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The Impact of Optimal Sizing and Placement of Capacitor Banks in Distribution Networks: Enhancing Voltage Profiles and Reducing Power Losses

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Abstract: In recent decades, the strategic placement of capacitors for compensating inductive reactive power has been extensively investigated by network operators and researchers globally, owing to its profound impact on minimizing power losses, improving voltage regulation, and enhancing overall voltage stability. The installation of shunt capacitors has been demonstrated to significantly improve the efficiency and performance of power systems by regulating voltage levels at load points, as well as at distribution and transmission system buses. This approach not only reduces inductive reactive power but also corrects the system's power factor, thereby optimizing energy utilization. In this study, the optimal sizing and placement of capacitor banks within a specific section of the Duhok city distribution network were systematically analyzed. The Electrical Transient Analyzer Program (ETAP) software was employed to simulate and evaluate power losses and voltage drops both before and after capacitor installation. The findings reveal a marked improvement in the voltage profile across the network, accompanied by a substantial reduction in power losses. These results underscore the critical role of capacitor banks in enhancing the operational efficiency of distribution networks, providing a robust framework for future implementations in similar systems. The methodology and outcomes presented herein offer valuable insights for network operators seeking to optimize power system performance through reactive power compensation.

Keywords: Power loss reduction; Capacitor placement; Voltage drop improvement; Power factor correction

1 Introduction

Electricity is produced at power plants and carried over high-voltage transmission lines. The distribution system serves as the link between the transmission network and consumers. Due to the higher voltage levels in transmission systems compared to distribution systems, along with the high reactance-to-resistance (X/R) ratio in distribution networks, power losses in distribution systems are significantly greater than those in transmission systems. A substantial portion of these losses results from the presence of reactive power, which reduces the thermal capacity of conductors while increasing both power losses and voltage drops. In most cases, reactive power is inductive, leading to a lagging power factor.

To mitigate inductive reactive power, capacitor banks are deployed, which enhances voltage stability, reduces power losses, and enables equipment to operate within their rated thermal capacity [1–3]. Studies have estimated that approximately 13% of the total generated power is lost within the distribution system [4–6] due to inductive reactive power. Maintaining voltage levels within acceptable limits, as defined by international standards, is crucial. Capacitor banks play a key role in keeping bus and load terminal voltages within the required range.

Installing capacitors for voltage improvement and loss reduction is a practical and effective approach. The proper selection of capacitor bank size and location significantly impacts system performance [7–9]. This study presents a method for determining the optimal capacitor bank size and placement using the ETAP Optimal Capacitor Placement (OCP) program.

OCP in power distribution systems, which uses the ETAP software to enhance voltage profiles, improve power factors, and minimize power losses, was investigated in this study. Due to the inductive nature of most loads, power distribution systems experience high losses and voltage drops. Tahir et al. [10] applied the Genetic Algorithm (GA) as an optimization method to determine the best locations and sizes for capacitor banks while minimizing costs. The research focuses on combined OCP and network reconfiguration in power distribution systems using the ETAP software to enhance system stability and minimize losses. The study applies load flow analysis to an Institute of Electrical and Electronics Engineers (IEEE) 33-bus radial distribution system, addressing undervoltage issues and power loss reduction [11–13]. The study aims to enhance power quality in an 11 kV distribution network by optimally placing capacitors, using Rivers State University's network as a case study. The primary focus is on improving voltage profile and power factor and reducing power losses [14]. The results show that the industrial loads, which integrate a capacitor bank and a solar photovoltaic (PV) system, achieved a 39% power factor increase, reducing maximum demand costs and providing a six-year payback period [15]. Mathenge et al. [16] used a method called the Crow Search Algorithm (CSA) to optimize capacitor placement in a radial distribution network, achieving a 30.41% reduction in active power losses and a 32.9% improvement in voltage deviation. Haq [17] applied the Particle Swarm Optimization (PSO) to the IEEE 14-bus system, resulting in a 21.02% reduction in power losses and improved voltage profiles. The integration of distributed generation (DG) sources has added complexity to capacitor placement strategies. A method has been proposed to investigate the optimal placement of capacitors in a distribution system with DG connections using PSO, leading to reduced power losses and enhanced bus voltages in the distribution network [18]. Addressing harmonics in distribution networks is crucial for effective capacitor placement. Moghadam et al. [19] employed the Non-dominated Sorting Genetic Algorithm II (NSGA-II) multi-objective genetic optimization algorithm to determine the optimal location and size of capacitor banks in the presence of harmonics. The objectives included reducing the annual cost of losses and capacitance, minimizing total harmonic distortion (THD), and improving the voltage index (VI). The proposed method was tested on an 18-bus distribution grid, and the results indicated its superiority over other approaches in balancing cost reduction and power quality improvement.

2 Methodology

Most electrical loads are inductive, including motors, transformers, and induction furnaces. These loads require a magnetic field to operate. While inductive loads consume active power to perform useful work, they also demand reactive power to sustain the magnetic field. However, reactive power does not contribute to actual work; instead, it continuously oscillates between the power source and the load. The total power in an electrical system is known as apparent power, which is the vector sum of active power (measured in watts) and reactive power (measured in vars). Apparent power is expressed in volt-amperes (VA), and the relationships between apparent, active, and reactive power are given by the following formulas [20].

$$\begin{aligned} S^2 &= P^2 + Q^2 \\ S &= P + jQ \end{aligned} \tag{1}$$

$$P = S * \cos \emptyset \tag{2}$$

$$Q = S * \sin \emptyset \tag{3}$$

where, S is the apparent power, P is active power, Q is reactive power, and $\emptyset$ is the angle between the apparent power and active power.

Figure 1 shows the power triangle.

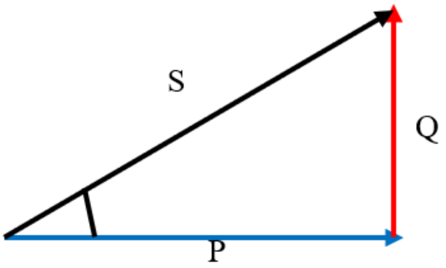

Figure 1. Power triangle diagram [20]

The methodology for this case study is shown in the steps below.

2.1 Network Modeling in ETAP

After creating the single-line diagram of the distribution network in ETAP, the network parameters, including buses, transformers, feeders, loads, and the grid, were defined. Then the ratings and operating conditions were assigned for each network component.

2.2 Load Flow Analysis

Buses with voltage violations and poor power factors were identified after performing a load flow study using the Newton-Raphson method to determine power losses, voltage deviations, and reactive power demand. Then active power losses, voltage profile, and power factor at all buses were recorded before capacitor placement.

2.3 Capacitor Placement Optimization

After opening the OCP module in ETAP, optimization constraints were set, such as voltage limits, power factor range, and the minimum and maximum capacitor bank sizes for each candidate bus. Then the candidate buses for capacitor placement (typically buses with high reactive power demand or voltage violations) were selected. In addition, the OCP simulation was run to determine the optimal locations and sizes of capacitor banks.

2.4 Network Validation with Placed Capacitors

The network model was modified by inserting capacitor banks at the recommended locations. Then the load flow analysis was performed again to compare the power factor improvement at each bus, voltage profile enhancement across the network and reduction in active power losses, ensuring that all voltage and power factor constraints are met after compensation.

2.5 Performance Evaluation and Comparison

Results before and after capacitor placement were compared to evaluate improvements. Reports and graphical visualizations in ETAP were generated for power factor correction, voltage improvement and power loss reduction. Furthermore, economic feasibility was validated by estimating the cost savings due to reduced losses and improved power factor.

2.6 Conclusion and Recommendations

The results confirm that OCP successfully improves power quality while minimizing costs, providing guidelines for real-world capacitor installation and monitoring. This methodology ensures an efficient, cost-effective, and technically sound OCP strategy for improving distribution network performance using ETAP.

Several distribution transformers in the Duhok city network were suspected to experience high power losses and significant voltage drops. However, a single transformer was selected as a case study to demonstrate the impact of optimal capacitor bank sizing and placement. Additional cases can be analyzed and compared to further highlight the benefits of this approach in minimizing power losses and improving voltage levels.

3 Case Study

In the ETAP program, a load with a lagging power factor was connected, and a load flow analysis was conducted on the system. This analysis helps to record the active and reactive power, the voltage and current of the buses and the current of each branch. By evaluating the obtained results, buses and load terminals with voltages falling below acceptable limits were identified. In addition, the percentage of the power losses can be determined. Moreover, by determining the optimal location and size of the capacitors required to be integrated, the voltage profile improvement and the power loss reduction can be assured [21, 22].

There are two main approaches to determining the appropriate capacitor size: the mathematical method and the coefficient table method [15, 23, 24]. Using the mathematical approach, the required compensated reactive power can be calculated using Eq. (4).

$$Q_C = P\left(\tan\emptyset_1 - \tan\emptyset_2\right) \tag{4}$$

where, P is the active power, $\emptyset_1$ and $\emptyset_2$ are actual and desired values of the power factor angle, and Q_C is the compensated reactive power.

If the value of the capacitance is known, then the compensated reactive power is obtained by Eq. (5) [1].

$$Q_C = 3 * V^2 * \pi * f * C \tag{5}$$

where, V is the voltage of the system, f is the frequency of the system, and C is the capacitance to be connected.

Figure 2 represents a simple inductive load which includes inductance and resistance in series with the load with no capacitor placement.

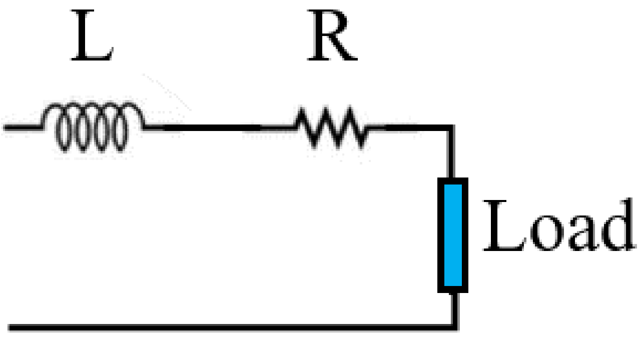

Figure 2. Inductive load without compensation

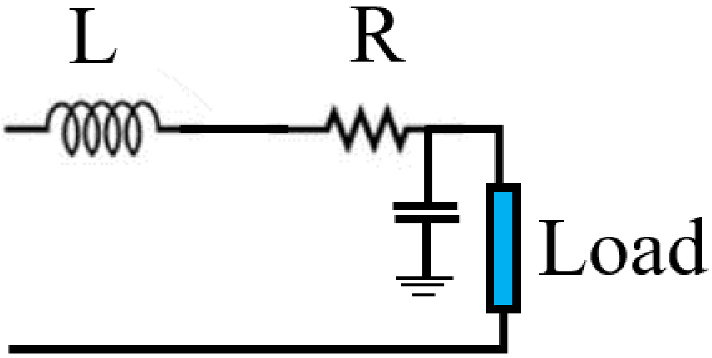

Figure 3. Inductive load with compensation

Figure 3 represents the capacitor connection in parallel with the inductive load.

The case study includes a distribution transformer with the data shown in Table 1.

Table 1. Transformer data

#	Parameters	Values
1	Capacity	250 kVA
2	Primary voltage	11000 V
3	Secondary voltage	416 V
4	Impedance	4%
5	Vector group	Dyn 11
6	Number of branches	2

The load flow analysis was performed on the low-voltage network, as illustrated in Figure 4, which includes the transformer, transmission lines, busbars, and load data. In the figure, busbars experiencing voltage drops are highlighted, with Bus 3 and Bus 4 showing a critical voltage drop.

The setting of busbars for over and under voltages is shown in Table 2.

Table 2. Setting values for bus voltages

#	Function	Critical	Marginal
1	Overvoltage	105%	102%
2	Undervoltage	92%	95%

Tables 3, 4, 5 and 6 illustrate general information of the load flow study, data of buses, cables and loads extracted from the load flow study before compensation.

Tables 4 and 6 indicate a significant undervoltage issue at Bus 3 and Bus 4, along with excessive voltage drops across all loads. Undervoltage negatively impacts the performance of the distribution system and causes major disruptions. Many power system components, including generators, transformers, and compressors, have a specific range of voltage during operation. During peak load conditions, severe undervoltage can lead to equipment failure, affecting multiple customers and, in some cases, the entire system. Therefore, addressing the undervoltage problem is crucial.

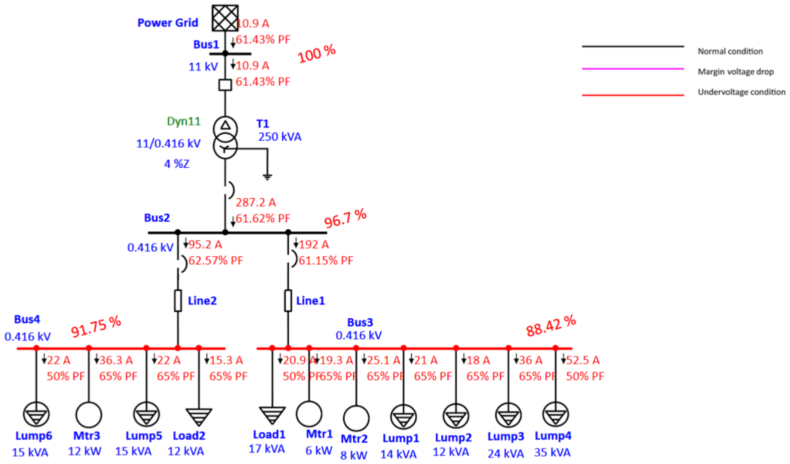

Figure 4. Load flow of the system without capacitor compensation shown in ampere and power factor

Table 3. General information about the load flow analysis before compensation

#	Study ID	Untitled
1	Study case ID	LF
2	Data revision	Base
3	Configuration	Normal
4	Loading cat	Design
5	Generation cat	Design
6	Diversity factor	Normal loading
7	Buses	4
8	Branches	3
9	Power grids	1
10	Loads	11
11	Load-MW	0.112
12	Load-Mvar	0.148
13	Generation-MW	0.127
14	Generation-Mvar	0.163
15	Loss-MW	0.0154
16	Loss-Mvar	0.0155

Table 4. Bus data before compensation

Bus ID	Nominal kV	Voltage	MW loading
Bus 1	11	100	0.127
Bus 2	0.416	96.7	0.123
Bus 3	0.416	88.42	0.0728
Bus 4	0.416	91.75	0.0389

One effective solution to mitigate voltage drop and reduce power losses is the integration of capacitor banks into the system. The most efficient approach involves using the ETAP OCP program, which optimizes capacitor sizing and placement while considering cost factors. Figure 5 presents the load flow analysis of the proposed network after selecting the optimal capacitor size and location using ETAP. The study recommends installing a capacitor bank of 200 kVAR at Bus 3 and another capacitor bank of 100 kVAR at Bus 4.

The voltage of buses before and after capacitor placement is shown in Figure 6.

Table 5. Cable data before compensation

ID	Type	Flow (kW)	Flow (kVAR)	Flow (amp)
Line 1	Line	72.83	98.31	192
Line 2	Line	38.86	49.52	95.21
TR	Transf. $2W$	127.1	163.3	10.86

Table 6. Load data before compensation

ID	Rating/limit	Rated	kW	kVAR	Amp	% PF	V
Load 1	17 kVA	0.416	6.65	11.51	20.86	50	**88.42**
Load 2	12 kVA	0.416	6.57	7.68	15.28	65	**91.75**
Lump 1	14 kVA	0.416	8.7	10.17	21.02	65	**88.42**
Lump 2	12 kVA	0.416	7.46	8.72	18.01	65	**88.42**
Lump 3	24 kVA	0.416	14.92	17.44	36.03	65	**88.42**
Lump 4	35 kVA	0.416	16.74	28.99	52.54	50	**88.42**
Lump 5	15 kVA	0.416	9.44	11.04	21.97	65	**91.75**
Lump 6	15 kVA	0.416	7.26	12.58	21.97	50	**91.75**
Mtr 1	6 kW	0.416	7.99	9.34	19.29	65	**88.42**
Mtr 2	8 kW	0.416	10.38	12.13	25.06	65	**88.42**
Mtr 3	12 kW	0.416	15.59	18.22	36.27	65	**91.75**

Note: The bold number represents critical voltage drop.

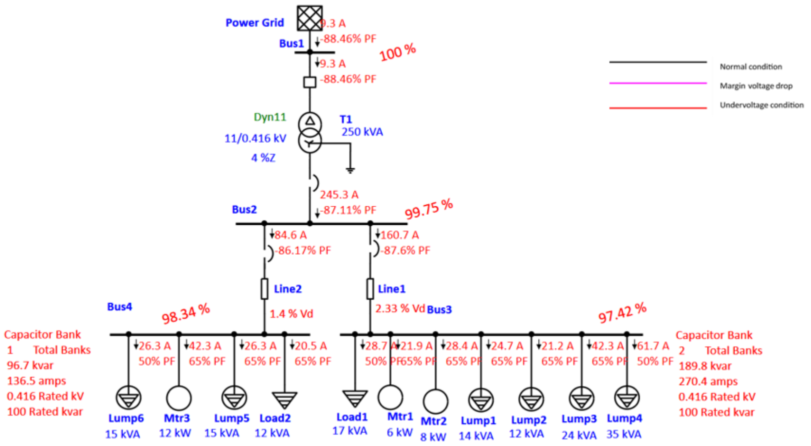

Figure 5. Load flow of the system with capacitor compensation shown in ampere and power factor

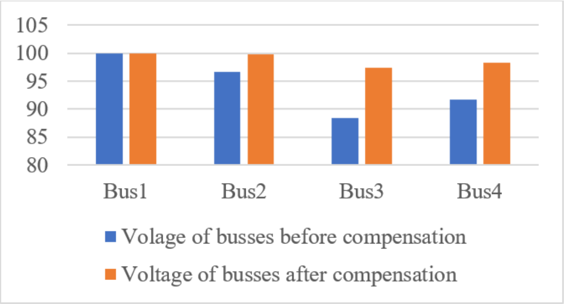

Figure 6. Voltage of buses before and after capacitor placement

It is obvious that after inserting the suggested capacitor banks, the value of voltages of busbars and loads is significantly improved and the voltage drop is mitigated.

3.1 Power loss calculations

Referring to Figure 4 and Figure 5, the overall power factor of the network is 61.43% lagging prior to inserting the capacitor banks. However, after the placement of the capacitor banks, the power factor is corrected to 88.46% which contributes to reducing the power losses significantly.

The power losses before placing the capacitor can be found from the data given in Table 2.

The apparent power generated based on Eq. (1) is $S = P + jQ$.

Generated power $= 127 + j163(kW + kVAR)$

Power losses = $15.4 + j15.5(\text{kW} + \text{kVAR})$.

The total losses of the network can be calculated using Eq. (6).

$$\text{Power losses \%} = \frac{\text{Power lost}}{\text{Power generated}} \times 100\% \qquad \text{Power losses \%} = \frac{15.4 + j15.5}{127 + j163} \times 100\% = 10.57\% \tag{6}$$

The generated power after placing capacitor banks for Bus 3 and Bus 4 is as follows:

Generated power $= 156 - j82(kW + kVAR)$

Power losses = $11.2 + j11.2(\text{kW} + \text{kVAR})$

Power losses $\% = \frac{11.2+\text{j}11.2}{156-j82} * 100\% = 8.98\%$

The summary of the load, power factor and power losses of the system before and after capacitor placement is shown in Table 7.

Table 7. Cable data before compensation

System Equipment	Before Compensation			After Compensation		
	Current (A)	Power Factor	Power Losses	Current (A)	Power Factor	Power Losses
Transformer	287.2	61.62%	10.57%	245.3	-87.11%	8.98%
Line 1	192	61.15%		160.7	-87.60%	
Line 2	95.2	62.57%		84.6	-86.17%	

4 Limitations of the Study

Despite providing valuable insights into the optimal sizing and placement of capacitor banks in distribution networks, this study has certain limitations that should be acknowledged.

4.1 Constant power factor assumption

The study assumes that the power factor of all loads remains constant throughout the analysis. In real-world distribution systems, load characteristics vary over time due to changing operational conditions and consumer demand patterns. This assumption may lead to an oversimplification of the network's dynamic behaviour and impact the accuracy of capacitor placement and sizing decisions.

4.2 Fixed primary side voltage

The voltage on the primary side of the transformer is considered to be within the permissible range and remains stable. However, in practical scenarios, voltage fluctuations occur due to variations in upstream network conditions, transformer loading, and reactive power flows. Ignoring these variations may result in suboptimal capacitor bank allocations that do not fully account for real-time network performance.

5 Conclusions

This study analyzed the effects of optimally placing capacitor banks in a distribution network on voltage profile, power factor, and power loss reduction. The findings highlight that selecting the appropriate size, number, and location of capacitor banks plays a crucial role in enhancing system voltage, improving power factor, and minimizing power losses. By properly sizing and positioning capacitor banks, this study significantly improves the voltage profile, mitigates voltage drop, and enhances system efficiency. The power factor shows a notable improvement from 61.62% to 87.11%, while power losses decrease from 10.57% to 8.98%. These results emphasize the importance of OCP, encouraging power system operators to consider capacitor bank installation as a key strategy for improving network performance. It is advisable to carry out a comprehensive assessment of the city's distribution network to pinpoint the areas experiencing significant voltage drops and high-power losses. Based on this analysis, appropriately sized capacitor banks should be installed at optimal locations to effectively mitigate these issues.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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