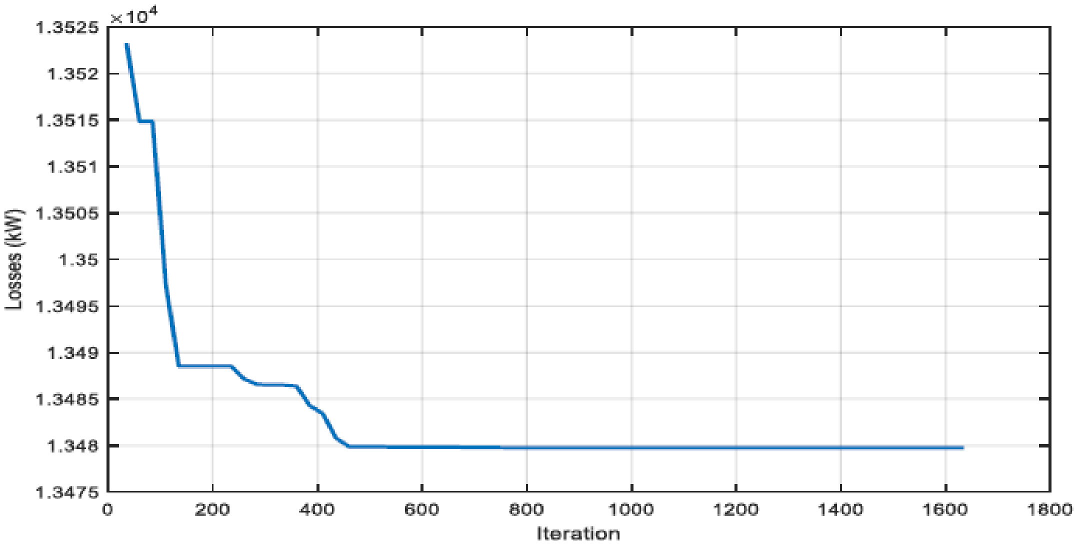


Figure 7: Cost function minimization

CONCLUSION

The results have shown that PSO algorithm is more efficient compered to other traditionel load flow methods. It effectively reduces the real power losses and requires less time to compute them. The study evaluated the optimal placement and sizing of the capacitor using PSO and OpenDSS in the IEEE 14-bus system, focusing on enhancing voltage profiles and decreasing losses. Simulation outcomes reveal that the total system losses decrease from 13,314.45 kW without capacitor to 11,958.9kW after installing the optimal capacitor, indicating a significant reduction. Overall, the power quality of the distribution system is notably improved through this approach.

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