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Reactive power compensation: a strategic approach to electrical efficiency at SEDA Huánuco

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In the company SEDA Huánuco, high consumption of reactive energy, attributed to the intensive use of motors, was identified, negatively affecting the power factor, which ranged between 0.73 and 0.77, and posing a significant challenge. The main objective of this study was to evaluate the relationship between reactive energy compensation and the electricity billing of SEDA Huánuco S. A. in Tingo María, 2024. The hypothetical-deductive method was applied with a quantitative approach and classified as applied research with a non-experimental design and a correlational-causal level of longitudinal scope. To obtain the data, the electric energy meter code No.74677479 of the company SEDA Huánuco was selected as a sample due to its high consumption of inductive reactive energy. Its behaviour during months of high and low demand was observed to determine the optimal amount of energy to compensate. After designing and simulating tariffs, it was identified that the MT3 tariff, with two energy charges and one power charge, was the most suitable for optimising billing costs in relation to the new power factor of 0.965. In conclusion, reactive energy compensation is significantly related to electricity billing, supported by the acceptance of the alternative hypothesis (H1), leading to the installation of a 73.5 kVAr capacitor bank in parallel at 440 V, distributed in three stages: one of 10.5 kVAr, two of 21 kVAr, and two of 10.5 kVAr.

Keywords: capacitor bank, reactive energy, power factor, electricity tariff

INTRODUCTION

Currently, reactive power compensation has gained relevance as a key factor in optimising costs and energy efficiency in the Peruvian industry. Coupled with the challenges associated with economic sustainability, the increasing energy demand has highlighted the importance of adopting efficient systems that enable responsible use of energy resources. Despite its potential benefits, many industrial sectors lack the technical knowledge or necessary investment to implement adequate compensation systems, directly impacting billing and the performance of their equipment.

From a theoretical perspective, this study focuses on analysing how reactive power compensation influences the financial and operational performance of companies. From a practical standpoint, it seeks to provide information that enables informed decision-making to reduce costs and improve energy efficiency in Peruvian industrial companies, emphasising the relevance and originality of this research in both academic and industrial contexts.

Consequently, the objective of this study was to evaluate the relationship between reactive power compensation through the design of a capacitor bank and the electricity billing of SEDA Huánuco S. A., Tingo Maria in 2024, thereby providing a solid foundation for formulating cost optimisation strategies in the industrial energy sector.

LITERATURE REVIEW

The industry faces challenges related to reactive power overload due to the presence of inductive loads and poor power factors [1]. Consequently, this situation results in penalties on electricity bills and negatively affects equipment efficiency, increasing operational costs and machinery wear [2]. The importance of implementing compensation solutions to reduce reactive power consumption and optimise energy flow in distribution systems has been emphasised in countries like the United States and Germany [3, 4]. Reactive power compensation reduces costs and improves industrial efficiency.

Reactive power compensation refers to using devices, such as capacitor banks, to neutralise reactive power generated by inductive loads, thereby improving the power factor and reducing reactive power consumption in the grid [4]. This improvement helps reduce billing costs and maximise equipment performance [5]. In countries like Colombia and Brazil, optimising the location of capacitor banks and implementing active filters have demonstrated significant improvements in the power factor and harmonic mitigation, resulting in economic and energy efficiency benefits [6, 7]. An appropriate power factor optimises the use of electrical networks.

On the one hand, [8] highlights that the lack of compensation systems in Peruvian industries causes low performance and increased billing due to excessive reactive power consumption. On the other hand, companies such as Volcán and Chungar in Pasco have experienced voltage fluctuations and higher operating costs due to the absence of an adequate compensation system [2]. In a different approach, studies in Ecuador have proposed strategies to optimise voltage profiles and reactive power through the design of alternating current power flows in industrial electrical systems [5]. The phase difference between voltage and current must be minimised for a good power factor.

According to [7], reactive power compensation systems in industries with high energy demand have contributed to mitigating billing surcharges by improving the power factor at points of common coupling. Similarly, in the context of the Peruvian industry, it is essential to implement strategies to reduce reactive power consumption, thereby minimising additional costs and promoting energy sustainability in the sector.

In Brazil, electricity billing is a crucial process for controlling costs and optimising energy use. A mathematical model developed for a poultry farm under the 'green tariff' showed how the power factor and the load inversely impact costs, enabling agro-industrial companies to manage their electricity consumption more efficiently [9]. On the other hand, [10] designed an Excel tool for Company X to detect irregularities in electricity bills, increasing accuracy and control over energy expenses. These studies underline the importance of tools that optimise electricity billing to reduce costs and improve operational efficiency.

Electricity billing is fundamental to company cost management. [11] evaluated different tariff options and identified that the medium-voltage MT-2 tariff offers the greatest savings for the Maestro store in Huancayo, highlighting the importance of appropriately selecting tariffs to optimise expenses. Similarly, [12] developed a mobile application for Electro Oriente S. A. in Jaén, which improved data collection accuracy and reduced billing errors, showcasing how technological innovation can facilitate processes and contribute to operational efficiency in electricity billing.

In [13], it was demonstrated that an adequate and fixed electricity tariff based on a Bayesian approach optimises electricity billing, improving customer retention and energy companies' revenues. In Poland, [14] analysed how changes in electricity billing for photovoltaic system users generated cost uncertainties, hindering investments in renewable energy. Conversely, [15] observed that subsidised tariffs in Jordan encouraged excessive consumption, especially during demand peaks, and suggested removing subsidies to promote more sustainable electricity use.

METHODOLOGY

To address the complexity of the relationship between reactive power and electricity billing, a quantitative approach and a hypothetical-deductive method were applied to analyse the effect of reactive power compensation on reducing electricity costs. Using a non-experimental, longitudinal design and an applied research approach, data were measured before and after the implementation of the design of capacitor banks, allowing for the observation of changes in consumption and billing over time. This correlational-causal research level demonstrated that capacitor banks can sustainably improve energy efficiency and reduce operational costs for the company.

Baseline model and fundamental principles of reactive power compensation

Reactive power compensation is a critical strategy in managing electrical systems to efficiently balance energy generation and demand, ensuring supply stability and cost optimisation [16]. This methodology involves implementing specific devices and strategies, such as capacitor banks and filtering systems, to enhance the reliability and quality of the Power System (SEP) by regulating parameters like voltage and power factor. By reducing reactive power in the system, these techniques contribute to more effective and stable performance, enabling distribution networks to respond efficiently and reliably to demand increases [5, 8]. Therefore, reactive power compensation enhances system stability and optimises energy costs.

Dimension: the power factor as a critical parameter

The power factor (PF) is essential to evaluate the efficiency and stability of an electrical system since it measures the ratio between the active power, which performs valuable work, and the apparent power, which includes all the energy of the system, as seen in equation (1). A PF close to 1 indicates efficient energy use, while lower values suggest inefficiencies and higher losses [3]. This study uses the formula $\cos\phi = P/S$ to calculate the power factor under different demand scenarios, optimising system performance and stability, where P represents the active power (kW), and S represents the apparent power (kVA) [17, 18]. In the industrial sector, the power factor is critical as it serves as a key indicator of the efficiency of an electrical system.

$$PF = \cos\varphi = \frac{P}{S}, \tag{1}$$

where φ – phase angle between current (A) and voltage (V), P – active power *i* kW, S – apparent power in kVA [19].

Design and parameters of the capacitor bank

The optimisation of energy efficiency in electrical systems is achieved through the use of capacitor banks, which correct the power factor and reduce reactive power. These devices, strategically placed, improve the power flow and minimise energy losses, especially during periods of high demand [17]. An optimisation algorithm is implemented to evaluate load variations and determine the optimal size and location of the capacitor banks, both before and after the load entry [5]. A strategic location of capacitor banks maximises efficiency.

$$Q_{\text{effective}} = Q_n \times \left(\frac{V_{\text{mains}}}{V_n} \right)^2, \tag{2}$$

where $Q_{\text{effective}}$ – effective power to be considered for the capacitor, Q_n – nominal power of the capacitor, V_{mains} – grid voltage, V_n – nominal voltage [20].

$$I_{\text{effective}} = \frac{Q_{\text{effective}}}{\sqrt{3} \times V_{\text{mains}}}, \tag{3}$$

where $I_{\text{effective}}$ – effective current, $Q_{\text{effective}}$ – effective power to be considered for the capacitor, V_{mains} – grid voltage [20].

The formula for the peak current of the capacitor:

$$Ik = \frac{Q_n}{\sqrt{3} \times V_{\text{mains}}}, \tag{4}$$

where Ik – peak current of the starting capacitor (A), Q_n – nominal power, V_{mains} – grid voltage (V) [20].

The formula for the conductor current:

$$I_c = 1.3 \times I_{condenser}, \tag{5}$$

where I_c – current of the conductor to be selected (A), $I_{condenser}$ – nominal current of the capacitor (A) [20].

Compensation methods for different load scenarios

Several compensation methods optimise the use of reactive power depending on the configuration and type of load in the system. Global compensation is located at the head of the system and provides a comprehensive solution by operating together with the electrical grid [19]. Applied to the distribution panel, partial compensation balances specific groups of loads and mitigates the overheating of the supply cables. Lastly, individual compensation is connected to high-impact loads, such as high-power motors, representing 25% of the load's kW [19].

Table 1. **Compensation methods**

Measured performance	Global	Partial	Individual
Avoid payment by KVAR	X	X	X
Provides KVAR to loads	X		X
Free the transformer	X	X	X
Frees cables from reactive current	–	X	X
Attenuates losses due to the Joule Effect	–	X	X
Number of installed banks	1	2	4

In Table 1, the chosen method of reactive power compensation affects both the technical performance and the required infrastructure. While the global method simplifies installation by requiring only one capacitor bank, partial and individual methods offer additional benefits, such as reducing losses from the Joule effect and relieving the cables from reactive current, though they require a greater number of banks. Therefore, there is a balance between installation simplicity and technical efficiency that must be considered when selecting the compensation method.

The C/K factor in the design of the capacitor bank

The C/K factor represents the ratio between the capacity of the capacitor bank step and the current adjusted by the grid voltage and the transformation ratio. This value is crucial for correctly activating the bank's steps and maintaining the proper power factor avoiding overcompensation [20].

Therefore,

$$\frac{C}{K} = \frac{Q_1 \times 1000}{\sqrt{3} \times V_{red} \times R_{tc}}, \tag{6}$$

where C/K – regulator scheduling, Q_1 – reactive power of the first step (VAR), V_{red} – grid voltage (V), R_{tc} – transformation ratio [20].

Automatic compensation

Automatic compensation allows for adjusting the power factor in systems or parts of the system that do not operate continuously, keeping the power factor variation within ±10% of its average value [21].

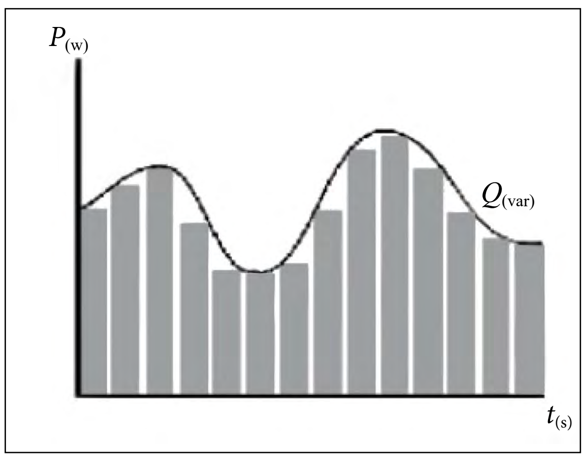

Fig. 1. Automatic compensation: active power *vs*. reactive power

Electrical load

The loads in an electrical system can be classified as resistive, inductive, capacitive, or composite, depending on their influence on the system's reactive power profile. This study considers the inductive load as the primary one as its electromagnetic nature causes a phase shift between current and voltage, creating a delay in the power factor [21].

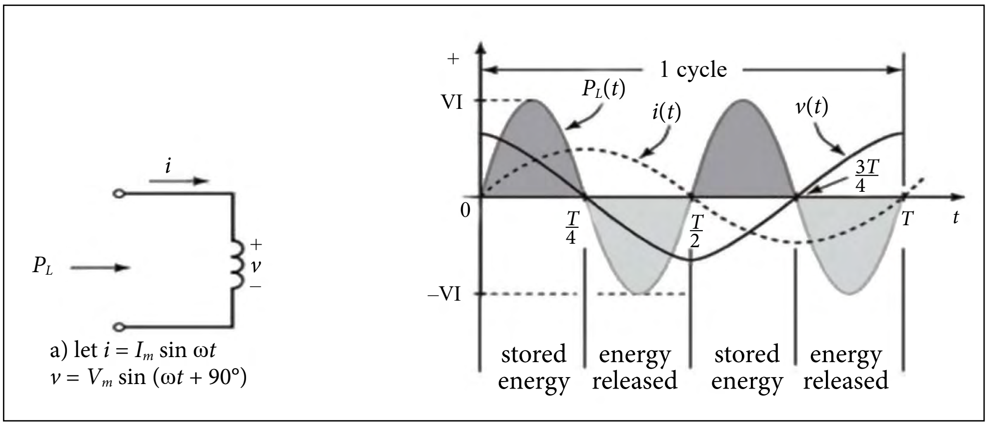

Fig. 2. Inductive load

Harmonics

Equipment that generates harmonics formed by nonlinear loads can oscillate at non-sinusoidal characteristic frequencies due to coupled capacitance and inductance. This results in multiple oscillations and various oscillation frequencies, affecting the quality of electrical power [19].

Non-harmonic generating elements

Linear loads do not generate harmonics, such as resistances, inductances, and capacitors [19].

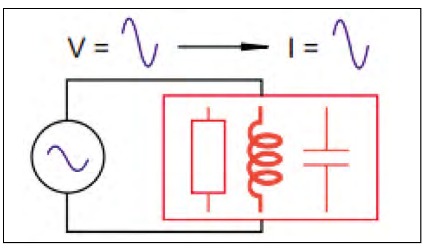

Fig. 3. Linear loads

Technical standard and quality standards in electrical services

To ensure compliance with quality and efficiency standards, this research is based on the Technical Standard for Quality of Electrical Services (NTCSE), which regulates minimum quality levels in voltage, frequency, and harmonic disturbances [18]. The standard provides essential guidelines for implementing compensation systems that minimise energy losses and optimise resource use in high-demand networks, promoting sustainability in the energy sector (Table 2).

Tariff options for medium voltage

According to [15], the electricity tariff is the price consumers pay for electricity. While energy subsidies facilitate access to power for the less privileged and stimulate the economy, they can be unsustainable in the long term due to their impact on the government budget and the environment. In Peru, the Electric Tariff Regulatory Agency (GART), under the supervision of OSINERGMIN, is responsible for setting the tariffs. Users can choose the tariff that best suits their consumption habits and voltage level, with options reviewed annually unless agreed otherwise [22] (Table 3). Therefore,

$$F = ER \times CER, \tag{7}$$

where F – total cost of reactive energy, ER – excess reactive energy, CER – reactive energy charge (expressed in S/. /kVArh) [22].

Table 2. **Quality standards for electrical services**

Quality criterion	Unit of measurement	Nominal value	Description
Strain	V (Volts)	220 V ± 5%	Allowable range of variation in the voltage level to maintain the quality of the electrical supply.
Frequency	Hz (Hertz)	60 Hz ± 0.5%	Range of variation of the nominal frequency to avoid fluctuations in the connected equipment.
Harmonic disturbances	THD (%)	THD ≤ 5%	Maximum level of total harmonic distortion (THD) in the system to minimize disturbances.

Table 3. **Tariff options for regulated users in medium voltage (MV)**

Medium voltage	Type of measurement		Regulated user plan
MT2	2E, 2P	Energy and Power during peak and off-peak hours	No plan
MT3	2E, 1P	On-peak and off-peak energy and power	Present during peak or off-peak hours
MT4	1E, 1P	Energy and Power	Present during peak or off-peak hours

RESULTS AND DISCUSSION

General description of the data obtained

In the first phase of the research, data on reactive energy consumption, peak power, off-peak power, and the power factor of SEDA Huánuco S. A. were analysed. Monthly data were collected before and after the implementation of the capacitor banks to assess the variation in consumption and energy efficiency. These results provide insight into the behaviour of electrical parameters and the load in each phase, which is crucial for understanding the impact of reactive energy compensation on reducing the company's electricity costs.

Figure 4 shows the reactive power to be compensated for all the months analysed, totalling 18 months. The reactive power required for the company SEDA to operate optimally varies across the months, with February 2024 being the month with the highest demand, utilising reactive power of 73.5459 kVAr.

Reduction of the power factor

After the implementation of capacitor banks, a significant improvement in the company's power factor was observed: it increased from an average of 0.721 to 0.965. This improvement implies greater energy efficiency, as the reduction of the amount of reactive energy allows for optimised equipment capacity and decreased energy waste. This change helps minimise penalties for a low power factor in electricity billing, representing an additional economic benefit (see Table 5).

Selection of the reactive energy value to be compensated

It is therefore concluded that to achieve a power factor greater than 0.965, eliminate penalties, and improve the electrical system of

Table 4. **Electrical measurement parameters by period**

Period	Reading date	Reactive energy (kVArh)	Peak hour power (kWh)	Off-peak power (kWh)	System cos phi	kVAr to compensate	Cos phi objective
2023-01	31-01-2023	66669.0242	112.909	113.2726	0.77862	60.5041	0.965
2023-02	28-02-2023	60298.1215	112.909	113.0908	0.77846	60.4538	0.965
2023-03	31-03-2023	65989.0249	112.909	113.0908	0.77836	60.4839	0.965
2023-04	30-04-2023	64356.2993	112.5453	112.909	0.77680	60.8490	0.965
2023-05	31-05-2023	66615.7152	112.5817	112.7999	0.77663	60.8426	0.965
2023-06	30-06-2023	64082.4814	111.6726	112.9453	0.77695	60.8264	0.965
2023-07	31-07-2023	65262.0256	111.3272	111.6544	0.77516	60.6576	0.965
2023-08	31-08-2023	65394.4801	109.7635	112.7272	0.77130	62.3870	0.965
2023-09	30-09-2023	63408.0457	108.509	108.5635	0.76806	61.0140	0.965
2023-10	31-10-2023	66119.9157	109.509	110.2544	0.76549	62.7133	0.965
2023-11	30-11-2023	64122.5177	111.0544	112.0544	0.76981	62.4556	0.965
2023-12	31-12-2023	64657.6444	112.5817	113.1635	0.77996	60.0461	0.965
2024-01	31-01-2024	67038.4239	113.1635	116.9999	0.77133	64.7422	0.965
2024-02	29-02-2024	67608.7506	112.0908	112.4544	0.73382	73.5459	0.965
2024-03	31-03-2024	72494.9821	107.4908	107.5817	0.73205	70.8806	0.965
2024-04	30-04-2024	70117.7117	108.2363	108.509	0.73396	70.9233	0.965
2024-05	31-05-2024	72183.7096	107.3635	107.7453	0.73277	70.7751	0.965
2024-06	30-06-2024	70064.2754	107.109	107.6363	0.73205	70.9155	0.965

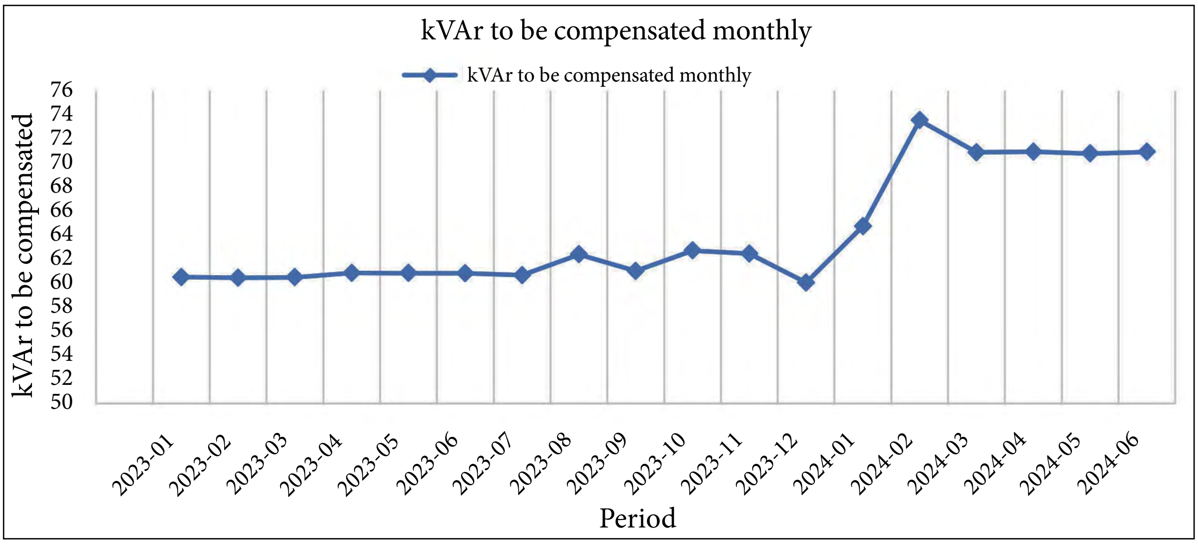

Fig. 4. Monthly kVAr to be compensated

Table 5. **Power factor for the 2023–2024 period**

Period	2023-01	2023-02	2023-03	2023-04	2023-05	2023-06	2023-07	2023-08	2023-09
FP Cosφ existing	0.7786	0.7785	0.7784	0.7768	0.7766	0.7769	0.7752	0.7713	0.7681
Period	**2023-10**	**2023-11**	**2023-12**	**2024-01**	**2024-02**	**2024-03**	**2024-04**	**2024-05**	**2024-06**
FP Cosφ existing	0.7655	0.7698	0.78	0.7713	0.7338	0.732	0.734	0.7328	0.7321

the company SEDA Huánuco SA, the reactive energy required to be compensated for the design of the capacitor bank is 73.5 kVAr, complying with the manufacturer's technical specifications [22].

1. Case (January 2023 – June 2024)
2. Power factor: 0.7628
3. Reactive energy to compensate: 73.5459 kVAr

Capacitor bank design parameters (see Table 6)

Table 6. **Electrical design parameters**

Electrical parameters	
Rated voltage	440 V – three-phase
Nominal frequency	60 Hz
Initial cos phi of the system	0.7328
Cos phi target	0.965
Reactive energy of the system to be compensated	73.5 kVAr
Due to its level of tension	BT capacitor bank
Due to its location in the system	Global capacitor bank
Due to its operation	Automatic capacitor bank

Design calculations

Capacitor bank design according to IEC 60831-1/2 [23].

Table 7. **Power selection in kVAr by steps**

Passed	Power (kVAr)	Number of units	Capacity, kVAr per unit	Voltage
1	10.5 kVAr	1	10.5	440 V
2	42 kVAr	2	21	440 V
3	21 kVAr	2	10.5	440 V

In total, seven units of 10.5 kVAr capacitors are required to complete the 73.5 kVAr capacitor bank at 440 V and 60 Hz (Tables 7, 8).

Table 8. General ITM selection

Parameter	Calculation	Result
Effective current ($I_{effective}$)	Given	96.4437 A
Effective power ($Q_{effective}$)	Less than or equal to 100 kVAr	≤100 kVAr
Adjustment factor (I_{tm})	1.43 × I total	
ITM calculation	1.43 × 96.4437 A	137.9145 A
Selected ITM current	**For the capacitor bank**	**137.9145 A**

The ITM selected for the capacitor bank should be 137.9145 A current.

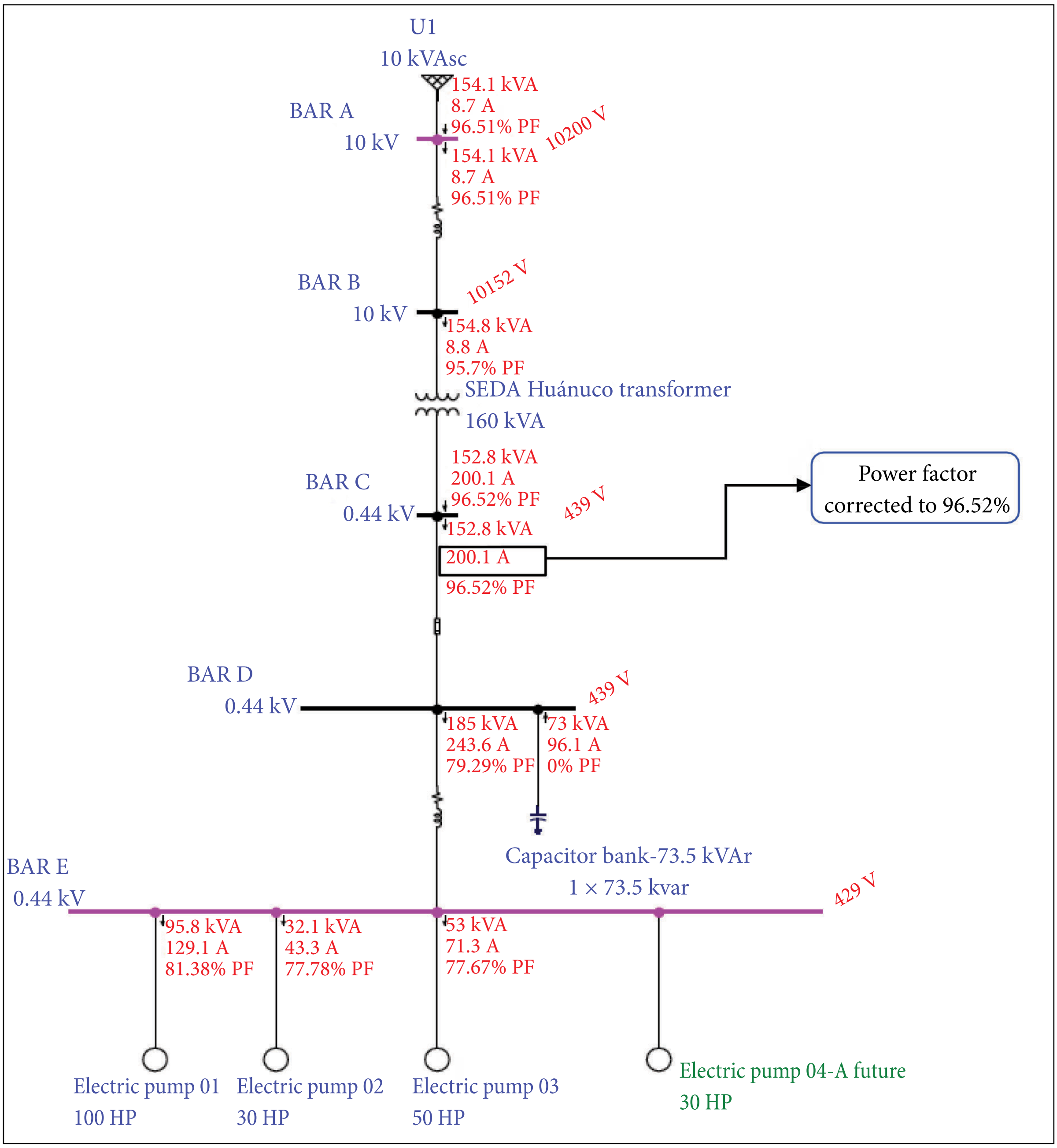

Fig. 5. Single-line diagram compensated with 73.5 kVAr, power factor 0.965. Software ETAP 20.0.0

Switch capacity per step

The following is the selection of the ITM per step, having a total of 3 steps (Tables 9–11):

Three circuit breakers will be provided for each of the steps of the system, with the following characteristics: Step 1 will have a 1-unit breaker of 20 A at 440 Vac; Step 2 will have a 1-unit breaker of 80 A at 440 Vac; and Step 3 will have a 1-unit breaker of 40 A at 440 Vac. This will allow for more efficient current management at each stage, ensuring adequate protection of the components. The selection of different capacities in the circuit breakers ensures optimum adaptation to the needs of each step of the system.

Contactor selection

The nominal power and voltage of the system were used to select the contactors, which were selected in three steps: step 1 was 13 kV Ar, step 2 was 43 kVAr, and finally, step 3 was 21 kVAr (Table 12).

Step 1

Table 9. **ITM selection step 1**

Parameter	Calculation	Result
Initial Data		
Effective power ($Q_{effective}$)	Given	10.5 kVAr
Reference voltage (V_{mains})	Given	440 V AC
Calculation of effective current (effective I)	$Q_{effective} / (\sqrt{3} \times V_{mains})$	–
Substitution of values	$(10.5 \times 1000) / (\sqrt{3} \times 440)$	13.7777 A
Regulatory verification (IEC 60831)	–	–
Required effective power	$Q_{effective} \leq 100$ kVAr	Compliant
Adjustment factor (I_{tm})	$1.43 \times$ I total	–
ITM calculation	1.43×13.7777 A	19.7021 A
Final result for ITM from step 1	**–**	**19.7021 A**

Step 2

Table 10. **ITM selection step 2**

Parameter	Calculation	Result
Initial Data	–	–
Effective power (effective Q)	Given	42 kVAr
Reference voltage (V_{mains})	Given	440 V AC
Calculation of effective current (effective I)	$Q_{effective} / (\sqrt{3} \times V_{mains})$	–
Substitution of values	$(42 \times 1000) / (\sqrt{3} \times 440)$	55.1107 A
Regulatory verification (IEC 60831)	–	–
Required effective power	$Q_{effective} \leq 100$ kVAr	Compliant
Adjustment factor (I_{tm})	$1.43 \times$ I total	–
ITM calculation	1.43×55.1107 A	78.8083 A
Final result for ITM from step 2	**–**	**78.8083 A**

Step 3

Table 11. **ITM selection step 3**

Parameter	Calculation	Result
Initial Data	–	–
Effective power (effective Q)	Given	21 kVAr
Reference voltage (V_{mains})	Given	440 V AC
Calculation of effective current (effective I)	$Q_{effective} / (\sqrt{3} \times V_{mains})$	–
Substitution of values	$(21 \times 1000) / (\sqrt{3} \times 440)$	–
ITM calculation for step 3	**–**	**39.4042 A**

Table 12. **Step contactor selection**

Passed	Parameter	Calculation	Result
1	Data	–	
	Rated power (Q_n)	Given	13 kVAr
	Reference voltage (V_{mains})	Given	440 V AC
	Current calculation (I_k)	$Q_n \times 1000 / (\sqrt{3} \times V_{mains})$	
	Substitution of values	$(13 \times 1000) / (\sqrt{3} \times 440)$	17.0581 A
	Supported power calculation	$\sqrt{3} \times I_k \times V_{mains}$	**13 kVAr**
2	Data	–	
	Rated power (Q_n)	Given	43 kVAr
	Reference voltage (V_{mains})	Given	440 V AC
	Current calculation (I_k)	$Q_n \times 1000 / (\sqrt{3} \times V_{mains})$	
	Substitution of values	$(43 \times 1000) / (\sqrt{3} \times 440)$	56.4229 A
	Supported power calculation	$\sqrt{3} \times I_k \times V_{mains}$	**43 kVAr**
3	Data	–	
	Rated power (Q_n)	Given	21 kVAr
	Reference voltage (V_{mains})	Given	440 V AC
	Current calculation (I_k)	$Q_n \times 1000 / (\sqrt{3} \times V_{mains})$	
	Substitution of values	$(21 \times 1000) / (\sqrt{3} \times 440)$	27.5554 A
	Supported power calculation	$\sqrt{3} \times I_k \times V_{mains}$	**21 kVAr**

Power factor regulator

Table 13. **Power regulator values**

Parameter	Worth
Regulator rated power (Q_n)	73.5 kVAr
Mains voltage (V_{mains})	440 Vac
Nominal frequency	60 Hz
Phases	Three-phase (3Φ)
Regulator design steps	3 steps
Selected steps for design	5 steps

The power factor regulator optimises reactive power control in a three-phase 440 Vac network, with a rated power of 73.5 kVAr. Although the original design includes three steps, five steps were selected to allow a more accurate and efficient regulation of reactive power in the system, better adapting to the needs of the network (Table 13).

C/K factor

Table 14. **C/K values**

Parameter	Worth
Step 1 (Q_1) Capacity	10.5 kVAr
Step 2 (Q_2) Capacity	42 kVAr
Step 3 (Q_3) Capacity	21 kVAr
Total, power of the capacitor bank (total Q)	73.5 kVAr
Mains voltage (V_{mains})	440 Vac
R_{tc}	15/5
Formula for C/K	$10.5 \times 1000/\sqrt{3} \times 440 \times 3$
C/K value	**4.5926**

The value of C/K is 4.5926, once this value is exceeded, the capacitor bank will start to operate; if this value is not passed, the bank will not operate correctly to avoid overcompensation (Table 14).

Fan selection

The fan selection is presented according to the design parameters for optimum operation (Table 15).

Table 15. **Fan value parameters**

Parameter	Calculation	Result
Initial Data	–	–
Specific dissipated power	3 W/kVAr	–
Effective power (effective Q)	Given	73.5 kVAr
Calculation of dissipated power (P dissipated)	$P_{dissipated} = Q_{effective} \times 3$ W/kVAr	–
Power dissipated in the capacitor bank	–	**220.5 W**

Selection of the conductor

The conductor gauge is selected based on the capacitor's rated current, ensuring that it can withstand the maximum expected current. (Table 16).

Table 16. **Driver selection**

Capacitor capacity	10.5 kVAr	42 kVAr	21 kVAr
Capacitor rated current	17.0581 A	56.4229 A	27.5554 A
Current to be withstood by the conductor	22.1755 A	73.3498 A	35.822 A
Caliber	2.8 mm^2	13.3 mm^2	5.26 mm^2

Board selection

The IEC 60831-1/2 [23] compliant panel design is optimised for indoor installation and features compact dimensions and a robust 45 kg structure. It includes additional space for mounted components and ensures functionality and accessibility in limited spaces (Table 17).

Table 17. **Values for board selection**

Parameter	Description	Worth
Standard to consider	Applicable standard for board design	IEC 60831-1/2
Installation location	Place where the capacitor bank will be installed	Inside
Board dimensions	Height (H)	700 mm
	Long (L)	500 mm
	Depth (P)	250 mm
Additional depth (P1)	Dashboard depth with components mounted	735 mm
Board Weight	Empty board weight	45 kg

Design with a future projection

Table 18 presents the analysis for future incorporation of a 30 Hp electric pump within a three-year period, which requires expanding the initial design of the capacitor bank to four steps. The study determined an increase of 12.33 kVAr in reactive power, with an overall design ITM of 161.2005 A, so an ITM of 170 A will be selected. In addition, the design switch is 23.6425 A, and a 25 A model is chosen for the fourth step. Similarly, a 20 A IK contactor will be implemented, based on a 17.0581 A design, together with a 13 kVAr Q 440 AC. The conductor section will be 2.08 mm^2; it will be capable of supporting a current of 22.1755 A, allowing the capacitor bank to reach a total of 85.91 kVAr. Finally, a space will be reserved on the cabinet board for future installation of the fourth step in the capacitor bank.

Impact on electricity billing after compensation

The reduction in reactive energy consumption and the improvement in power factor translated into a decrease in electrical billing costs of SEDA Huánuco S. A. These economic savings (Table 19) were reflected in each monthly billing cycle since penalties for low power factors were practically eliminated. In this way, implementing capacitor banks was an effective strategy to reduce the company's operating costs and improve its profitability. The amounts will be given in US dollars (USD), considering that the local currency in Peru is the sol, one Peruvian sol (S/1) being equivalent to USD 0.27.

Rate summary

Table 20 shows the results of the tariff analysis carried out on different medium voltage options MT2, MT3, and MT4, where the cost of the rate that best fits consumer demand was evaluated for contracting with the electric company; here, the MT3 rate stands out as the most economical option, with a monthly cost of USD 12,910.54, being the optimal option in terms of financial efficiency. This rate

Table 18. **Electrical design parameters**

Item	Item tag		Description	Qty	Voltage (V)	HP	EFF	PF	Factor simul-taneity	Factor demand	Nominal power	Maximum demand		Target power factor	Required reactive power
	Code	No.							LF	DF	kW	kW	kVA	0.965	kVAr
SEDA HUÁNUCO S. A															
1	E1	001	ELECTRIC PUMP 1	1	440	100.00	0.92	0.75	1.00	0.85	81.09	68.92	91.90	0.965	42.05
2	E2	002	ELECTRIC PUMP 2	1	440	50.00	0.92	0.77	1.00	0.85	40.54	34.46	44.76	0.965	19.19
3	E3	003	ELECTRIC PUMP 3	1	440	30.00	0.90	0.76	1.00	0.85	24.87	21.14	27.81	0.965	12.33
4	E4	004	ELECTRIC PUMP 4	1	440	30.00	0.90	0.76	1.00	0.85	24.87	21.14	27.81	0.965	12.33
Initial															**73.58**
Final (3 years later)															**85.91**

Table 19. **Monthly savings with the implementation of the US dollar capacitor bank**

Period	Total active energy	Reactive energy	Reactive energy to be billed	ctm. S// kVar.h	Penalty amount, USD	Total, billing without Compensation, USD	Total, billing with Compensation, USD
	Consumption (kwh)	Consumption (kvar)	Consumption (kvarh)				
2024-10	78,661.12	66,119.92	42,521.58	0.0486	557.97	13,212.20	12,654.23
2024-11	77,337.10	64,122.52	40,921.39	0.0486	536.97	12,989.82	12,452.85
2024-12	80,582.77	64,657.64	40,482.81	0.0486	531.21	13,534.97	13,003.75
2025-01	82,725.37	66,669.02	41,851.41	0.0486	549.17	13,894.85	13,345.67
2025-02	74,781.74	60,298.12	37,863.60	0.0486	496.85	12,560.61	12,063.76
2025-03	81,812.65	65,989.02	41,445.23	0.0486	543.84	13,741.54	13,197.70
2025-04	79,385.38	64,356.30	40,540.69	0.0486	531.98	13,333.85	12,801.87
2025-05	82,125.32	66,615.72	41,978.12	0.0486	550.84	13,794.06	13,243.22
2025-06	79,083.99	64,082.48	40,357.28	0.0486	529.57	13,283.23	12,753.66
2025-07	80,073.77	65,262.03	41,239.89	0.0486	541.15	13,449.48	12,908.33
2025-08	79,247.32	65,394.48	41,620.28	0.0486	546.14	13,310.66	12,764.52
2025-09	76,049.51	63,408.05	40,593.19	0.0486	532.66	12,773.55	12,240.88
2025-10	78,661.12	66,119.92	42,521.58	0.0486	557.97	13,212.20	12,654.23
2025-11	77,337.10	64,122.52	40,921.39	0.0486	536.97	12,989.82	12,452.85
2025-12	80,582.77	64,657.64	40,482.81	0.0486	531.21	13,534.97	13,003.75

is currently in force with the concessionaire company. In comparison, the MT2 rate has a slightly higher cost of USD 12,985.04, while the MT4 rate reaches USD 13,014.53, reinforcing the financial advantage of maintaining the MT3 option.

Table 20. **Summary of tariff options**

Rate option	Amount, USD
MT2	12,985.04
MT3	12,910.54
MT4	13,014.53

Capacitor bank efficiency projections

The implementation of capacitor banks is only a first step towards optimising energy efficiency. For future improvements, it is recommended to explore the possibility of incorporating additional technologies, such as active filters, which can mitigate the effects of harmonics and further improve power quality. In addition, constant monitoring of electrical parameters will allow for precise adjustments and further optimise energy costs of SEDA Huánuco S. A. in the long term.

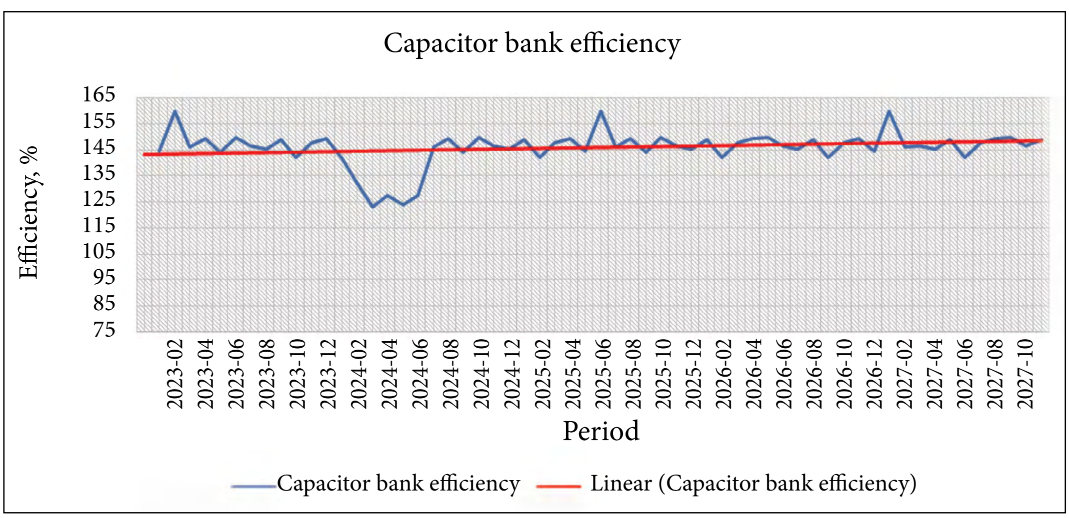

Fig. 6. Efficiency of the capacitor bank

Table 21. **Comparison: before and after compensation**

ID	Before compensation			After compensation		
	Amp flow	% PF	% loading	Amp flow	% PF	% loading
Line 1	–	72.54	–	–	97.08	–
Line 2	–	73.47	–	–	73.47	–
Transformer	138.3	72.54	65.5	102.7	97.08	49.3

Comparison: before and after compensation

Table 21 shows the operation of the SEDA Huánuco electrical system, highlighting a significant improvement after implementing a reactive energy compensation system. The system transitioned from an initial state with unbalanced load and low efficiency to optimised performance. Without compensation, line 2 registered a high current flow (138.3 A) compared to line 1 and the transformer (both at 60.83 A), indicating an imbalance that could lead to overloads and additional losses in the network. The average power factor of the system was only 73%, reflecting limited efficiency, which increased costs due to reactive energy consumption, while the transformer operated at 65.5% of its load, suggesting room for improvement. After compensation, the system achieved a power factor of 97.08% in line 1 and the transformer, reducing energy losses and improving efficient energy use. The current flow decreased to 45.18 A, relieving the load on the conductors, and the transformer load dropped to 49.3%, reducing the risk of overload and expanding the operational margin. These results demonstrate that reactive compensation balances the system, optimises transformer performance, reduces losses, and enhances overall energy efficiency.

DISCUSSION

The null hypothesis (H0) was rejected in the general hypothesis, and the alternative hypothesis (H1) was accepted, demonstrating a significant relationship between reactive energy compensation and the reduction of billing costs. The Mann-Whitney U statistical correlation test (p = 0.001) provides strong evidence to support this conclusion. This finding aligns with previous research, such as [3], which highlights the economic benefits derived from reactive energy compensation, and [16], which underscores cost reductions in the industrial sector due to efficient energy management.

Regarding the specific hypothesis H0a, the results show that high reactive energy consumption in SEDA Huánuco, with the power factor fluctuating between 0.732 and 0.771 during February 2024, is directly related to energy inefficiency and economic penalties. This result aligns with studies like [2], who state that a low power factor increases operating costs, and [8], which emphasises the importance of proper reactive energy management to avoid additional costs and optimise efficiency.

Concerning the specific hypothesis H0b, it was concluded that an adequate capacitor bank design significantly improves the power factor. The implementation of an automatic capacitor bank under a global compensation system allowed for achieving an optimal power factor of 0.965, eliminating penalties for excessive reactive energy consumption. These findings are supported by studies like [1], which highlights the importance of efficient design in reducing energy costs, and [5], which emphasises how proper compensation improves operational efficiency in industrial systems.

From a technical perspective, the results show significant improvements after implementing the reactive compensation system. Current flow and transformer load decreased, optimising the operating margin of the equipment and reducing losses in the network. These observations align with theoretical and experimental research by [24] and [17], highlighting a positive impact of capacitor banks on energy efficiency and operational sustainability.

In summary, the research demonstrates that reactive energy compensation is a key tool for improving the power factor and reducing operational costs and contributes significantly to sustainability and business competitiveness. These results reaffirm the importance of efficient energy management for companies like SEDA Huánuco, ensuring regulatory compliance, resource optimisation, and long-term profitability.

CONCLUSIONS

This study analyses the relationship between reactive power compensation and cost optimisation in electricity billing at SEDA Huánuco S. A., Tingo María. The findings show that the implementation of a 73.5 kVAr compensation system not only eliminates monthly penalties for excessive reactive energy consumption, which averaged USD 570.57 but also significantly improves the company's power factor, raising it to an optimal 0.965. This progress is especially relevant given that the reactive energy consumption of 66.6 kVAr exceeded the regulatory parameter of 30% of the total active energy, generating additional costs and inefficient power factor fluctuations, ranging between 0.732 and 0.771. The effectiveness of an optimised compensation system design, including an automatic power factor regulation mechanism was validated through a comprehensive analysis of 18 months of billing and simulations performed in ETAP software. These results underscore the importance of effective reactive power compensation strategies to mitigate economic penalties and ensure operational efficiency and financial sustainability in industrial contexts with high energy demand.

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REAKTYVIOSIOS GALIOS KOMPENSACIJA: STRATEGINIS POŽIŪRIS Į ELEKTROS VARTOJIMO EFEKTYVUMĄ ĮMONĖJE „SEDA HUÁNUCO“

Santrauka

Įmonėje „SEDA Huánuco“ buvo nustatytas didelis reaktyviosios energijos suvartojimas, susijęs su intensyviu variklių naudojimu, kuris neigiamai paveikė galios koeficientą, svyruojantį tarp 0,73 ir 0,77, ir sukėlė reikšmingą iššūkį. Pagrindinis šio tyrimo tikslas buvo įvertinti reaktyviosios energijos kompensacijos ir sąskaitų už elektros energiją ryšį įmonėje „SEDA Huánuco“, esančioje Tingo Marijoje (2024 m.). Buvo taikytas hipotetinis dedukcinis metodas (kiekybiniu požiūriu) ir tyrimas apibrėžtas kaip taikomasis, naudojant neeksperimentinį dizainą ir koreliacinį priežastinį išilginį pjūvį. Duomenims kaupti buvo pasirinktas tiekimas Nr. 74677479 dėl didelio reaktyviosios energijos suvartojimo, stebint situaciją didelės ir mažos paklausos mėnesiais, siekiant nustatyti optimalią kompensuojamos energijos kiekį. Sukūrus projektą ir atlikus tarifų modeliavimą, nustatyta, kad MT3 tarifas, turintis dvi energijos ir vieną galios sudedamąsias dalis, buvo tinkamiausias sąskaitų išlaidoms optimizuoti, atsižvelgiant į naują galios koeficientą 0,965. Apibendrinant galima teigti, kad reaktyviosios energijos kompensacija yra reikšmingai susijusi su elektros sąskaitų išlaidomis – tai patvirtina alternatyvios hipotezės (H1) priėmimas, o tai paskatino įdiegti 73,5 kVAr talpą turintį kondensatorių banką, prijungtą lygiagrečiai 440 V, padalintą į tris etapus: vieną 10,5 kVAr, du 21 kVAr ir du 10,5 kVAr.

Raktažodžiai: kondensatorių bankas; reaktyvioji energija; galios koeficientas; elektros tarifas