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Capacitor Bank Placement Enhancement Using Grey Wolf Algorithm for Reducing Harmonics in Low-Voltage Radial Distribution Networks

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Abstract

Background: Low-voltage distribution systems are increasingly affected by harmonic distortion due to nonlinear loads, leading to power losses, reduced efficiency, and poor power quality. Capacitor banks are commonly used for reactive power compensation; however, improper placement may worsen harmonic conditions due to resonance effects.
Objective: This study aims to optimize capacitor bank placement in a low-voltage radial distribution system while improving power quality and minimizing harmonic distortion using the Grey Wolf Optimizer (GWO).
Method: A quantitative, simulation-based approach was applied using a 12-bus radial distribution model of an integrated laboratory system. Power flow analysis was conducted using the Backward/Forward Sweep (BFS) method, while optimization of capacitor placement and sizing was performed using the Grey Wolf Optimizer (GWO), considering multi-objective criteria including power loss, total harmonic distortion of current (THDI), total harmonic distortion of voltage (THDV), and power factor.
Result: The proposed GWO allocated a total of 1000 kVAr across selected buses, resulting in a 4.41% reduction in active power loss, a decrease in THDV from 6.181% to 1.517%, and an improvement in power factor to unity (1.0 pu). However, THDI remained at 18.71%, exceeding IEEE 519-2014 limits, indicating the need for additional harmonic filtering solutions.
Conclusion: The Grey Wolf Optimizer (GWO) is effective for optimizing capacitor placement and improving voltage-related power quality. However, additional harmonic mitigation techniques are required to comprehensively address current distortion.

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INTRODUCTION

The demand for a reliable, efficient, and high-quality electricity supply has increased significantly across institutional sectors, particularly in higher education, where modern laboratory and computing systems require stable power to support academic and operational activities (Judijanto et al., 2025; PLN, 2025). The education sector requires stable voltage and low harmonic distortion for the operation of sensitive electronic equipment such as computers, printers, and laboratory instruments (Jalil et al., 2019; PLN, 2025). Poor power quality can negatively affect equipment performance, reduce operational efficiency, and increase energy losses within electrical distribution systems (Nugroho et al., 2025).

One of the major challenges in maintaining power quality is harmonic distortion caused by nonlinear electrical loads. Harmonics are waveform distortions that occur at frequencies that are multiples of the fundamental frequency of 50 Hz used in Indonesia. The dominant harmonics commonly found in low-voltage systems are the 3rd, 5th, and 7th orders, which can increase power losses, create voltage distortion, and damage electrical equipment such as transformers and control systems (Chamdareno et al., 2026; Koerniawan & Hasanah, 2019). The national PLN standard (SPLN D5.004-1:2012) establishes upper limits of 20% for Total Harmonic Distortion Current (THDI) and 5% for Total Harmonic Distortion Voltage (THDV) in low-voltage systems. Similarly, IEEE Std 519-2014 specifies stricter thresholds of THDI ≤ 15% and THDV ≤ 5% for systems below 1 kV. The discrepancy between these two standards necessitates that system designers target the more stringent IEEE threshold to ensure international compliance. When harmonic levels exceed these limits, equipment degradation accelerates, transformer overheating occurs, and protective relay misoperation becomes more likely (Chamdareno et al., 2026; IEEE, 2014; Koerniawan & Hasanah, 2019).

Capacitor banks are widely employed to improve power factor and reduce reactive power losses, potentially increasing system efficiency by 5–10% with proper configuration (Ahmad & Khan, 2020; Ibnu et al., 2025; Sukendar et al., 2024). However, incorrect placement can trigger harmonic resonance, increasing voltage distortion and power losses by 15–20% due to complex harmonic interactions (Barlian et al., 2020; Romadhon, 2025). This research proposes enhancing capacitor bank placement through the Grey Wolf Algorithm (GWA), a metaheuristic approach introduced by Mirjalili et al. (2014) and Romadhon (2025). GWA emulates the social hierarchy of grey wolves (*Canis lupus*), consisting of alpha, beta, delta, and omega roles, and operates through three main stages: encircling prey, hunting, and attacking prey. The study applies this optimization framework to improve power quality in distribution systems.

Prior studies have demonstrated the effectiveness of the Grey Wolf Algorithm (GWA) for capacitor bank placement optimization. El-Fergany and Abdelaziz (2014) applied GWA to IEEE test systems and achieved power loss reductions of up to 7% (Murillo & Aguila Téllez, 2026), while Ali et al. (2016) confirmed improved voltage stability in radial distribution networks (Mathenge, 2025). However, these studies primarily focused on standard test systems without incorporating harmonic spectrum data from actual field measurements. Ghatak and Mukherjee (2017) reviewed capacitor placement methods but noted the absence of integrated harmonic analysis in metaheuristic approaches (Sundar et al., 2026). Similarly, Hachemi et al. (2023) compared optimization algorithms but did not address the interaction between capacitor placement and harmonic resonance risk. The present study addresses these gaps by integrating GWA optimization with field-measured harmonic spectrum data from a Power Quality Analyzer, specifically targeting the 3rd, 5th, and 7th harmonic orders measured in a real low-voltage distribution system. The objectives of this research are: (1) to evaluate the impact of harmonic distortion on the performance of the low-voltage distribution system at the Integrated Laboratory Building 1, Institut Teknologi Kalimantan (ITK); (2) to determine the optimal capacitor bank placement and sizing using GWA; and (3) to assess the resulting improvements in power factor, THDV, and active power losses. The scope of this study is limited to a 12-bus radial system, GWA-based optimization without comparative algorithm benchmarking, MATLAB-based simulation, and analysis of low-order odd harmonics in accordance with IEEE Std 519-2014.

METHOD

This research adopted a quantitative, simulation-based approach integrating power system modeling with metaheuristic optimization. The methodology followed a sequential four-stage framework: (1) problem identification and data acquisition, (2) system modeling and baseline simulation, (3) Grey Wolf Optimizer (GWO)-based optimization, and (4) post-optimization performance evaluation. In the first stage, the problem was identified as excessive harmonic distortion caused by non-linear loads at the Integrated Laboratory Building 1, ITK, which significantly reduces the power factor and increases energy losses. A capacitor bank installation was proposed as the mitigation strategy, with optimal placement and sizing determined through GWO optimization.

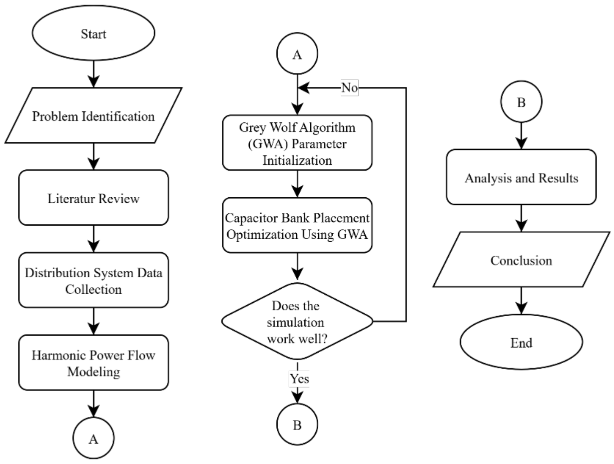


Figure 1. Research Flowchart

After identifying the problem, a literature review was conducted, covering harmonic theory, electrical distribution system modeling, and metaheuristic optimization techniques. The Grey Wolf Optimizer (GWO) was selected due to its effectiveness in handling nonlinear optimization problems with strong convergence capability and robustness. Subsequently, real-world data were collected from the electrical distribution system of the Integrated Laboratory Building 1, ITK, including current, voltage, network impedance, and harmonic levels for the 3rd, 5th, and 7th orders. These data were then used to develop a 12-bus radial distribution system model for simulation purposes.

The developed model was analyzed using the Backward/Forward Sweep (BFS) method to compute harmonic power flow, enabling the calculation of voltage profiles, current distribution, power losses, and harmonic distortion effects. The model's accuracy was validated through field measurement comparisons. Next, the optimization parameters were defined using the GWO, including wolf population size, maximum iteration count, capacitor bank capacity limits at each bus, and weighting factors for multiple objectives such as power loss, total harmonic voltage distortion ($THD_{(}V_{)}$), total harmonic current distortion ($THD_{(}I_{)}$), and power factor improvement.

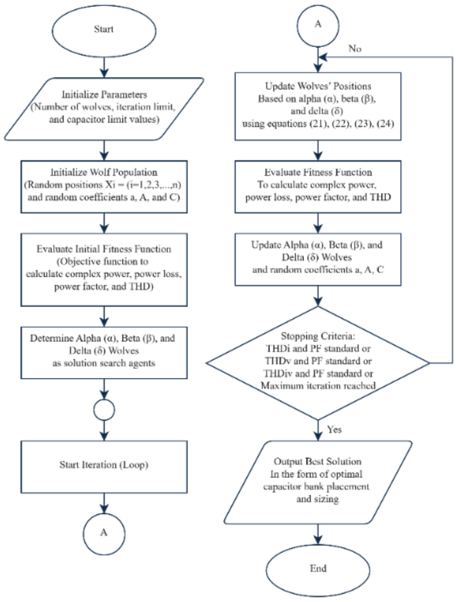


Figure 2. Flowchart of Grey Wolf Algorithm for Capacitor Bank Placement Optimization

The optimization using the Grey Wolf Algorithm began by randomly initializing wolf positions, where each position corresponded to a capacitor placement configuration on specific buses. The leading three wolves (alpha, beta, and delta) were selected to guide the position updates of the remaining wolves, following the mathematical framework of the Grey Wolf

Optimizer (GWO). Each iteration adjusted positions using stochastic coefficients and a linearly decreasing parameter a, achieving a balance between global exploration and local exploitation. Candidate solutions were evaluated using an objective function that incorporated multiple power quality metrics. This process continued until either the power quality constraints were satisfied or the maximum iteration limit was reached. The final output of the method is a validated optimal capacitor bank configuration that minimizes the multi-objective fitness function, yielding optimal bus locations, capacitor sizes, and corresponding improvements in power quality parameters.

RESULTS AND DISCUSSION

The analysis commenced with a comprehensive examination of the baseline conditions of the electrical distribution system at the Integrated Laboratory Building 1, Institut Teknologi Kalimantan (ITK), with a focus on the Low Voltage Main Distribution Panel (LVMDP) as the central distribution hub. Initial insights were drawn from the Single Line Diagram (SLD), illustrating a radial layout with a nominal voltage of 380 V (phase-to-phase) and a transformer capacity of 1000 kVA, supporting 12 buses from Bus 0 (source) to Bus 11 (loads, including PP-UTAMA LANTAI 1 to LP-R. POMPA and R. POWER HOUSE). The analysis revealed a total nominal active power of 436.427 kW, distributed across phases as 147,892.6 W (Phase R), 146,584.6 W (Phase S), and 141,949.6 W (Phase T), alongside an apparent power of 545.638 kVA. The starting power factor was computed as:

$$PF = \frac{P}{S} = \frac{436{,}427}{545{,}638} = 0.929\ PU \qquad (1)$$

Total reactive power was obtained by:

$$Q = \sqrt{S^2 - P^2} = \sqrt{(545{,}638)^2 - (436{,}427)^2} = \sqrt{297.720{,}934 - 190.465{,}317} = 329{,}963\ kVAR \qquad (2)$$

This indicates a prevalence of inductive loads from devices such as motors and air conditioning units, calling for reactive power compensation to improve system efficiency. A 4% imbalance between phases R and T, with the highest load observed at Bus 6 (124.899 W, 28.6% of the total) as shown in Table 1, points to potential power losses and voltage drops, particularly on high-impedance lines. Over 19 days of field measurements (February 5–25, 2025), a peak active power of 90.7 kW was recorded on February 19, 2025, with an apparent power of 95.6 kVA and a power factor of 0.948, indicating that the load reached only 20.78% of the nominal capacity, calculated as:

$$\text{Load Percentage} = \left(\frac{\text{Actual Load}}{\text{Peak Load}}\right) \times 100 = \left(\frac{90.7}{436.427}\right) \times 100 = 20.78\% \qquad (3)$$

This low load condition was influenced by limited laboratory activities during the academic transition period.

Tabel 1. Initial Load Conditions per Panel at LVMDP

Distribution Panel	Active Power Phase R (W)	Active Power Phase S (W)	Active Power Phase T (W)	Total Active Power (W)	Total Apparent Power (VA)	Power Factor	Line Length (m)	Cross-Sectional Area (mm²)
PP-UTAMA LANTAI 1	27,941	26,511	25,362	79,814	85,860	0.929	30	35
PP-UTAMA LANTAI 2	12,781	12,251	11,768	36,800	39,598	0.929	35	35
PP-UTAMA LANTAI 3	10,663	10,697	9,644	31,004	33,373	0.929	58	70
PP-OUT DOOR AC LT 1&2	24,566	24,566	24,566	73,698	79,304	0.929	67	150
PP-OUT DOOR AC 3	41,633	41,633	41,633	124,899	134,408	0.929	40	70
PP-KONTROL ELECTRIC	25,000	25,000	25,000	75,000	80,753	0.929	40	4

Distribution Panel	Active Power Phase R (W)	Active Power Phase S (W)	Active Power Phase T (W)	Total Active Power (W)	Total Apparent Power (VA)	Power Factor	Line Length (m)	Cross-Sectional Area (mm^2)
PUMP								
PP-KONTROL POMPA JOCKEY	1,416	1,416	1,416	4,248	4,573	0.929	40	4
PP-KONTROL POMPA BOOSTER	950	950	250	2,150	2,314	0.929	40	4
PP-KONTROL POMPA TRANSFER	1,250	1,250	250	2,750	2,960	0.929	40	4
LP-POMPA R. POWER HOUSE	1,790	2,040	2,040	5,870	6,318	0.929	40	4
Total	147,892.6	146,584.6	141,949.6	436,427	545,638	0.929	430	380

Source: Reseach Data

Table 1 shows that the PP-OUTDOOR AC 3 (Bus 6) carries the highest load at 124,899 W, while PP-KONTROL POMPA BOOSTER (Bus 9) has the lowest load at 2,150 W. Phase imbalance is evident in smaller buses such as Bus 9, where Phase T records only 250 W compared to 950 W on Phase R, indicating potential risks of voltage drop and increased power losses.

Data Collection at Integrated Laboratory

Data were collected using Power Quality Analyzers (PQA), specifically the Hioki PQ3100 and PW3360, to evaluate power quality at the LVMDP panel. The objective was to obtain real-time measurements of voltage, current, active power, power factor, and harmonic distortion for optimization purposes. Data collection was conducted over 19 days (February 5–25, 2025), with a focused harmonic monitoring period from February 20–24, 2025, using 15-minute sampling intervals in a 3P3W system (380 V, 50 Hz). This process was interrupted by a power outage on February 18, 2025, caused by a landslide at Building D that resulted in a fallen PLN pole.

Harmonic Measurement Results

Measurements of THDI and THDV at Bus 1 during February 20–24, 2025, show THDI values ranging from 3.81% to 14.92% (with the highest 3rd-order harmonic component reaching 14.92% on Phase T), while THDV ranges from 0.13% to 1.20% (peaking at U12 with 1.20%). These values remain within the IEEE 519-2014 standard limit of 5% for voltage distortion at the point of common coupling. The maximum recorded THDI reached 16.88%, calculated as follows:

$$THD_I = \sqrt{I_3^2 + I_5^2 + I_7^2} \cdot 100\% = \sqrt{\left(\frac{14.5}{100}\right)^2 + \left(\frac{7.5}{100}\right)^2 \left(\frac{4.3}{100}\right)^2} \cdot 100 = 0.1688 \cdot 100 = 16.88\% \quad (4)$$

$$THD_v = \sqrt{V_3^2 + V_5^2 + V_7^2} \cdot 100\% = \sqrt{\left(\frac{0.17}{100}\right)^2 + \left(\frac{1.07}{100}\right)^2 \left(\frac{0.19}{100}\right)^2} \cdot 100 = 0.0001209 \cdot 100 = 0.0109995 \cdot 100 = 1.09995\% \quad (5)$$

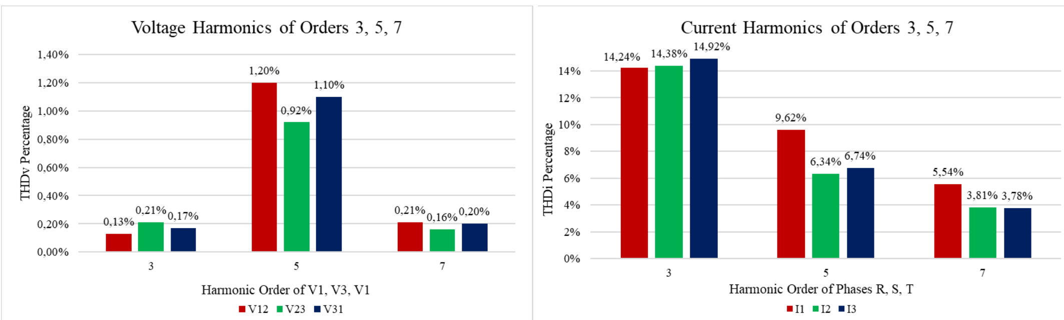


Figure 3. Average THDV and THDI Profile for Orders 3, 5, 7 at LVMDP, February 20-24, 2025
Source: Reseach Data

Load Distribution to 12-Bus Radial System

The load was distributed across 12 buses based on a peak value of 90.7 kW recorded on February 19, 2025, to model the radial configuration. The proportions were derived from the SLD (single-line diagram), with a total load of 436.427 kW, as follows:

$$Proportion\ Bus\ 2 = \frac{79,814}{436,427} = 0.1829 \quad (6)$$

to

$$Proportion\ Bus\ 11 = \frac{5,870}{436,427} = 0.0134 \quad (7)$$

Active power was allocated, e.g.:

$$P_{Bus2} = 0.1829 \times 90.7 = 16.584\ kW \quad (8)$$

Per phase, e.g.:

$$P_{Bus2,R} = 0.3387 \times 16.584 = 5.615\ kW \quad (9)$$

$$P_{Bus2,S} = 0.2838 \times 16.584 = 4.706\ kW \quad (10)$$

$$P_{Bus2,T} = 0.3776 \times 16.584 = 6.262\ kW \quad (11)$$

Apparent and reactive power were calculated as:

$$S_{Bus2,R} = \frac{P_{Bus2,R}}{PF_R} = \frac{5.615}{0.928} = 6.051\ kVA \quad (12)$$

$$S_{Bus2,S} = \frac{P_{Bus2,S}}{PF_S} = \frac{4.706}{0.990} = 4.754\ kVA \quad (13)$$

$$S_{Bus2,T} = \frac{P_{Bus2,T}}{PF_T} = \frac{6.262}{0.993} = 6.306\ kVA \quad (14)$$

And:

$$Q_{Bus2,R} = \sqrt{S^2 - P^2} = \sqrt{(6.051)^2 - (5.615)^2} = \sqrt{36.615 - 31.528} = 2.263\ kVAR \quad (15)$$

$$Q_{Bus2,S} = \sqrt{S^2 - P^2} = \sqrt{(4.754)^2 - (4.706)^2} = \sqrt{22.600 - 22.146} = 0.675\ kVAR \quad (16)$$

$$Q_{Bus2,T} = \sqrt{S^2 - P^2} = \sqrt{(6.306)^2 - (6.262)^2} = \sqrt{39.766 - 39.212} = 0.745\ kVAR \quad (17)$$

Pre-Optimization Simulation Results

Power Flow Simulation Using Backward Forward Sweep

The power-flow simulation was conducted in MATLAB using the Backward–Forward Sweep (BFS) method to evaluate system performance under a 90.7 kW load, with Bus 1 (LVMDP) voltage set to 1.0 p.u. (380 V). The approach involved a backward sweep to calculate currents based on load power and a forward sweep to update voltages through voltage drops from the source to the load. Results presented in Table 2 indicate the lowest voltage of 0.99231 p.u. at Bus 7 due to relatively high line impedance, a total power loss of 0.152 kW, and an average power factor of 0.977 (Phase R: 0.928, Phase S: 0.990, Phase T: 0.994).

Tabel 2. Power Flow Simulation Outcomes Using Backward Forward Sweep

Bus	Status Bus	VR (PU)	VS (PU)	VT (PU)	P (PU)	Q (PU)	PFR (PU)	PFS (PU)	PFT (PU)	Type
0	Slack Bus	1	1	1	1	1	0.928	0.990	0.994	Unity
1	Slack Bus	1	1	1	1	1	0.928	0.990	0.994	Unity
2	Load Bus	0.99935762	0.999475267	0.999303881	0.99935762	0.999475267	0.928	0.990	0.994	Lagging
3	Load Bus	0.99965456	0.999717805	0.999625666	0.99965456	0.999717805	0.928	0.990	0.994	Lagging
4	Load Bus	0.999758884	0.999803025	0.999738718	0.999758884	0.999803025	0.928	0.990	0.994	Lagging
5	Load Bus	0.999691007	0.999747578	0.999665163	0.999691007	0.999747578	0.928	0.990	0.994	Lagging
6	Load Bus	0.999329817	0.999452559	0.999273752	0.999329817	0.999452559	0.928	0.990	0.994	Lagging
7	Load Bus	0.992909946	0.994216903	0.992314706	0.992909946	0.994216903	0.928	0.990	0.994	Lagging

Bus	Status Bus	VR (PU)	VS (PU)	VT (PU)	P (PU)	Q (PU)	PFR (PU)	PFS (PU)	PFT (PU)	Type
8	Load Bus	0.999601219	0.999674235	0.999567864	0.999601219	0.999674235	0.928	0.990	0.994	Lagging
9	Load Bus	0.99979821	0.99983515	0.999781334	0.99979821	0.99983515	0.928	0.990	0.994	Lagging
10	Load Bus	0.999741882	0.999789136	0.999720293	0.999741882	0.999789136	0.928	0.990	0.994	Lagging
11	Load Bus	1	1	1	1	1	0.928	0.990	0.994	Lagging

Source: Reseach Data

Tabel 3. Branch Impedance and Current of the Distribution System

Branch	From Bus	To Bus	R (ohm)	X (Ohm)	R (PU)	X (PU)	IR (PU)	IS (PU)	IT (PU)
1	0	1	0.01	0.049	0.01	0.049	0	0	0
2	1	2	0.007928571	0.000792857	0.054907004	0.0054907	0.006060092	0.004758837	0.006060092
3	1	3	0.015857143	0.001585714	0.109814009	0.010981401	0.002793309	0.002193634	0.002793309
4	1	4	0.0185	0.00185	0.128116343	0.012811634	0.002353117	0.001847979	0.002353117
5	1	5	0.015328571	0.001532857	0.106153542	0.010615354	0.005593852	0.004392979	0.005593852
6	1	6	0.008263333	0.000826333	0.0572253	0.00572253	0.009483555	0.007447159	0.009483555
7	1	7	0.010571429	0.001057143	0.073209339	0.007320934	0.005731553	0.004495457	0.005731553
8	1	8	0.185	0.0185	1.281163435	0.128116343	0.000322462	0.000253233	0.000322462
9	1	9	0.185	0.0185	1.281163435	0.128116343	0.000163173	0.000128146	0.000163173
10	1	10	0.185	0.0185	1.281163435	0.128116343	0.000208721	0.000163915	0.000208721
11	1	11	0.185	0.0185	1.281163435	0.128116343	0.00045	0.00035	0.00046

Source: Reseach Data

Harmonic Power Flow Simulation

The simulation of harmonic power flow, conducted in MATLAB, revealed a peak THDI of 10.36% and THDV of 0.137% at Bus 7, with the 3rd-order harmonic being the most prominent, likely due to nonlinear loads such as electronic devices.

Tabel 4. Harmonic Power Flow Analysis Results for 12-Bus System

Bus	THDIR (%)	THDIS (%)	THDIT (%)	THDVR (%)	THDVS (%)	THDVT (%)	Dominant Order (R)	Dominant Order (S)	Dominant Order (T)
0	0	0	0	0	0	0	0	0	0
1	10.35615759	10.35615759	10.35615759	0.077719449	0.060975383	0.080834167	3	3	3
2	10.35615759	10.35615759	10.35615759	0.016319413	0.012803029	0.01697373	3	3	3
3	10.35615759	10.35615759	10.35615759	0.008738893	0.006855966	0.009089236	3	3	3
4	10.35615759	10.35615759	10.35615759	0.007736225	0.006069349	0.008046364	3	3	3

Bus	THDIR (%)	THDIS (%)	THDIT (%)	THDVR (%)	THDVS (%)	THDVT (%)	Dominant Order (R)	Dominant Order (S)	Dominant Order (T)
5	10.35615759	10.35615759	10.35615759	0.017337005	0.013600092	0.018032877	3	3	3
6	10.35615759	10.35615759	10.35615759	0.025707931	0.020167072	0.026739574	3	3	3
7	10.35615759	10.35615759	10.35615759	0.016117415	0.012644177	0.016763859	3	3	3
8	10.35615759	10.35615759	10.35615759	0.005113626	0.004011666	0.005318723	3	3	3
9	10.35615759	10.35615759	10.35615759	0.00258709	0.002029732	0.002690764	3	3	3
10	10.35615759	10.35615759	10.35615759	0.003309442	0.002596409	0.003442096	3	3	3
11	10.35615759	10.35615759	10.35615759	0.007068304	0.005544809	0.007351984	3	3	3

Source: Reseach Data

Case Study: Harmonics Exceeding IEEE 519-2014 Standards

A critical scenario was simulated to represent operational conditions in which THD_I reached 18.71% and THD_V reached 6.181%, both exceeding the IEEE 519-2014 permissible limits of 15% for THD_I and 5% for THD_V. This scenario represents peak harmonic distortion conditions that may occur during periods of high nonlinear load utilization, such as the simultaneous operation of laboratory equipment and HVAC systems. The exceedance of both THD_I and THD_V thresholds confirms the necessity of systematic harmonic mitigation through optimized capacitor bank placement.

Tabel 5. Harmonic Power Flow Analysis for 12-Bus System with Exceeded Standards

Bus	THDIR (%)	THDIS (%)	THDIT (%)	THDVR (%)	THDVS (%)	THDVT (%)	Dominant Order (R)	Dominant Order (S)	Dominant Order (T)
0	0	0	0	0	0	0	0	0	0
1	18.70828693	18.70828693	18.70828693	5.924387613	4.648023186	6.11815916	3	3	3
2	18.70828693	18.70828693	18.70828693	1.255043761	0.984616407	1.305363936	3	3	3
3	18.70828693	18.70828693	18.70828693	0.681280268	0.534488067	0.708592821	3	3	3
4	18.70828693	18.70828693	18.70828693	0.605836803	0.475300932	0.630124296	3	3	3
5	18.70828693	18.70828693	18.70828693	1.350345183	1.059284417	1.404545265	3	3	3
6	18.70828693	18.70828693	18.70828693	1.978130067	1.551781507	2.0575112	3	3	3
7	18.70828693	18.70828693	18.70828693	1.244973335	0.976686618	1.294907214	3	3	3
8	18.70828693	18.70828693	18.70828693	0.428741902	0.336350196	0.445937788	3	3	3
9	18.70828693	18.70828693	18.70828693	0.21690942	0.1701789	0.225601796	3	3	3
10	18.70828693	18.70828693	18.70828693	0.277473604	0.21769074	0.288595713	3	3	3
11	18.70828693	18.70828693	18.70828693	0.592627991	0.464893532	0.616412587	3	3	3

Source: Reseach Data

Power Loss Analysis

The overall active power loss amounted to 0.152 kW (0.000152 PU), with reactive power loss at 0.0152 kVAR, where Branch 7 accounted for 75% (0.114 kW). The active power loss percentage was:

$$Active\ Power\ Loss\ Percentage = \frac{0.152}{90{,}7} \times 100\% = 0.168\% \quad (18)$$

Annual energy loss was:

$$Annual\ Energy\ Loss = 0.153471 \times 24 \times 365 = 1344.40\ kWH/year \quad (19)$$

With an average PLN electricity tariff of IDR 1500/kWh, financial loss was:

$$Financial\ Loss = 1344.40 \times 1500 = Rp\ 2.016.615/year \quad (20)$$

Implementation of Grey Wolf Algorithm (GWA) for Capacitor Bank Placement Optimization

Implementation of Grey Wolf Algorithm (GWA) for Capacitor Bank Placement Optimization

Optimization Concept with GWA

The Grey Wolf Algorithm (GWA), introduced by Mirjalili et al. (2014) and (Romadhon, 2025), is a metaheuristic technique inspired by the social structure of grey wolves (Canis lupus), providing a robust solution for complex optimization problems. It operates through three main stages: encircling, hunting, and attacking. In the encircling phase, the positions of the wolves are updated relative to the prey (the optimal solution) using:

$$\vec{D} = |\vec{C} \cdot \vec{X}_P(t) - \vec{X}_{(t)}| \quad (21)$$

$$\vec{X}(t+1) = \vec{X}_P(t) - \vec{A} \cdot \vec{D} \quad (22)$$

Where D⃗ represents the distance between the wolf and the prey, and t denotes the current iteration. X⃗_P(t) represents the prey's position (best solution), while X⃗(t) denotes the wolf's current position. The coefficients are defined as follows:

$$\vec{A} = 2\vec{a} \cdot \vec{r}_1 - \vec{a} \quad (23)$$

$$\vec{C} = 2 \cdot \vec{r}_2 \quad (24)$$

The parameter a⃗ decreases linearly from 2 to 0 to balance exploration and exploitation, while $\vec{r}_1$ and $\vec{r}_2$ are random vectors within the range [0, 1]. During the hunting process, the positions are updated based on the alpha, beta, and delta wolves:

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot (\vec{D}_\alpha) \quad (25)$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot (\vec{D}_\beta) \quad (26)$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot (\vec{D}_\delta) \quad (27)$$

$$\vec{X}_{(t+1)} = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3} \quad (28)$$

The attacking phase occurs when convergence is achieved, focusing on the best solution. The Grey Wolf Algorithm (GWA) demonstrates strong capability in handling multidimensional optimization problems (10-bus systems), making it suitable for complex power distribution applications like ITK's.

GWA Algorithm Parameters

The GWA parameters were fine-tuned for optimal performance, featuring 100 wolves, 200 iterations, 10 dimensions (Buses 2-11), a capacity range of 0-1.2 PU (0-1200 kVAR), and a fitness function:

$$Fitness = w1 \cdot P_{rugi} \cdot 10^2 + w2 \cdot THDV_{max} + w3 \cdot THDI_{max} + w4 \cdot (1 - PF_{min}) + \sum penalti \quad (29)$$

Information:

$w1$: 0.4 (weight for power loss)
$w2$: 0.3 (weight for maximum THDV)
$w3$: 0.2 (weight for maximum THDI)
$w4$: 0.1 (weight for minimum power factor)

Tabel 6. Main GWA Algorithm Parameters

Parameter	Value	Description
Number of Wolves	100	Initial population for exploration
Maximum Iterations	200	Iteration count for optimal convergence
Solution Dimensions	10	Number of buses for capacitor placement (Bus 2-11)
Capacity Limit per Bus	0–1.2 PU (0–1200 kVAR)	Capacity range per bus
Total Maximum Capacity	1200 kVAR (12 *Step*)	Total system capacity limit
Maximum Number of Capacitors	7 Units	Limit for technical feasibility
Objective Function Weights	$w_1 = 0.4$ $w_2 = 0.3$ $w_3 = 0.2$ $w_4 = 0.1$	Weights for power loss, THDI, THDV, and power factor

Source: Reseach Data

GWA Optimization Simulation Process

The simulation began by initializing 100 wolves with sensitivity weights (50% load, 30% THD-I, and 20% power factor), resulting in an initial objective function value of 67.67351 at iteration 1. The process ran for 200 iterations, reducing the objective function value to 3.85013 by iteration 94. To avoid stagnation, the population was reinitialized at iteration 154, leading to the optimal placement configuration presented in Table 7: Bus 2 (200 kVAr, 2 steps), Bus 3 (100 kVAr, 1 step), Bus 5 (200 kVAr, 2 steps), Bus 6 (300 kVAr, 3 steps), and Bus 7 (200 kVAr, 2 steps), with a total installed capacity of 1000 kVAr.

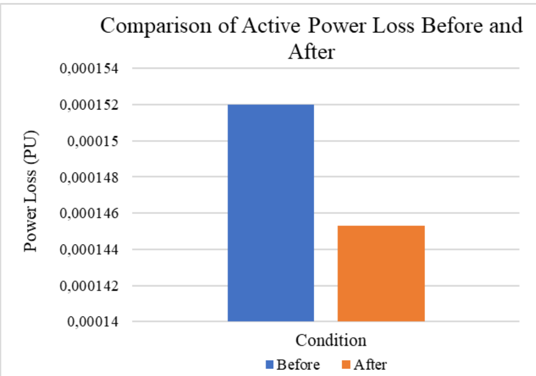
Tabel 7. Optimal Capacitor Bank Placement

Bus	Capacity (PU)	Capacity (Kvar)	Number of Capacitor Steps
Bus 2	0.2	200	2
Bus 3	0.1	100	1
Bus 5	0.2	200	2
Bus 6	0.3	300	3
Bus 7	0.1	100	2
Total	**1.0**	**1000**	**10**

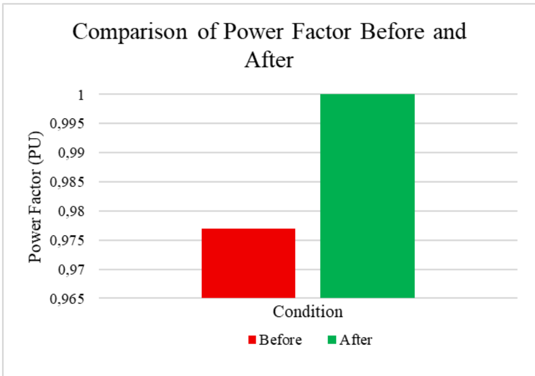
Source: Reseach Data

Post-Optimization Simulation Results

After optimization, power loss decreased by 4.41% to 0.1453 kW, THDV dropped by 75.46% to 1.517%, and the power factor rose to 1.0 PU, as depicted in Figure 4.



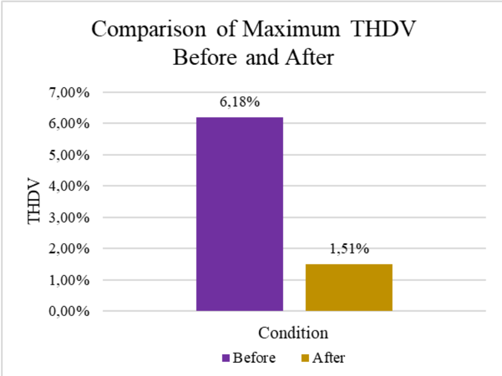
(a)



(b)

Figure 4. (a) Comparison of Active Power Loss Before and After Optimization, (b) Comparison of THDV Before and After Optimization

Source: Reseach Data



(c)

Figure 4. (c) Comparison of Power Factor Before and After Optimization
Source: Reseach Data

The system profile in Table 8 indicates a 0.98% rise in active power and a 6.98-7.04% reduction in current at buses equipped with capacitors, demonstrating improved efficiency.

Tabel 8. Comparison of System Parameters Before and After Optimization

Bus	Parameter	Before	After
Bus 1 (LVMDP)	Active Power (PU)	0.000000	0.000000
	Current (PU)	0.0312166	0.0310488
	Voltage (PU)	0.9993748	1.0042695
	Power Factor (PU)	0.997	1.000
Bus 2 (PP-UTAMA LANTAI 1)	Active Power (PU)	0.0165946	0.0167572
	Current (PU)	0.0057108	0.0053085
	Voltage (PU)	0.9990625	1.0039568
	Power Factor (PU)	0.997	1.000
Bus 3 (PP-UTAMA LANTAI 2)	Active Power (PU)	0.0076513	0.0076513
	Current (PU)	0.0026329	0.0026200
	Voltage (PU)	0.9990867	1.0039818
	Power Factor (PU)	0.997	1.000
Bus 4 (PP-UTAMA LANTAI 3)	Active Power (PU)	0.0064462	0.0064462
	Current (PU)	0.0021849	0.0021742
	Voltage (PU)	0.9990899	1.0039860
	Power Factor (PU)	0.997	1.000
Bus 5 (PP-OUT DOOR AC LT 1&2)	Active Power (PU)	0.0153230	0.0154735
	Current (PU)	0.0052745	0.0049049
	Voltage (PU)	0.9988184	1.0037127
	Power Factor (PU)	0.997	1.000
Bus 6 (PP-OUT DOOR AC 3)	Active Power (PU)	0.0153230	0.0154735
	Current (PU)	0.0052745	0.0049049
	Voltage (PU)	0.9988184	1.0037127
	Power Factor (PU)	0.997	1.000
Bus 7 (PP-KONTROL ELECTRIC PUMP)	Active Power (PU)	0.0155937	0.0157465
	Current (PU)	0.0053001	0.0049301
	Voltage (PU)	0.9989839	1.0038783
	Power Factor (PU)	0.997	1.000
Bus 8 (PP-KONTROL POMPA JOCKEY)	Active Power (PU)	0.0008832	0.0008832
	Current (PU)	0.0003039	0.0003024
	Voltage (PU)	0.9989873	1.0038817
	Power Factor (PU)	0.997	1.000
Bus 9 (PP-KONTROL POMPA BOOSTER)	Active Power (PU)	0.0004470	0.0004470
	Current (PU)	0.0001535	0.0001527
	Voltage (PU)	0.9991779	1.0040732

Bus	Parameter	Before	After
	Power Factor (PU)	0.997	1.000
Bus 10 (PP-KONTROL POMPA TRANSFER)	Active Power (PU)	0.0005718	0.0005718
	Current (PU)	0.0001967	0.0001957
	Voltage (PU)	0.9991231	1.0040182
	Power Factor (PU)	0.997	1.000
Bus 11 (LP-R. POMPA POWER HOUSE)	Active Power (PU)	0.0012205	0.0012205
	Current (PU)	0.0004200	0.0004180
	Voltage (PU)	0.9988402	1.0037346
	Power Factor (PU)	0.997	1.000

Source: Reseach Data

CONCLUSION

Based on the analysis and discussion, this study concludes that the Grey Wolf Optimizer (GWO) effectively optimizes capacitor bank placement across several buses (Buses 2, 3, 5, 6, and 7), with a total installed capacity of 1,000 kVAr (10-step configuration), using sensitivity weights of load power, THDI, and power factor, demonstrating strong capability in handling complex power distribution systems. The individual compensation strategy reduces active power losses by 4.41%, from 0.152 kW to 0.1453 kW, although THDI remains at 18.71%, indicating the need for additional mitigation measures such as harmonic filters. Total Harmonic Distortion Voltage (THDV) significantly decreases from 6.181% to 1.517%, meeting IEEE 519-2014 standards (<5%), although potential capacitor–system resonance effects still require further evaluation. The system power factor improves to 1.0 p.u., reflecting effective reactive power compensation and improved energy efficiency, but also indicating a boundary condition of leading power factor that requires careful monitoring to avoid overcompensation. From an economic perspective, the payback period of approximately 2,841 years indicates that the investment is not financially viable based solely on energy savings; however, indirect benefits such as regulatory compliance, equipment protection, and operational reliability should also be considered in decision-making. Overall, the optimized 1,000 kVAr capacity distributed across five buses must be assessed against the 1,000 kVA transformer rating to avoid potential overcompensation risks. This study confirms that GWO is an effective metaheuristic approach for capacitor placement in harmonic-rich distribution systems, while future work should focus on field validation, integration of harmonic filters, and multi-objective optimization incorporating economic constraints to improve practical applicability.

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AUTHOR CONTRIBUTION STATEMENT

Oik Rizki Septianto conceptualized the study, gathered data, and conducted simulations. Happy Aprillia, Barokatun Hasanah, and Suratno oversaw the project, offered technical expertise, and edited the manuscript. Funding statement was funded by the Institut Teknologi Kalimantan Research Grant [ITK-RG-2025-001], 2025. The authors declare no conflict of interest.

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