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Optimization of Bank Capacitor Placement to Improve Power Quality in the Electrical System

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***Abstract* – Inductive and nonlinear loads in office buildings increase reactive power demand, lower the power factor, and inject harmonic currents into low-voltage distribution panels. The power quality of the Rectorate Building of Universitas Khairun, Ternate, has not been assessed despite its growing demand. This study evaluates its main distribution panel and determines the capacitor bank rating required for power factor correction. Voltage, current, active, reactive and apparent power, power factor, and total harmonic distortion (THD) of each phase were recorded with a power quality analyzer at 30-min intervals from 10:30 to 16:00. The required compensation and capacitance were calculated per phase for a target power factor of 0.95. The phase voltage ranged from 214.5 to 219.7 V and the frequency from 50.05 to 50.08 Hz. Phase S carried the highest current, 134–155 A, showing unbalance. The power factor exceeded 0.92 for most of the day. At 13:30–14:00, it fell to 0.778–0.832 on all phases because reactive power rose to 11.6–20.1 kVAR per phase. Voltage THD remained between 3.6% and 4.5%, within the IEEE 519-2022 limit. Current THD reached 8.2–11.6% and was dominated by the third harmonic. The required compensation was 7.6, 11.9, and 8.2 kVAR on phases R, S, and T, corresponding to 528, 800, and 558 µF. Compensation reduces the estimated line current by 12.5–18.2%. An automatically switched, detuned capacitor bank of about 30 kVAR is recommended to keep the power factor above the 0.85 utility threshold without overcompensation. Load rebalancing and a harmonic resonance study should accompany the installation.**

Keywords: Capacitor bank, Power factor correction, Power quality, Reactive power compensation, Total harmonic distortion, University building.

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I. INTRODUCTION

The electricity demand of university campuses continues to grow as new buildings, air-conditioning systems, computers, and laboratory equipment are added to existing low-voltage distribution networks. Many of these loads are inductive, such as the compressors and fans of air conditioners, pumps, transformers, and magnetic ballasts, while an increasing share is nonlinear, such as switch-mode power supplies and LED drivers [1]–[3]. Inductive loads draw reactive power to establish their magnetic fields, which lowers the power factor (PF) and raises the line current for the same useful active power [4], [5]. A low PF therefore increases conductor losses and voltage drop, occupies transformer and cable capacity that could otherwise serve additional load, and, in Indonesia, may result in a charge for excess reactive energy (kVArh) when the monthly average PF falls below 0.85 [6].

Nonlinear loads introduce a second concern. They draw non-sinusoidal currents whose harmonic components distort the supply voltage, overheat neutral conductors and transformers, and cause measurement errors [1], [7]. Measurements in a healthcare facility showed that harmonic and interharmonic content can cause fundamental-frequency-based meters to underestimate energy consumption by 4–10% [1], and studies of office and research buildings showed that widespread LED lighting alters the harmonic content and even the character of the reactive power seen at the building supply [2], [3]. Consequently, power quality (PQ) assessment has evolved from checking a single index toward evaluating several phenomena together, including voltage and current distortion, unbalance, and PF [8].

Shunt capacitor banks remain the most widely used and economical means of supplying reactive power locally and correcting PF, and their optimal sizing and placement have been studied extensively [9]. In Indonesian buildings, measurement-based capacitor bank studies have been reported for hospitals [4], high-rise office towers [10], university laboratory buildings [11], commercial buildings [12], motor control centers [13], and water pumping stations, where the investment payback was found to be only a few months [14]. Nevertheless, capacitors form a resonant circuit with the inductance of the supply transformer, and in harmonic-rich networks this can amplify harmonic voltages and currents unless detuned or tuned reactors are used [15]–[17]. Harmonic mitigation must therefore be considered together with PF correction, as demonstrated in a campus building of a health polytechnic [18].

At Universitas Khairun, Ternate, earlier work evaluated harmonic distortion at the campus

distribution substation [19], and the installed power demand of a government office building in the region has been analyzed [20]–[23]. However, the Rectorate Building, which hosts the university's central administrative activities, has not been assessed at the level of its distribution panel, and no reactive power compensation has been designed for it. Moreover, many building studies size the capacitor bank from a single operating point or from aggregated three-phase data, which can hide phase unbalance and the short intervals in which PF drops below the utility threshold.

This study addresses that gap by measuring the per-phase PQ of the Rectorate Building distribution panel throughout the working day and using the measurements to size a PF-correction capacitor bank. The contributions are threefold: (i) a time-resolved, per-phase profile of voltage, current, active, reactive, and apparent power, PF, and total harmonic distortion (THD); (ii) identification of the critical interval in which PF falls below 0.85 and calculation of the per-phase reactive power and capacitance required to raise PF to 0.95; and (iii) an estimate of the resulting current reduction, together with practical recommendations on switching strategy, harmonic resonance, and phase balancing for implementation.

II. METHOD

A. Research Site and Measurement

The research was conducted at the Rectorate Building of Universitas Khairun, Ternate, North Maluku, Indonesia, over approximately three months, including data collection and analysis. The building is supplied through a three-phase four-wire low-voltage system, and the measurement was carried out on the secondary (outgoing) side of the building's main distribution panel. A METREL MI 2892 power quality analyzer was used to record the phase voltage V, phase current I, frequency f, active power P, reactive power Q, apparent power S, PF, voltage THD (THD_V), current THD (THD_I), and the current harmonic spectrum of phases R, S, and T, as well as the neutral current. Measurements were taken on 1 December 2025 at 30-min intervals from 10:30 to 16:00 local time (WIT), giving 12 records per phase that cover the working hours of the building. The research procedure is summarized in Figure 1.

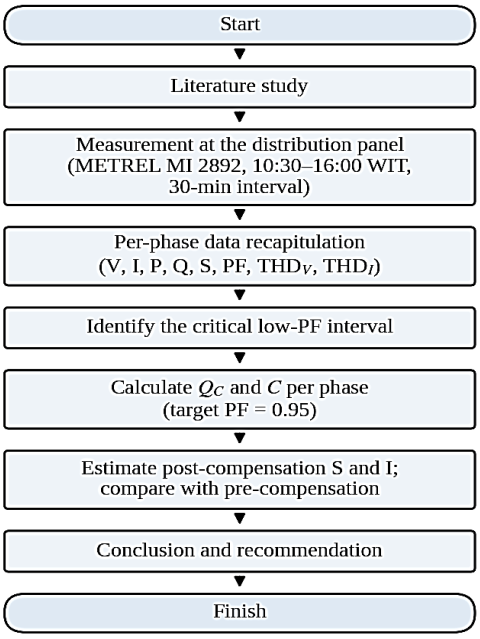


Figure 1. Research flowchart

The recorded data were first recapitulated per phase. The profiles of PF and Q were then examined to identify the interval in which PF fell below the 0.85 limit set by the electricity tariff regulation [6]. The capacitor bank was sized for that critical interval, and the pre- and post-compensation conditions were compared in terms of PF, apparent power, and line current. The harmonic measurements were evaluated against IEEE Std 519-2022 [7] and used to assess the risks associated with installing capacitors.

B. Power Quality Parameters

For each phase, the active, reactive, and apparent power are related to the RMS voltage V, the RMS current I, and the displacement angle φ between voltage and current by (1)–(3), and PF is defined by (4) [4], [11].

$$P = V\,I\,\cos\varphi \tag{1}$$

$$Q = V\,I\,\sin\varphi \tag{2}$$

$$S = V\,I = \sqrt{P^2 + Q^2} \tag{3}$$

$$PF = \cos\varphi = \frac{P}{S} \tag{4}$$

where P is in W, Q in VAR, and S in VA. The harmonic content of the voltage or current is quantified by THD in (5) [7], where X_h is the RMS value of the h-th harmonic component, X_1 is the fundamental component, and H is the highest harmonic order considered.

$$\mathrm{THD} = \frac{\sqrt{\sum_{h=2}^{H} {X_h}^2}}{X_1} \times 100\% \tag{5}$$

C. Capacitor Bank Sizing

The reactive power that a shunt capacitor must supply to raise the power factor from $\cos\varphi_1$ to a target

value cos φ_2, while the active power P is kept unchanged, is given by (6) [5], [12]. The corresponding per-phase capacitance at supply frequency f and phase voltage V is obtained from (7), and the line current after compensation is estimated with (8) [11], [13].

$$Q_C = P(\tan\varphi_1 - \tan\varphi_2) \quad (6)$$

$$C = \frac{Q_C}{2\pi f V^2} \quad (7)$$

$$I_2 = \frac{P}{V\cos\varphi_2} \quad (8)$$

In this study, tan φ_1 was taken directly from the measured values as Q/P, the target PF was set to 0.95 to leave a margin above the 0.85 threshold [6], and f = 50 Hz. Because a capacitor supplies reactive power only, the active power used in (6) and (8) is the measured value P, and the apparent power after compensation is $S_2 = P/\cos\varphi_2$.

III. Results and Discussion

A. Daily Profile of Electrical Parameters

Table 1 summarizes the ranges of the measured parameters for the three phases, and Figure 2 shows the PF and reactive power profiles. The phase voltages varied between 214.5 V and 219.7 V, i.e., within approximately −2.5% to −0.1% of the 220 V nominal value, and the frequency remained between 50.045 Hz and 50.081 Hz. The loading of the three phases was noticeably unbalanced: phase S carried 134–155 A, whereas phases R and T carried 85–116 A and 85–104 A, respectively. This unbalance, together with the triplen harmonic currents discussed in Section 4.B, explains the neutral current of 24.9–48.2 A recorded during the measurement.

Table 1. Ranges of measured parameters, 10:30–16:00

Parameter	Phase R	Phase S	Phase T
Voltage, V (V)	214.5–219.0	215.4–219.7	216.2–218.3
Current, I (A)	84.6–116.1	134.3–155.4	85.2–103.5
P (kW)	18.03–24.30	23.48–31.69	17.06–20.84
Q (kVAR)	3.25–13.66	8.64–20.07	4.62–13.79
S (kVA)	18.30–24.65	28.78–32.99	18.36–22.17
PF	0.800–0.983	0.780–0.956	0.780–0.967
THD_V (%)	3.85–4.15	3.68–4.47	3.63–3.93
THD_I (%)	8.24–11.64	9.83–11.21	8.48–9.65

For most of the day the PF remained high: 0.974–0.983 on phase R, 0.926–0.956 on phase S, and 0.930–0.967 on phase T (Figure 2(a)). At 13:30 and 14:00, however, the PF of all three phases dropped abruptly to 0.778–0.832, below the 0.85 limit. Figure 2(b) shows that this drop was caused by a sharp rise in reactive power rather than by a change in active power: Q increased from about 4–10 kVAR to 11.6–20.1 kVAR per phase, while P decreased slightly. The total three-phase reactive demand reached 45.2 kVAR at 13:30 against 60.4 kW of active power, corresponding to a three-phase PF of 0.80. The timing and the step-like shape suggest that inductive equipment, such as air-conditioning compressors or pumps, operated during this interval while part of the lighting and electronic load was reduced during the midday break; identifying the specific equipment requires sub-metering of the outgoing feeders. The interval of 13:30–14:00 was therefore taken as the critical condition for capacitor sizing.

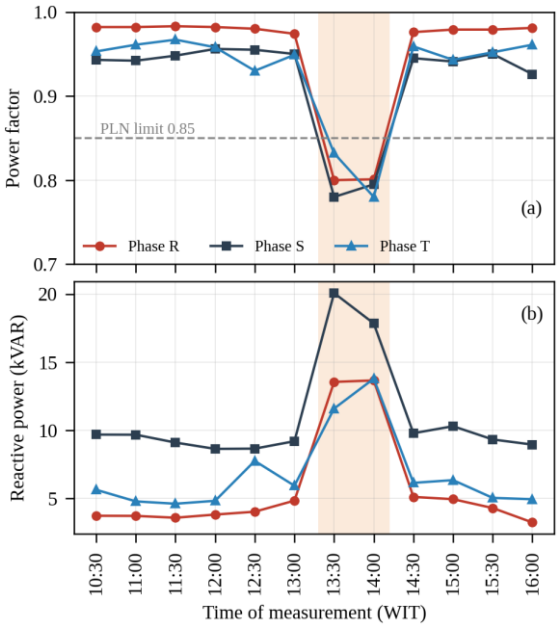


Figure 2. Daily profile of (a) power factor and (b) reactive power per phase; the shaded area marks the critical interval

B. Harmonic Distortion

Figure 3 presents the THD profiles. The voltage THD ranged from 3.63% to 4.47%, well below the 8% limit specified by IEEE Std 519-2022 for systems rated 1 kV and below [7], and also below the 5% value often used as a planning level. The current THD was markedly higher, namely 8.24–11.64% on phase R, 9.83–11.21% on phase S, and 8.48–9.65% on phase T, with the highest values coinciding with the critical interval. IEEE Std 519-2022 limits current distortion in terms of the total demand distortion (TDD) at the point of common coupling, with a limit that depends on the ratio of the short-circuit current to the maximum demand load current, I_{SC}/I_L [7]. Because THD_I is referred to the instantaneous fundamental current rather than to the maximum demand current, the measured THD_I is a conservative indicator; nevertheless, values of 8–12% would exceed the 5% and 8% TDD limits of the two lowest I_{SC}/I_L categories if the panel were supplied by a relatively weak source. Determining I_{SC}/I_L from the transformer rating and impedance is therefore necessary before compliance can be concluded.

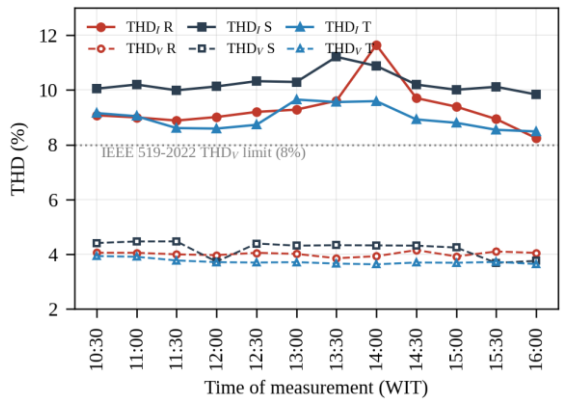


Figure 3. Voltage and current THD profiles of phases R, S, and T

The measured current spectrum in the critical interval (Figure 4) is dominated by the third harmonic, at 5.0–8.2% of the fundamental, followed by the second (3.4–4.1%), fifth (1.9–2.6%), seventh (1.3–1.9%), and ninth (1.3–2.0%) harmonics. The prevalence of the third harmonic is typical of single-phase electronic loads such as computers and LED drivers [2], [3]. Because triplen harmonics are zero-sequence components, they add in the neutral conductor, which is consistent with the neutral current observed. The noticeable second harmonic, which is unusual in steady-state operation, may reflect loads with half-wave rectification or the fact that the analyzer reports the maximum value of each harmonic within the recording interval; it should be confirmed by longer monitoring.

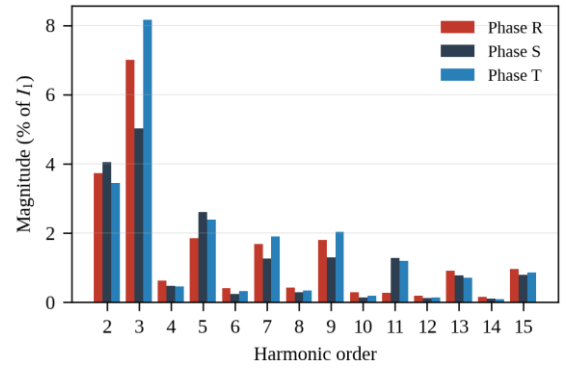


Figure 4. Measured current harmonic spectrum at 13:30 (orders 2–15, in percent of the fundamental)

C. Capacitor Bank Requirement

Table 2 lists the compensation calculated with (6)–(8) for the six critical records. To raise PF to 0.95, the required reactive power was 7.57 and 7.63 kVAR on phase R, 11.92 and 10.13 kVAR on phase S, and 5.90 and 8.19 kVAR on phase T at 13:30 and 14:00, respectively, corresponding to per-phase capacitances of 401–800 µF. Designing for the larger value of the two intervals gives approximately 7.6, 11.9, and 8.2 kVAR (528, 800, and 558 µF) for phases R, S, and T, or 27.7 kVAR in total.

Table 2. Capacitor bank requirement in the critical interval (target PF = 0.95)

Parameter	**13:30**			**14:00**		
	R	**S**	**T**	**R**	**S**	**T**
P (kW)	18.21	24.82	17.33	18.35	23.48	17.06
S_1 (kVA)	22.70	31.93	20.85	22.88	29.49	21.94
PF_1	0.802	0.778	0.831	0.802	0.796	0.778
Q_1 (kVAR)	13.56	20.07	11.60	13.66	17.85	13.79
Q_C (kVAR)	7.57	11.92	5.90	7.63	10.13	8.19
C (µF)	522	800	401	528	683	558
Q_2 (kVAR)	5.98	8.16	5.70	6.03	7.72	5.61
S_2 (kVA)	19.17	26.13	18.24	19.32	24.71	17.96
I_1 (A)	105.6	146.6	96.3	106.7	135.8	101.5
I_2 (A)	89.2	120.0	84.2	90.1	113.8	83.1
ΔI (%)	15.6	18.2	12.5	15.6	16.2	18.1

Because P is unchanged, compensation reduces the apparent power demand and the line current in the same proportion. The estimated line current decreases by 12.5–18.2%, for example from 146.6 A to 120.0 A on phase S at 13:30 and from 101.5 A to 83.1 A on phase T at 14:00. Since resistive losses in the feeder conductors are proportional to the square of the current, the corresponding reduction in these losses is approximately 23–33%, and the released capacity of the supply cables and transformer can accommodate future load growth [5], [11]. These findings agree with building studies in which capacitor banks raised PF above 0.9 and reduced the line current [4], [10], [12].

D. Implementation Considerations

Three observations from the measurements shape how the bank should be implemented. First, the reactive demand is strongly time-dependent. Outside 13:30–14:00, Q on phase R was only 3.2–5.1 kVAR; a fixed 7.6 kVAR bank would then overcompensate the phase and drive it into leading PF, with a risk of voltage rise. An automatic bank switched in steps by a PF regulator, for example six 5-kVAR steps giving 30 kVAR in total, is therefore preferable to a fixed bank. Second, the reactive demand is unbalanced: phase S requires about 56% more compensation than phase R. A conventional three-phase bank supplies equal kVAR per phase, so redistributing single-phase loads from phase S to phases R and T, or using phase-segregated compensation, would improve the effectiveness of the bank and reduce the neutral current. Third, the harmonic content means that capacitors must not be applied without a resonance check. The parallel resonant harmonic order h_r of a bank of rating Q_C connected to a bus with short-circuit power S_{SC} can be estimated by (9) [15], [16].

$$h_r \approx \sqrt{\frac{S_{SC}}{Q_C}} \tag{9}$$

If h_r approaches a harmonic order present in the spectrum, notably the third, fifth, or seventh order observed in Figure 4, the resonance amplifies the harmonic voltage and current and may cause capacitor failure. Detuned reactors connected in series with each capacitor step shift the resonance below the lowest significant harmonic; a detuning factor of 7% is common in networks dominated by the fifth harmonic, whereas 14% is preferred when interaction with the

third harmonic is expected [15]–[17]. Because the supply transformer data were not part of this study, a harmonic resonance study using the actual S_{SC} is recommended before procurement. Compared with the earlier study at Universitas Khairun that focused on harmonic levels at the distribution substation [19], the present results link the measured profile of the building directly to the specification of the compensation equipment. The assessment is, however, based on a single working day; longer monitoring covering different weekdays and seasons is required to confirm the critical interval and refine the step size.

IV. CONCLUSION

The per-phase measurements at the Rectorate Building of Universitas Khairun showed that the supply voltage and frequency were stable and that PF exceeded 0.92 for most of the working day, but a surge of reactive demand at 13:30–14:00 lowered the PF of all phases to 0.778–0.832, below the 0.85 utility threshold. The voltage THD remained below 4.5%, whereas the current THD reached 8.2–11.6% and was dominated by the third harmonic, which, together with load unbalance, produced a neutral current of up to 48 A. Raising PF to 0.95 in the critical interval requires approximately 7.6, 11.9, and 8.2 kVAR of compensation on phases R, S, and T (528, 800, and 558 µF per phase), which reduces the line current by 12.5–18.2%. An automatically switched, detuned capacitor bank of about 30 kVAR is recommended in preference to a fixed bank. Future work should extend the monitoring period, determine the short-circuit level for a harmonic resonance study, evaluate the economic benefit, and verify the performance of the installed bank by post-installation measurement.

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